Department of Naval Architecture, Ocean
and Marine Engineering

A Decision Support System for the Selection of Most Appropriate Antifouling Coatings for Fishing Vessels Operating in the Mediterranean and the Black Sea

Refik Özyurt

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:  Date: 20 December 2021

Dedicated to:

Sonsuz sevgi ve bitmek bilmeyen desteklerini her daim arkamda hissettiğim büyük aileme.

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Abstract

This PhD thesis focuses on biofouling of fishing vessel hulls and investigates the impacts of biofouling on ships' frictional resistance "in real" conditions, specifically for industrial fishing vessels operating in the Mediterranean and the Black Sea coated with different types of paints.

As part of the PhD study, face to face interviews with the fishermen were conducted in order to understand their awareness about the impact of the biofouling and the coating selections. Following that, an extensive and systematic experimental study was carried out for investigating the impacts of two different antifouling coating systems, namely foul release (FR) and self-polishing copolymer (SPC) coatings. Static immersion tests were conducted for SPC antifouling coatings. Eight different antifouling coatings were applied on immersion test panels and immersed for over a year. Biofouling accumulation on the panels was observed periodically. Next, various antifouling coating patches were applied on a fishing vessel to compare performances of the SPC coatings under the same conditions after a year of operation. Then, ship tests results were compared with the static immersion tests results. Finally, case studies were employed with the data generated from the static immersion tests for three fishing vessels operating in two different locations equipped with either trawl or purse seine.

Results showed that although most of the fishermen are aware of the penalties caused by the biofouling, a significant number of fishermen have limited knowledge on the impacts of the biofouling. Furthermore, results also showed that biofouling accumulation shows different characteristics among the same antifouling coatings and among the different antifouling strategies (Foul release vs self-polishing copolymer coatings). In addition to that, ship test results showed similar results (insignificant differences) in comparison to case studies conducted in the Black Sea.

1 Introduction

1.1 Chapter Introduction

This chapter introduces the subjects covered in this thesis by presenting the background behind this work, the motivation of the research aims and objectives, the layout of the thesis and finally, the chapter summary section, respectively.

1.2 Background

Fishing is an activity that has always attracted people since the early times of humanity (Gartside and Kirkegaard, 2009). According to the Food and Agriculture Organisation (FAO), fish and other types of seafood provide a considerable amount of protein for the global population per capita intake of dietary protein. The approximate fish consumption per capita in the world was 20 kg in 2017 (FAO, 2019). This reflects the importance of fishing for the world population for thousands of years.

Despite there are no specific limits when classifying fishing activities, it can be said that fishing activities vary between region, fish species, technology, investment, boat type, gear type and purpose of fishing activity (Cooke and Cowx, 2006; O'Farrell et al., 2019). In the literature, industrial fisheries or large-scale fisheries, artisanal fisheries, small-scale fisheries, and recreational fisheries found namely the most popular categories among the fishing activities (Charles W. and Makowski, 2015; Jafarzadeh et al., 2016; Marine Management Organisation, 2017; Watson and Tidd, 2018). For that reason, regional fishing practices along with the authorities' descriptions of the fishing practices should be carefully considered when classifying fishing activities.

Watson and Tidd (2018) demonstrated industrial fisheries statistics regarding global catch and landings between 1950 and 2015. What can clearly be seen in this study is the dominance of industrial fisheries. In this study, taking only the number of principal species caught into account, it can be said that trawl and seine catches constitute the majority of the fish caught by industrial fisheries. Examining the worldwide capture of principal species indicated that pelagic fish such as anchovy, pollock, tuna, sardine, cod, and mackerel are the main species caught by the fishing industry (FAO, 2019). Hence, this evidence presents and supports the idea that seines and trawls are the most commonly used gear types of modern-day commercial/industrial fisheries.

According to FAO's fishery and aquaculture statistics yearbook, in 2019, there are 4.5 million fishing vessels globally, and more than half of them (2.8 million) are propelled by engines. By only taking this number into account, the dependency of fishing activities on fossil fuel is very clear. Considering that fishing vessels are the fundamental assets of industrial fisheries (Uğurlu et al., 2020), it can be stated that most fishing activities, including industrial fisheries, are highly fossil-fuel dependent and energy-intensive economic activities (Parker and Tyedmers, 2015). Therefore, there have been several research studies carried out indicating GHG emission rates by industrial fishing vessels.

Tyedmers et al. (2005), Winther et al. (2009) and Tyedmers and Parker (2012) stated that the amount of fossil fuel used and GHG emissions released by the fishing vessels are at remarkable levels within different periods. In addition to that, Basurko et al. (2013) examined fuel consumption and the carbon footprints of 3 fishing vessels. They showed that the calculations could not be generalised and specific analysis has to be made by considering variables such as the fishing vessel type, target species, gear type and site. These results show the significance of determining the fishing activity classification for consistency and further emission calculations. However, another critical point has to be made clear in these studies. Although emission rates of larger fishing vessels are considered seriously, emission rates of smaller fishing vessels, including smaller commercial fishing vessels, are not considered by many researchers (Coello et al., 2015). This is an indicator showing that GHG emissions from industrial fisheries are at unprecedented levels, and yet the results obtained from the studies focusing on GHG emissions might be higher than the estimated amounts.

In 1997, the International Maritime Organisation (IMO) introduced a new regulation, Annex VI, in the International Convention for the Prevention of Pollution from Ships (MARPOL) with the aim of limiting air pollution from ships. After MARPOL Annex VI was introduced, several revisions were made, such as introducing the Energy efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) in 2011. Although newly introduced EEDI and SEEMP bring stricter emission standards, MARPOL Annex VI regulations are limited to several types of ships (such as bulk and gas carriers, tankers, container ships, general freight carriers, refrigerated freight ships and combination carriers) over 400GT (IMO, 2009a, 2009b). Therefore, considering the volume of the fishing fleet and the types of the ships are referred to, it is not difficult to conclude that the fishing vessels are not covered by the MARPOL Annex VI regulations (Behrendt, 2014). Although IMO’s regulations do not include fishing vessels, they will likely be expanded to the fishing vessels in the future (Bazari and Longva, 2011; Jafarzadeh et al., 2017). In other words, the question is not if but when MARPOL will include fishing vessels. As a result, these studies and regulations should be considered as an indicator and the motivation for fishing vessel owners to reduce fuel costs and hence the emissions towards a more sustainable environment.

Looking at the problem in detail, there are several approaches to reduce fuel consumption and the impact on the environment for both new and existing fishing vessels. Improving the operation profile, improving the ship hull design and/or hull form for the relevant fishing activity, improving the fishing gear design, using alternative fuels, improvements in propulsion systems, or improving the roughness values with the help of hull coatings can be listed as some of the intervention examples (He and Winger, 2010; Latorre, 2001; Notti et al., 2019; Rihan, 2010; Schau et al., 2009; van Marlen, 2009).

What is more, recent studies in the literature show increasing interest in energy efficiency improvements in the fisheries. For example, Gabiña et al. (2016) investigated various magnetic devices to improve fishing vessels' energy efficiency. Similarly, Jafarzadeh et al. (2017) studied liquefied natural gas (LNG) as a fuel in a fishing vessel with a system engineering approach and showed possible environmental/economic benefits. Palomba et al. (2017) approached fuel consumption reduction by assessing waste-heat refrigeration technologies in fishing vessels.

Notti et al. (2019) conducted an experimental study to show the impact of biofouling accumulation on a foul-release coated trawler by comparing a trawler's fuel consumption in three time periods with the help of a monitoring system. Moreover, onboard monitoring devices were used to estimate the performance predictions of the antifouling coatings for the fishing vessels. What is more, their results showed that onboard monitoring devices could give an idea for the performance prediction of the antifouling coatings for the fishing vessels. However, lacking availability of monitoring devices on every fishing vessel and low frequency of data sampling from the devices are still in question, as Armstrong (2013) stated. Overall, although these studies show the great effort put into improving energy efficiency for the fishing vessels, none of them focuses on hydrodynamic performance investigation of the hull protections and biofoulings for the fishing vessels. Among the proposed solutions mentioned above, this thesis focuses on the advantages of hull protection for the fishing vessels and biofouling impacts on hydrodynamic performances of the industrial fishing vessels.

A hydrodynamically smooth hull surface is a desired phenomenon for the ships. The reason behind this is to avoid additional forces acting in the opposite direction to the ship’s motion on the ship hull surface. That is to say, these forces cause additional resistance on ships which results in powering penalties and are often caused by the fouling of marine coatings. There are several studies conducted showing the detrimental effects of biofouling on ships. Moreover, biofouling is a well-known problem in the shipping industry and causes a significant increase in the total drag of ship hulls. To detail, from light to advanced fouling accumulation on ship hulls showed an increase ranging from 8% to 86% in shaft power (Haslbeck and Bohlander, 1992; Schultz, 2007; Watanabe et al., 1969). Thus, it is one of the most challenging problems that the researchers have to cope with in the shipping industry towards more environmentally friendly and economical shipping (Abarzua and Jakubowski, 1995; Schultz et al., 2011).

Because the air resistance of a ship consists of only a small proportion of the total ship resistance, it is assumed that ship hydrodynamic resistance consists of two main components: residual and frictional resistance. With frictional resistance consisting of up to 87% of the ship's total resistance at lower speeds (when the vessels sails at a low Froude number), it is not difficult to assume that it is the dominant resistance component of the ship's total resistance for the ships cruising at slower speeds (Woods Hole Oceanographic Institution, 1952). Hence, as the majority of the fishing vessels are considered slow speed ships, frictional resistance's importance for fishing vessels is remarkable. Nevertheless, any possible improvement in energy efficiency for the fishing vessels by considering the frictional resistance improvements would significantly reduce the fuel consumption of fishing vessels on a global scale.

Biofouling is a natural but unwelcome settlement process of certain marine organisms on the ships' submerged surfaces. Moreover, there are known to be more than 4000 kinds of aquatic organisms causing biofouling on ship hulls (Yebra et al., 2004). Abarzua and Jakubowski (1995) detailed biofouling accumulation in three steps: molecular fouling, microfouling and macrofouling. Molecular fouling is the adsorption period of organic polymers in the marine environment initiated as soon as a human-made object is immersed in water. Another critical point to remember is that, in this period, a conditional organic film is formed. Thus, this conditional film initiates a sequence of events causing micro and macro fouling (Compère et al., 2001; Loeb and Neihof, 1975). After molecular fouling accumulation, together with the alterations on the conditional film surface, microorganisms, bacteria, and diatoms as primary colonisers and spores of macroalgae and protozoa as second colonisers are attached on the surface. At this point, a biofilm layer forms and is called microfouling accumulation. After that, sessile organism larvae as tertiary colonisers attach to microfouling and called macrofouling accumulation (Abarzua and Jakubowski, 1995; Balqadi et al., 2018; Bhosle et al., 2005).

Biofouling on ship hulls can easily be linked to the parameters such as temperature, salinity, light, geography, depth, and voyage speed (Admiraal, 1976; Yebra et al., 2004). Several methods have been developed with many different parameters to minimise biofouling's detrimental effects in the shipping industry. Satheesh et al.

(2016) and Flemming (2020) summarised antifouling methods into three categories: physical, biological and chemical. Several physical methods were developed to combat biofouling on ship hulls, such as electrolysis, acoustic technology, radiation, and surface topography modification. However, problems like power requirement, corrosion, difficulties in application, stability make physical antifouling methods insufficient to overcome biofouling's adverse impacts (Branscomb and Rittschof, 1984; Cao et al., 2011; Liang and Huang, 2008). For the biological methods, some organisms' enzymes and secondary metabolites for preventing biofouling settlement on ship hulls can be given as examples. However, due to the reason that the extraction of these enzymes and metabolites are complex, labour-intensive processes and stability of enzymes in the natural environment is a challenging topic, more studies have to be conducted to overcome biofouling's impacts (Chandrakant and Murlidhar, 2017; Satheesh et al., 2016).

Chemical methods are the most popular antifouling methods in the present day, as there are many commercialised antifouling coatings available today. Biocides used in coatings constitute the majority of the chemical methods. Tin based, copper-based, zinc-based, silver-based coatings can be given as examples. Satheesh et al. (2016) classified chemical methods as: (i) Organotin containing coatings, (ii) Copper with booster biocides coatings, (iii) Self-polishing copolymers coatings, (iv) Foul release coatings (v) Chlorination.

Antifouling coatings have been the most sufficient and adequate coatings to escape from penalties caused by biofouling to date (Swain, 1999, 2010; Swain et al., 2007). Furthermore, antifouling coatings can be divided into two sections: traditional and modern chemical compounds containing coatings. Traditional coatings are divided into subsections; insoluble and soluble coatings. Insoluble or hard coatings consist of vinyl and epoxy, which are mainly used for faster ships. Soluble coatings are resin and toxic materials-based coatings suitable for relatively slower vessels. On the other hand, modern antifouling coatings can be considered in 2 time periods; TBT era and post-TBT era antifouling coatings (Zhang, 2019). A tin-based organotin compound, tributyltin (TBT), was one of the most efficient antifoulants used in coatings until IMO banned it entirely in 2008 (IMO, 2002). The reason behind this prohibition was the deleterious effects of TBT based antifouling coatings on aquatic life, as first discovered by Alzieu et al. (1981). After the ban, there has been more focus on tin free coatings and copper-containing coatings by the paint companies (Yebra et al., 2004). Self-polishing copolymers (SPCs) and controlled depletion systems (CDPs) are the two types of Tin free antifouling coatings.

'How can you forecast if an antifouling coating has the potential to be successful or not in the long term?'. The answer to this question was identified as 'very difficult' by Sánchez and Yebra (2009). Several methods predict coating effects on skin friction of representative hull surfaces and in-service ship performance. Although field tests and laboratory setups are considered as the two main categories within this scope, field test methods are considered to be challenging but more reliable and yet the most informative methods. Field test methods include sea station tests, static tests, dynamic tests and ship tests. The field tests can be considered as natural (static tests and ship tests) and artefact simulating test methods (Sea station tests and Dynamic tests). Sánchez and Yebra (2009) and Atlar et al. (2019) provided a further explanation of these methods in detail.

A systematic investigation is the data collection and analysis to answer a specific question or a problem of concern. Furthermore, when finding the answers to the relevant questions and problems, all the process is broken up into steps leading to conclusions. In other words, a planned structure and method are used to reach a conclusion or the answer to the question in concern. To give an example from this PhD thesis, to answer the question "What are the fishermen's knowledge about the antifouling strategies, their preferences, and behaviours?" a questionnaire was prepared with the experts as a first step and interviews were conducted with the fishermen later. Following that, the generated qualitative and quantitative data was analysed, and evaluations were made with the help of plotted graphs. Therefore, from survey preparation to plotting the data to make an evaluation, this process can be considered a systematic investigation.

A keynote has to be taken here for the context of what is meant by “in real” conditions. As detailed in the literature review chapter of this thesis, there are many studies conducted investigating the impacts of biofouling on ships. However, it can be seen that most of the studies conducted are carried out with the ideal conditions, such as using the most successful antifouling coating strategies or professionally applied antifouling coating applications. For that reason, a survey was conducted with the fishermen to determine their current application methods, antifouling coating choices, and practices they use in the field. In addition, the field and ship tests detailed in Chapter 4 are conducted in the natural marine environment so that biofouling growth over time for each antifouling coating is determined as a result of the survey conducted.

Within this perspective, evaluations made after analysis of the survey results show the currently used applications or so-called “in real” conditions. To give an example, survey results showed that certain SPC antifouling coating brands are used for the industrial fishing vessels and therefore determined antifouling coatings were used in the static immersion field tests and the ship tests. Therefore, rather than using a random antifouling coating manufacturer brand’s most successful antifouling coating, the most currently used antifouling coatings among the industrial fishermen or antifouling coatings in so-called “in-real” conditions were considered when conducting field tests and ship tests.

For the reasons mentioned above, in this PhD thesis, industrial fishing vessels and penalties caused by a widespread phenomenon, marine biofouling, were taken into consideration and systematically investigated. Although many studies have been conducted on the impacts of biofouling on ship resistance, to the best of the authors’ knowledge, no specific research has been performed for comparing several the self-polishing copolymer and foul release coatings’ performances through static and ship field tests over time with a focus on ship resistance and powering of purse seiners and trawler fishing vessels in real conditions. Two different antifouling coating systems (namely foul release (FR) and self-polishing copolymer (SPC) coatings), field tests (namely ship tests and static immersion tests), automatic identification system (AIS), and face to face surveys were performed in order to investigate the impact of biofouling on industrial fisheries by focusing on the resistance and powering of fishing vessels. Thus, this thesis aims to fill this gap and get the fishermen's attention to the importance of selecting the most appropriate antifouling coatings.

1.3 Structure of Thesis

This section explains the structure followed in this thesis. The general structure followed in this thesis can be seen in Figure 1-1 in order.

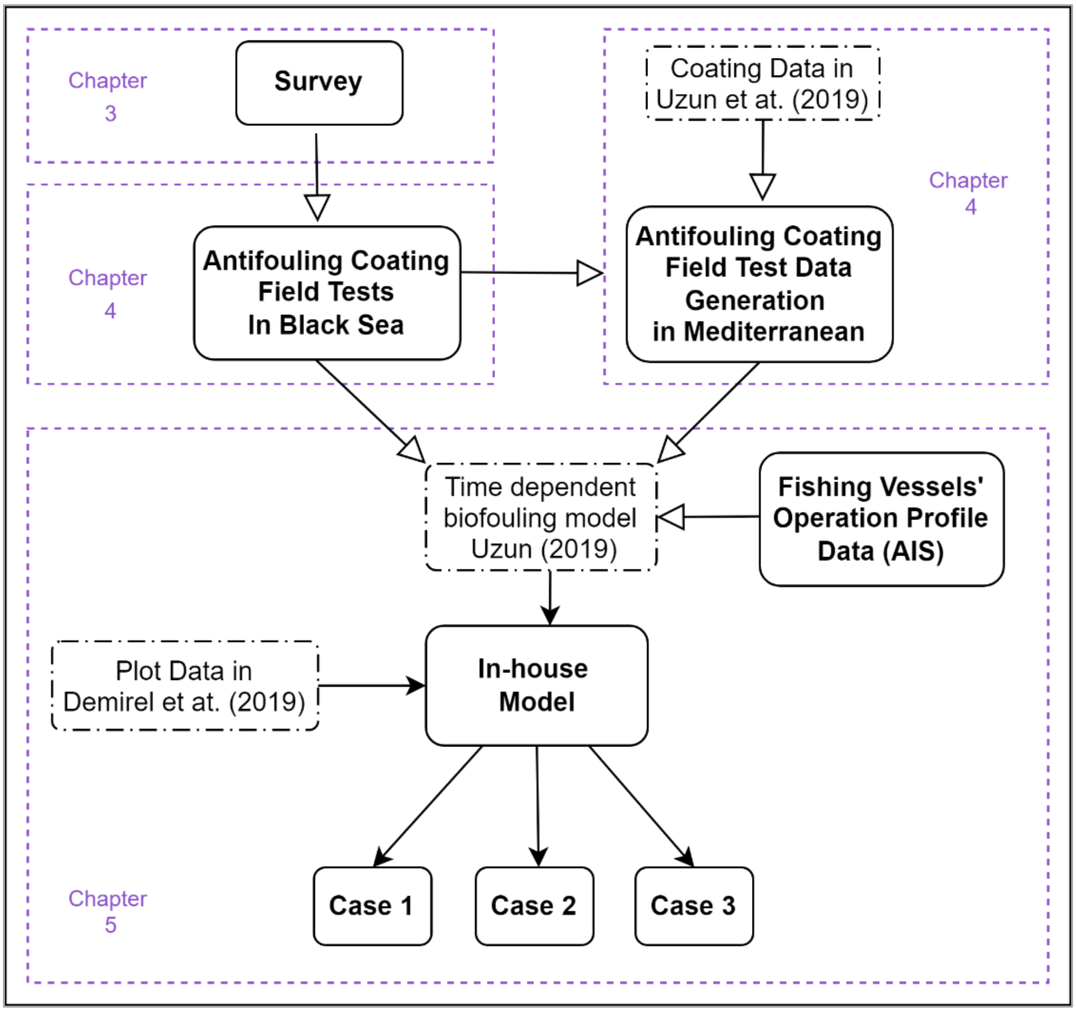


Figure 1-1: Structure followed in this thesis.

As shown in Figure 1-1, to determine the awareness and the approach of fishermen regarding antifouling, a survey is conducted with fishermen. After determining the most commonly used antifouling coatings and the methods, the most common five coatings used in the fishing industry are applied on panels to be immersed to determine fouling characteristics of the relevant coatings in the Black Sea. Following that, similar data is generated with the same coatings in the Mediterranean Sea with the help of similar immersion field test data used in Uzun et al. (2019). Next, an in-house model is developed in order to predict frictional resistance and power increase in full-scale by using automatic Identification System (AIS) data for the fishing vessels, Uzun, (2019)' time-dependent biofouling growth model, Demirel et al. (2019)'s added resistance plots for the ships with different LOA(m) operating with a variety of speed under different fouling conditions, and Granville (1958)'s similarity law scaling method. As a result, three case studies are conducted to show the antifouling performance of the relevant coatings on different fishing techniques and in different fishing zones.

As stated in the previous chapter, one of the first things that enable us to calculate the added resistance and power requirements of the relevant ships is the roughness function and Reynolds numbers of the relevant surfaces. As the surface conditions of the ship hulls are directly related to antifouling coatings, determining the antifouling coating behaviours of the fishing vessels is a necessity. For that reason, the first step was taken as conducting a survey among fishermen in order to understand and determine the common practice with regards to antifouling methods for fishing vessels, how the maintenance is conducted, how the coating types are selected, how the most common application is chosen, most commonly used fishing techniques, whether the fishermen get trained or not and so on. In order to prepare the survey first step was taken as determining the questions after getting in 4 professionals' help within the academia. After weeks of discussions, 34 open-ended questions are determined to be asked to the fishermen. The results of the survey are presented in Chapter 3. In addition, biofouling accumulation of several fishing vessels' underwater hulls is investigated, and results are presented in Section 3.3 to generate adhesion strength data for the fouler organisms.

In order to obtain roughness heights values (k_s), immersion field tests are designed and conducted for the most common coating brands by following the most common coating methods and applications used, as obtained from the survey. In Chapter 4, novel roughness data showing the biofouling growth over time in 2 different antifouling coating types over a year in the Black Sea is presented together with analysis. In addition to that, a selected fishing vessel is coated with five different coatings available commercially. After a year of operation, biofouling accumulation is observed and measured and then compared with the static field immersion test data. After starting the field test data, test panels are investigated systematically. In other words, field test panels are taken out of the water first and then observed with eyes, hands, and rulers. Fouling on each panel is recorded, and notes are taken related to the species accumulated on them. This procedure is repeated weekly in the first month and then biweekly over a year. Biofouling growth on both panels and the ship hull are rated using the Naval's ship technical manual (NSTM) standards. Finally, the fouling rating results of ship tests and static field tests are compared.

After that, fouling ratings are converted to k_s values by using the conversion table between NSTM fouling ratings and k_s values of Schultz (2007). These obtained k_s values are further used when generating antifouling field test data for the Mediterranean Sea. In addition to that, antifouling coating field test data is generated for the Mediterranean Sea by using the similar field test data used in Uzun et al. (2019) and presented in Chapter 4.

In Chapter 5, three case studies are conducted. Following that, results are presented. After getting fouling ratings and k_s values from the field tests, the first step is to determine the relevant fishing vessels which are fishing in different fishing zones with different fishing techniques. After that, relevant fishing vessels' operation profiles, vessel speed and locations are determined over time from an automatic identification system (AIS) from marinetraffic.com. Next, the fouling ratings of the antifouling coatings from the field tests, plot data in Demirel et al. (2019), which is generated by using Granville (1958)'s similarity law scaling method, and specific fishing vessels' operation profile over time are implemented in an in-house model by taking advantage of Uzun, (2019)'s time-dependent biofouling model to generate the relevant added frictional resistance and power increases for three fishing vessels. Therefore, comparisons between different fishing zones and different fishing techniques can be conducted in terms of economic and environmental impacts due to fouling accumulation.

The in-house model was developed to conduct all the calculations using MATLAB when inputs are given. The in-house model can be detailed in several steps. First, once the NSTM fouling ratings of biofouling growth over time on selected antifouling coatings for two different locations is determined, fouling ratings are set as an input for the MATLAB and then defined as input-1. Following that, selected ships' operating profiles are obtained from marinetraffic.com and set as another input for MATLAB, defined as input-2. Next, Uzun (2019)'s time-dependent biofouling growth model was implemented and set as another input for the MATLAB, named as input-3. Following that, input-1 and input-2 were run in input-3 and fouling ratings of the specific antifouling coatings over time that are applied on the selected fishing vessel is determined. As a result, relevant fouling ratings over time results are set as another input for the in-house MATLAB model, named input-4. Following that, fouling ratings are converted into ks values using Equation 33. Equivalent sand roughness heights over time are then used as another input for the MATLAB, named input-5. After that, selected ship characteristics are determined and set as another input for the inhouse MATLAB model, named as input-6. Next, added resistance values are determined for the selected ships operating with certain fouling conditions at given speeds using Demirel et al. (2019)'s added resistance plots and defined as another input for the in-house model, named input-7.

For that reason, once all the inputs from input-1 to input-7 are known, the impact of biofouling for a fishing vessel coated with the selected antifouling coating can be calculated. Consequently, impacts of biofouling can be illustrated with the output graphics for the case studies in regards to financial analysis and CO_2 emission calculation results by using the in-house model developed using MATLAB.

1.4 Motivation of Research

This section provides the Author's motivation behind the work carried out in this thesis and clarifies how the gaps were challenged and addressed in the literature. 21st Century has brought technological advancements in our lives and contributed considerably to our understanding of the impacts of human activities, such as GHG emissions, in the world and the importance of environmental sustainability. For that reason, authorities in shipping introduced related legislative regulations such as the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) in 2011 to encourage more energy-efficient shipping. The maritime world offered several solutions to overcome emission problems and have more energy-efficient shipping. Moreover, Energy-saving devices (ESDs), better designs, trim and ballast optimisation, solar power integration, wind power integration, and hull protection can be given as possible solution examples. Furthermore, although decision-making authorities firstly excluded smaller vessels from the legislation's scope, IMO's 2050 targets include all the ship sizes. For that reason, the author noted the gap in the literature; to the best of the author's knowledge, there is no systematic study showing the benefits of the fouling control systems (hull protection) on fishing vessels involved in industrial fishing activities.

In addition to that, ITTC (2011) stated and so drew attention to the lack of databases with regards to the roughness on the coated surfaces invaded by different fouler organisms. The reason behind this is that the impact of biofouling (roughness) on frictional resistance and the ship's power requirements can be determined through experimental field studies. As of the author's knowledge, there is no such biofouling database over time available from field tests, including static field and ship tests with different antifouling coatings conducted in the margins of the Atlantic Ocean between Asia and Europe. Therefore, it has been the motivation behind the routine field immersion tests and ship tests conducted in the Black Sea in this PhD thesis.

Although there have been many studies examining biofouling in the shipping world, most of the work done focuses on hydrodynamic performances of the ships or the biological characteristics of the fouler organisms. Furthermore, to the best of the author's knowledge, there is no social science research relevant to the biofouling phenomenon conducted about fishermen and their opinions about the antifouling strategies, preferences, and behaviours systematically. This gap in the literature motivated the author for the survey conducted in this thesis.

Besides, the support of local coating companies as well as international coating companies made this work achievable. So this motivated the author to conduct extended field tests to make a comparison between the locally and internationally available coatings.

1.5 Research Aims and Objectives

This PhD thesis aims to investigate the impacts of biofouling on ships' frictional resistance “in real” conditions, specifically for industrial fishing vessels. To reach this aim, the specific objectives of this PhD project are listed below.

- To conduct a literature review on the impact of biofouling and hull surface conditions on ships’ hydrodynamic performance and resistance, current antifouling strategies, antifouling coating test methodologies, fisheries importance, classification of the fisheries, and current fishing methods to determine the gaps in the literature.

- To perform a field survey together with the regulatory framework introduced by authorities to manage fishing stocks with the aim of determining the operating profiles of the industrial fishing vessels.

- To survey fishermen about how they maintain their vessels, how they select the coating types, what are the most common coating application chosen and so on.

- To determine fouling characteristics of fishing vessels in selected fishing zones together with antifouling coatings applied on the hull (if applied) by inspecting the vessels at the end of their annual fishing operation.

- To select the most appropriate commercially available antifouling coatings while considering the fouling characteristics in collaboration with coating manufacturers,

- To select the most suitable fishing vessel with the aim of this thesis,
- To apply these coatings as patches on a fishing vessel to determine the comparative performance of these coating under the same working and weather conditions. Inspect the patches between two maintenance periods to determine the time-based fouling.
- To place similar patches (coated panels) in the sea statically and observe the fouling patterns in regular intervals. Inspect the patches regularly to determine the time-based fouling,
- To compare antifouling coatings' performance in terms of biofouling, between ship tests and static test patches and between different coatings.
- To conduct various case studies for typical fishing vessels to investigate the impacts of determined coating/roughness/fouling on powering requirements of these boats, based on analysis of the coating/roughness/fouling data collected from the field tests,
- To determine the most suitable coating in terms of fouling performance and in terms of energy efficiency, environmentally friendliness and costs,
- To analyse the performance data to guide specified fishing vessel communities to change or improve their current practice to get the best performance out of their vessels as well as making the least undesirable impact on the environment,

1.6 Thesis Outline

In this section structure of this thesis is briefly summarised and outlined below.

- Chapter 1 presents a general introduction for the research conducted in this PhD thesis, including the background, structure of thesis, motivation of the research, research aim and objectives, thesis outline, and finally, chapter summary.

- Chapter 2 presents the literature review about the subjects covered in this PhD thesis. Biofouling and its impacts in the shipping industry, the theoretical background of roughness effects in the boundary layer, antifouling strategies, antifouling coating test methodologies, economic and environmental importance of fisheries, classification of the fisheries, and current fishing techniques are covered. Also, gaps in the literature are presented in this chapter.

- Chapter 3 proposes a new dataset regarding biofouling and presents the survey results conducted with the fishermen/stakeholders to determine fishermen's knowledge and actions to address biofouling on fishing vessels. Furthermore, fishing vessels' operation profiles, common fishing techniques, maintenance process of fishing vessels, coating selection, the most common coating brands, coating application process etc., are some of the topics stated in this chapter. Results are also presented and illustrated when necessary. In addition to that, the field surveys conducted in the fishing ports are presented to determine fouling characteristics and fouling conditions of the fishing vessels after a year of fishing activities and relevant shear stress of the particular fouler organisms presented.

- Chapter 4 proposes new biofouling datasets over time for the relevant field tests in realistic conditions for two different antifouling technologies; Foul Release (FR) and Self-Polishing Copolymer (SPC) coatings. This chapter was presented in three parts. Firstly, together with the coatings selected as a result of the survey, static immersion tests were tested, and fouling conditions were monitored weekly for the first month and then afterwards monitored biweekly. Then, the data collected were analysed and reported about antifouling performances of the coatings in the Black Sea. After that, fouling conditions of the same coatings on a fishing vessel after a year of fishing operation were surveyed, compared, monitored, and analysed.

- Chapter 5 provides added resistance and ship's effective power increase predictions due to biofouling in terms of frictional resistance by presenting case studies with three fishing vessels fishing in the Black Sea and the Mediterranean Sea. This chapter starts with a brief introduction. Following that, fouling accumulation for the determined fishing vessels over a fishing season is predicted. Moreover, the time-dependent biofouling model by Uzun (2019) is used for the predictions. This procedure is briefly described in Chapter 5. Next, added resistance diagrams from Demirel et al. (2019) are used to correlate ship speed, ship length, roughness height, and added resistance for the determined fishing vessels under given fouling conditions used in the case studies. After that, the calculation of the fuel consumption, fuel costs and CO_2 emissions are given. Finally, case study results are compared for different antifouling coatings, different fishing methods and different fishing regions.

- Chapter 6 presents the investigation results of this thesis together with a discussion. As stated in previous sections, what was achieved, the contribution of this study to the current literature, and so the outputs were stated concerning this PhD thesis's aim and objectives, were presented in Chapter 6.

- Chapter 7 presents the conclusions and the recommendations for further research.

1.7 Chapter Summary

The background, motivation of the research, research aims and objectives, and the thesis outline were presented in this chapter.

2 Literature Review

2.1 Chapter Introduction

In order to make a novel contribution, it is essential to carry out a critical review of the state-of-art work in the relevant field. For that reason, in order to identify the gaps and research motivations behind the research performed in this thesis, a comprehensive literature review was conducted and presented in this chapter. That is also important to state that the particular subjects covered in this literature review are dedicated to the work done throughout this thesis.

This chapter is divided into two major sections. The first section gives an introduction to the fisheries. In this section, fishing activities, the importance of fisheries both on a global and local scale, distribution of the fishing vessels in terms of ship characteristics (hull materials, LOA in metres, engine power etc.), common fishing techniques and nets used, and classification of the fishing activities are presented. The second section focuses on biofouling. In this section, the marine biofouling process is briefly reviewed, and starting from a traditional perspective, up-to-date biofouling control technologies and antifouling strategies are discussed. In addition, impacts of biofouling for a ship in terms of resistance and so the power requirements are considered. After that, the boundary layer and effects of roughness, in terms of biofouling, on the turbulent boundary layer are presented. Finally, the literature review is concluded with identified gaps and overall objectives formulated.

2.2 Fisheries

Fishing is hunting, gathering, and collecting food from world oceans. Food, in this context, varies from fish to mammals and algae to planktons. Besides its vital contribution to the ecological system, fish and fisheries have an important place in people's lives. Fisheries is considered one of the oldest activities known to mankind and a tradition dating back to prehistoric times. Together with the changes in needs, fishing tradition has developed and transformed over time. Fishing activities were limited to local areas, lakes, rivers, and coastal areas. However, as being one of the oldest representatives of this tradition, fishing settlers with children, men and women developed new skills, techniques and crafts that made them available to go fishing in further and deeper fishing sites over time. Thus, this leads to fisheries becoming a day-to-day survival activity to a vital food supply for billions of people (Olaoye et al., 2012; Olubanjo et al., 2006; Williams, 1987). Saying that, any possible improvement on the fisheries would not only affect millions of people's lives globally but also improve the health, economic condition, welfare.

2.2.1 Fisheries and Nutrition

The world population is growing and rapidly approaching 8 billion people. Furthermore, the growing population also increases the demand for protein, one of the most critical components of the human diet. The amount of protein that an adult needs to take is around 0.75 g per kg each day with varying body weight and age (Pedersen et al., 2013). According to FAO (2020a), global per capita fish consumption was 20.3 kg, with marine living stocks being at the back of about 17.3 per cent of the world population's intake of animal proteins and 6.8 per cent of all proteins consumed. In addition to that, globally, fish provides approximately 3.3 billion people with almost 20 per cent of their average per capita intake of animal protein and 5.6 billion people with 10 per cent of such protein. A good illustration showing the utilisation and food supply per capita of the world fish given by FAO (2020a) can be seen in Figure 2-1.

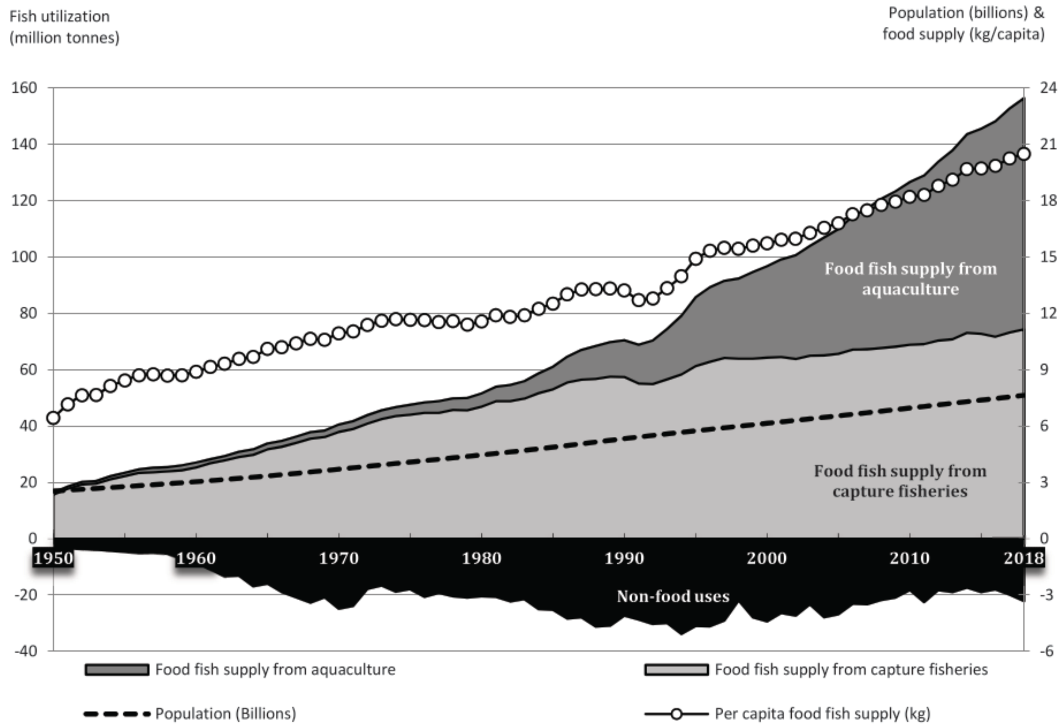


Figure 2-1: World Fish Utilization (FAO, 2020a)

What can clearly be seen in Figure 2-1 is the continual growth of fish utilization since the 1950s. To be more specific, it can be seen that whilst the fish utilization was only 20 million tonnes during the 1950s, it reaches 180 million tonnes in 2018, including non-food uses and food-uses total. On the other hand, although the non-food uses show fluctuations over time, food fish supply from capture fisheries and aquaculture keeps growing over time. Moreover, with an average of 91 million tonnes of annual captured seafood production in the last two decades, and 96.4 million tonnes of annual capture production, there is undoubtedly an increase in captured fish production. In addition, a similar trend can be observed for food supply per capita of the world population. Furthermore, considering the increasing world population, it is hardly possible to obtain this amount of protein requirements from domesticated meat animals. For that reason, increasing trends over time, as shown in Figure 2-1, confirms the assumption that the fisheries is and will be playing a significant role in food supply for the world population.

What is more, Béné et al. (2016) conducted a comprehensive review assessing the contribution of the fisheries to food security and poverty reduction. Thilsted et al. (2016) investigated capture fisheries, aquaculture production, and nutrition relation in healthy diets. They concluded that the authorities must praise fisheries as seafood products improve nutrition and health outcomes, especially for the poor. Bennett et al. (2018) conducted another comprehensive literature review and highlighted the importance of the role of fish in food security, livelihoods and nutrition. Bennett et al. (2018) also stated that due to the particular nutritional characteristics of fish, fisheries mean more than a source of protein. Hence, it is predictable that most of the protein deficiencies are inevitably met by seafood products today and will be in the future. Thus, it can be said that fish and fisheries play an active and significant role in meeting the deficit for adequate and balanced nutrition of people besides red meat and poultry meat. For the reasons mentioned above, any improvement in the fisheries sector would not only offer an alternative protein intake for humans and but also contributes to supplying healthy diets for people.

2.2.2 Fisheries and Economy

In addition to being one of the high-quality nutrition providers for people, it is an indisputable fact that fisheries supply industrial raw materials for many industries, such as fishmeal and fish oil. For that reason, fish and fish products are one of the most traded products international. To be more specific, 35% of the total production in fisheries is exported. Therefore, global fishing creates an important employment area, provides livelihoods to millions of people from production to marketing, and contributes to rural economic development and national economies (Andrew et al., 2007). According to recent statistics from the Food and Agricultural Organisation of United Nations, the total first-sale value of the global capture fisheries was USD 151 billion. In addition to that, there were 38.98 million people who engaged in the primary sector of fisheries in 2018. (FAO, 2020a). Furthermore, there are estimations stating that marine capture fisheries might be providing employment directly and indirectly up to 200 million men and women (Sumaila and Munro, 2009). These statistics give a good agreement with the statement that fisheries economically take an important role in people's lives that can not be underestimated (The World Bank, 2012).

On the other hand, after emphasising the importance of the fisheries economy on a global scale, it is also important to state what economy means to a fishing vessel as in a micro perspective. Although there is not enough study conducted in the literature showing the costs of fishing on a global scale, some of the studies conducted by several countries for the fisheries' earnings and costs can be considered enough to generalise. Arnason et al. (2009) stated that the major costs for the most fisheries, in general, can be considered in 5 factors as in following: (i) labour (30% – 50% of total costs); (ii) fuel (10% – 25%); (iii) fishing gear (5% – 15%); (iv) repair and maintenance (5% – 10%); capital cost, such as depreciation and interest (5% – 25%). Thus, it can be seen that by only reducing the fuel costs, a considerable amount of saving is possible for industrial fishing vessels. Yet, any improvement on cost reduction for the fisheries would significantly contribute to millions of people's incomes directly or indirectly. Therefore, a further study investigating energy-efficient fisheries and reducing the fuel costs would increase people’s welfare economically.

2.2.3 Fisheries and Classification

Before focusing on industrial fisheries, it is important to state and define different fisheries categories. It can be seen that categorising the fisheries is a complex process as definitions in the literature vary, and there are no specific limits to classifying fisheries or fishing activities. However, there are certain boundaries as definitions vary between the amount of the catch, fish behaviours for different biotopes, distance from the shore, and fishing area, fuel consumption, number of employed people, region, species, technology, investment, boat type, gear type and purpose of fishing activity (Cooke and Cowx, 2006; O’Farrell et al., 2019). In the literature, industrial fisheries or commercial fisheries, large-scale fisheries, artisanal fisheries, small-scale fisheries, and recreational fisheries can be named as the most popular categories among the fishing activities (Charles W. and Makowski, 2015; Jafarzadeh et al., 2016; Marine Management Organisation, 2017; Watson and Tidd, 2018). The most common fishery types, namely, found in the literature, are detailed in subsections.

2.2.3.1 Subsistence Fisheries

According to FAO (n.d.), when subsistence fisheries come into question, the fish caught are consumed by either fishermen or the families of the fishermen rather than selling to either middlemen/middlewomen with the aim of selling it to a larger market. On the other hand, Tyedmers (2004) made an indirect definition for the subsistence fisheries. His study stated that subsistence fisheries are related to the energy animated by human muscles that engage in the fishing activity. In addition, Tyedmers (2004) also stated that artisanal fishery is a type of subsistence fishery. Similarly, Rousseau et al. (2019) stated no difference between artisanal, small-scale, traditional and subsistence fisheries. Teh and Sumaila (2013) conducted a study to relate marine fisheries' contribution to worldwide employment. According to their definition, subsistence fisheries is any fishing activity that does not bring any income but only a minimum amount to live at the subsistence level. Moreover, they explained what subsistence fisheries are and the differences between artisanal, subsistence and small-scale fisheries. It was clearly stated that although it is difficult to separate one from another, the intended use of catch was the key subject to distinguish.

2.2.3.2 Artisanal Fisheries

Artisanal fisheries are underestimated and overlooked by academics, particularly in comparison with industrialised fisheries (Rousseau et al., 2019). This statement can be supported by reviewing the literature about similar fisheries types and their definitions, such as subsistence, small-scale, traditional, and recreational fisheries. As it can be seen from the previous section, the definition of artisanal fisheries is not an easy task to overcome because of its overlapping nature with similar fisheries types.

Many definitions have been made in the literature for the artisanal fisheries (Bhagooli and Kaullysing, 2018; Muniz et al., 2018; Olaoye et al., 2012; Rousseau et al. Nevertheless, The Fish Project (2015) can be considered as the most comprehensive definition among the others. In their definition, artisanal fisheries are traditional fishing practices conducted in participation with the family members, using limited investment and energy need, conducted with smaller fishing vessels, if there is any fishing vessel used and short fishing operations close to shores. Although the definition of artisanal fisheries differs among different countries, the range changes from a single-man handed fishing activity with a canoe in a developing country to 20 metres length trawlers, purse seiners, or longliners fishing vessels in developed countries. However, an additional statement was made in the Fish Project (2015). Although it is sometimes referred to as small-scale fisheries, artisanal fisheries can also be a member of subsistence or commercial fisheries to contribute to local consumption or trade.

2.2.3.3 Recreational Fisheries

Recreational fisheries is described as a sport or a leisure time activity conducted by individuals that do not involve any profit, trade, sale, nutritional requirement or scientific research (FAO, n.d.). Similar to artisanal fisheries, there is limited research conducted for recreational fisheries (Griffin et al., 2021). Besides being a pastime activity, there are millions of people enjoying recreational fisheries globally, accounting for a substantial proportion of the total fish landed, particularly in developed countries (Arlinghaus et al., 2019; Coleman et al., 2004; Henry and Lyle, 2003; Hyder et al., 2018; West et al., 2015). For that reason, these numbers raised awareness for potential environmental problems due to recreational fisheries on marine fish stocks and ecosystems (Lewin et al., 2019). In addition to that, Cooke and Cowx (2006) conducted thorough research for the contrasting recreational and commercial fisheries. In that study, they concluded that recreational fisheries have a potential rarely considered to be an important factor to affect fish, fisheries, and aquatic habitats.

2.2.3.4 Small-Scale Fisheries

As there are many different techniques, methods and gears used in fisheries, the scale takes an important role, thus, which is divided into large scale (industrial fisheries) and small-scale fisheries. Small-scale fisheries often involve or are interchangeably used as recreational, artisanal, subsistence, coastal, traditional, local, poor, and low-tech fisheries as an aggregative topic. Yet, due to the complexity of defining small-scale fisheries, different definitions are made from many perspectives. For example, a global definition and extent of small-scale fisheries were defined by The World Bank (2012). In that report, answers to ‘what small-scale fisheries are’ are sought and further discussed.

Consequently, although there are many different factors when defining small-scale fisheries, a key criterion is considered to be vessel size when considering whether it is a small-scale fisheries or not (Chuenpagdee et al., 2006). For example, the EU considers any fishing vessel smaller than 12 m overall (LOA) a small-scale fishing vessel. Another example can be given from a local perspective. Teh and Sumaila (2013) made a local generalisation for the small-scale fisheries in tropical countries. In their definition, small-scale fisheries are mainly conducted in parts of poorer areas of tropical developing countries where there is no alternative to employment or famine/war uprooted people to coastal areas where they engage in fishing activity. A further and detailed study conducted regarding the definition of small-scale fisheries has been brought to attention by Smith and Basurto (2019). A good illustration for differentiating fishing activities can be seen in Figure 2-2 (The Fish Project, 2015).

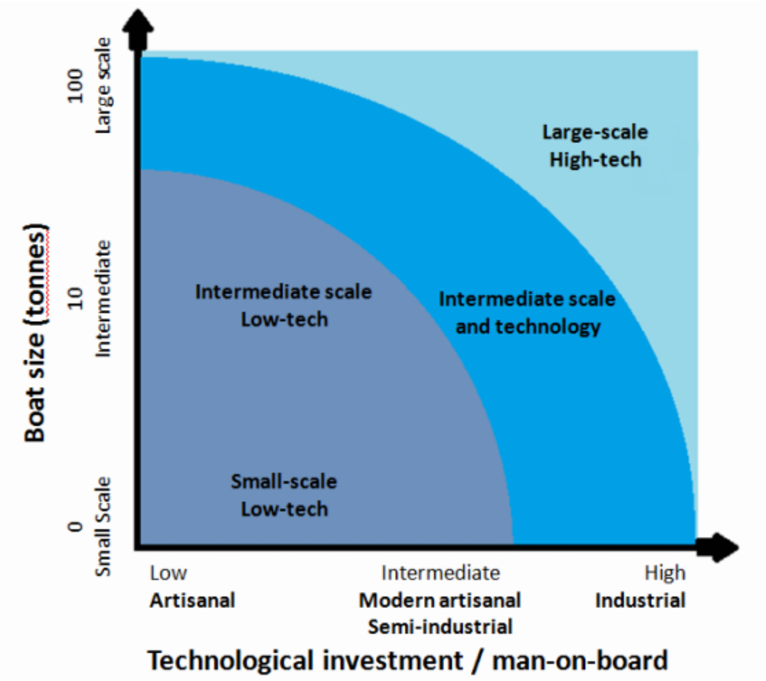


Figure 2-2: Differentiation of fishing types according to FAO, adapted from The Fish Project (2015).

It has been accepted that authorities and scientists have underestimated small-scale fisheries (Ifremer, 2007). However, considering the fact that small-scale fisheries supply 50% of the world's fish catch and yet when the number of people employed in this sector makes 90% of the world's fishers, the importance of small-scale fisheries can be pointed out easily (Berkes et al., 2006; FAO, 2012; Teh and Sumaila, 2013). With this in mind, it should also be noticed that there is an ongoing transition from small-scale fisheries to industrial/large-scale fisheries in the world (Berkes, 2003; Johnson, 2006).

Overall, although there are overlapping definitions between small-scale, recreational, and artisanal fisheries, and yet studies indicate the transition towards industrial fisheries, this ongoing transition from small scale fisheries may be linked to any study conducted for the industrial fisheries. In other words, any study conducted for the industrial-large scale fisheries would directly influence the many other kinds of fisheries, including small-scale, recreational, and artisanal fisheries and the people that have direct or indirect relation with it.

2.2.3.5 Industrial / Large-Scale Fisheries

The industrialisation of fisheries received attention, particularly after the iconic factory fishing vessels' invention by European countries in the early 1950s (Peet et al., 2010). These vessels did catch the fish and could process fish on board, which was a game-changer for the fishing industries to supply the need for fish during post-war conditions (Standal, 2008).

In contrast with the small scale fisheries, industrial/commercial/large-scale fisheries are operated by large companies with relatively more significant investments (Tyedmers, 2004). According to European Parliment (1998), industrial fisheries is characterised by net mesh sizes and target species. To be more specific, most of the species caught in industrial fisheries are selected to be used in industrial fish meal and fish oil production. Thus, most of the caught fish, coming from industrial fisheries, is not used for human consumption. Besides that, although small-scale fisheries are practised all around the world, high input fisheries account for the majority of global landings (Tyedmers, 2004). That should also be noted that industrial fisheries consist of 30% of the total fish caught annually worldwide.

According to FAO (2020b), there are 4.5 million fishing vessels globally, and 63% of them are motorised fishing vessels. Moreover, there are 2.86 million motorised fishing vessels in the world. Nevertheless, 514800 of the total motorised fishing vessels have more than 12 m LOA. In other words, motorised fishing vessels in the LOA class of more than 12 m constitute 11% of the total number of fishing vessels (of 4.5 million) in the world. Furthermore, the number of motorised fishing vessels with at least 24 m or larger LOA was estimated as 67800, constituting approximately 2% of the total number of fishing vessels (of 4.5 million) globally (FAO, 2020b). Considering that vessels in 24 metres length overall or over are defined within industrial fisheries, it can be said that these numbers represent the number of industrial fishing vessels globally (McCauley et al., 2018). There are several types of industrial fishing vessels reported by FAO (1985). Among these vessels, purse-seining, trawling, and longlines are considered as the most significant ones (Peet et al., 2010). Further details about these vessels are discussed in detail in the following sections.

Looking at the historical data, from 1950 to 2015, the number of fishing vessels doubled. Although fossil-fuelled engines were started to be used in fishing vessels at the beginning of the 20th century, World War II played a significant role in accelerating this integration. As a result, with the ongoing technological advancements, gasoline and diesel have dominated the large-scale; industrial fisheries sector as an energy input over the past half-century (Tyedmers, 2004).

In recent years, however, effective fisheries management has started showing its benefits, and so that the number and size of motorised fishing vessels have dropped approximately around 6% from 3 million fishing vessels to 2.86 million fishing vessels since 2015. Although these statistics might look as an indication for more sustainability for the fisheries, that should be noted that the main reason behind the decrease in the fishing vessel numbers is that the efficient regulations and their impact in the developed countries. Rousseau et al. (2019) stated that with developing countries' integration to modern world fisheries, 1 million more vessels propelled by engines could join the global fleet by 2050s.

Several studies conducted in the literature show the fossil fuel dependency of industrial fisheries. As a result, the combustion of these fuels contributes an enormous amount of greenhouse gases and contamination to the atmosphere that increases the climate change effects (Driscoll and Tyedmers, 2010). Tyedmers et al. (2005) stated that an industrial fishing vessel's engine outputs are "in a range of many tens to thousands of kilowatts". Next, they generated a map showing the global fuel consumption intensity that covers the majority of the industrial fisheries in the world. In their estimation, 42 million tonnes of fuel were burnt, and 134 million tons of CO_2 were released into the atmosphere all around the world in 2000 due to fisheries.

Another comprehensive and historical study illustrating the growth of greenhouse gas emissions due to fisheries was conducted by Parker et al. (2018). In this study, global fuel used and total GHGs emissions were estimated between 1990 and 2011. Between these periods, fishing vessels consumed 40 billion litres of fuel for their fishing activities in 2011. This fuel consumption released 179 million tonnes of CO_2 and equivalent greenhouse gases into the atmosphere, which constitutes 4% of the total global food production. Furthermore, emission rates from fishing activities showed an increase of 28% from 1990 to 2011. Conducted research can be accepted as an excellent indicator for the world fisheries and the impacts on the environment.

Furthermore, Suuronen et al. (2012) conducted comprehensive research to highlight possible improvements by focusing on the low impact and fuel-efficient capture technologies for the fishing vessels. This study gave examples of energy-saving techniques and operational adaptations to reduce fuel consumption and environmental impacts of demersal trawling, as shown in Table 2-1.

Basurko et al. (2013) showed energy implementations of three fishing vessels by examining three case studies to reduce the fuel costs of fishing vessels. Their study concluded that no generalisation could be made for the energy consumed by onboard systems between the fishing vessels that use different fishing gears. Martelli et al. (2016) conducted hydrodynamic computations to encourage improving the energy efficiency of the existing industrial fishing vessels by assessing a trawler's propulsion system. They found that a 2-4% efficiency increase is possible by optimising the vessel speed. Furthermore, they also stated that the gain in efficiency might be much higher when the costs are considered on a global scale.

Table 2-1: Potential techniques for energy-saving and their effect with the constraints and barriers adapted from *Suuronen et al. (2012)*

Technique/measure	Effect	Constraints–barriers
Use of thinner and stronger twines, super fibres, knotless netting, square mesh netting, T90 net, less netting, larger mesh size	Reduces the amount, weight and surface area of netting and increases water flow through the net, thereby reducing the overall drag	High price and availability of materials; use of larger meshes can reduce the catch of marketable species and sizes; cost benefit analyses not carried out for most fisheries
Use of smaller and/or multiple nets for species that exhibit poor avoidance behavior to the presence of the fishing gear (e.g. shrimp, flatfish)	Reduces the overall netting surface area and thereby the weight and the drag without reduction in catch	Policy, complexity of rigging, resistance to change
Use of effective bycatch and benthos reduction devices (BRDs)	Allows the escape of unwanted species or sizes of fish and other unwanted objects thereby reducing the weight and overall drag	Variability in performance, lack of technical support to test and optimize BRDs, loss of revenues of target species and sizes, perceptions
Using four-panel design (instead of typical two-panel) in the belly, extension piece and codend, using square mesh netting in the belly	Ensures easier installation of BRDs and better geometry and stability for the back end of the trawl	Cost benefit analyses not carried out for most fisheries
Use of hydrodynamic trawl doors and use of optimal warp length (that corresponds to optimal door efficiency)	Less drag (traditional trawl doors contribute up to 25-35% of the overall gear drag), less weight, better fuel efficiency	Price, performance monitoring, control in different sea conditions and depths
Use of raised or flying trawl doors where the weight element of the door is separated from the spreading element (doors can be flown above the seabed to open the trawl)	Better spread, less drag and less pressure on the bottom (less seabed disturbances)	Price, performance monitoring, control in different sea conditions, depths, not suitable for all species
Better rigging of the gear, lighter ground-gear, shorter ground-gear, less discs and better rotation capacity, self-spreading ground gear, composite ropes, lengthened bridles, off-bottom bridles, lightweight warps, and proper matching of trawl net and trawl doors	Lighter and reduced contact points to seabed, less seabed pressure, smaller impact area, less drag	Performance monitoring
Use of hydrodynamic shape of floats, kites, beams, pulse trawls, SumWing-design	Reduced drag, reduced seabed contact	Performance monitoring, speed dependence
Converting from single boat trawling to pair trawling	Reduces fuel consumption, less seabed damages	Policy, human behavior
Improving real-time monitoring and control of gear with acoustic gear surveillance technology	Maintenance of optimal gear performance, reduces energy consumption and bycatch	Price, training
Installing real-time camera observation system for informing skipper of fish behavior and composition in the trawl	Helps to maintain optimal gear performance, reduces bycatch and collateral impacts. The next step may be an active mechanism to release unwanted catch	Price, training
Improving navigation and fish finding, and improving knowledge on fishing grounds (GPS, electronic charts, sea-bed mapping)	Maximizes catches and minimizes time, energy and collateral impacts	Price, training
Use of speed controls, reduction of towing speed	Reducing speed directly reduces the fuel consumption	Human behavior
Vessel and propulsion system optimization, preventive maintenance of vessel and engine, change in trip planning practices	Reduces fuel consumption	Price, human behavior

One of the studies regarding energy efficiency in fishing vessels was conducted by Gabiña et al. (2016). They tested magnetic devices on diesel engines to improve energy efficiency and reduce GHG emissions from the fishing vessels. Their results showed that an average 5% saving in annual fuel consumption (l/h) for a trawler is possible by using the magnetic device on engines after two years of operation. However, this reduction was lower than what the manufacturers stated.

2.2.3.6 Other Types of Fisheries

Besides the most commonly classified fisheries, there are many other definitions for the fisheries types. These definitions vary between different factors. Deep-sea fisheries, pelagic fisheries, coastal fisheries, offshore fisheries, high seas fisheries, indigenous fisheries etc. can be given as examples.

- **Deep-sea fisheries** take place between 200 and 2000 metres depths on continental slopes, oceanic seamounts, and ridge systems banks to catch demersal/benthic species.
- **Coastal fisheries** take place within 200 nautical miles from the coasts, so-called Exclusive Economic Zones and using fishing vessels up to 10 tons. In addition, it also includes vessel-free fisheries, set-net fisheries and beach seine fisheries (Japan International Cooperation Agency, 2007).
- **Pelagic Fisheries** is the fisheries that take place in order to catch the fishes that spend most of their time near the sea surface ranging from forage fish to apex predators such as sharks, tuna fish and billfish (Joseph et al., 2019).
- **Offshore fisheries** are the fisheries that take place between the territorial waters and the limits of Exclusive Economic Zones (EEZ) and the fishing beyond EEZ as known as high seas fisheries (Wijesekara, 2016).
- **High sea fisheries** are the fisheries that take place in the open ocean where outside the exclusive economic zone (EEZ), territorial seas or internal waters of any state (The Fish Project, 2015).
- **Indigenous fisheries** is the fishing activities undertaken by indigenous people to satisfy their needs or for educational purposes, which do not include any commercial purpose (ABARES, 2020).
- **Target species fisheries** are the fisheries that the name of the target species given to the fishing activity. Yellowfin tuna fisheries, Bluefin tuna fisheries, shark fisheries, and forage fish fisheries can be given examples. That should be noted that the given examples can be replicated.

2.2.4 Fisheries and Fishing Fleet Segments Techniques

There are many modern and economically effective, however, “ruthless” fishing techniques used, particularly in industrial fisheries (Standal, 2008). In addition to that, Cheilari et al. (2013) stated that pelagic trawls and seiners are fishing techniques that are reported to have the lowest fuel use intensity ratio. However, a comprehensive study conducted by Kroodsma et al. (2018) in popular Science magazine presents significant details about fisheries. In this study, industrial fishing vessels were scrutinised. An automatic identification system (AIS) was used, and more than 70 thousand industrial fishing vessels were tracked between 2012 and 2016. Footprints of industrial trawlers, purse seiners, and longliners were then generated and illustrated on a map in terms of total fishing activity per square kilometres (h km^{-2}), a so-called fishing effort.

Interestingly their results showed that industrial fishing is practised in more than half of the ocean area (>55%), which is more than four times that of cultivation area. The results of this study can be seen in Figure 2-3. It should be noted that this study was conducted with the fishing vessel with AIS; however, AIS is not used by every single fishing vessel. Hence, the results of this study could be higher than reported.

In addition, by looking at the results that Kroodsma et al. (2018) presented, it is evident that purse seining and trawling activities are conducted within coastal areas where people live. Within this perspective, a comment may be underlined as the impacts of industrial fishing vessels, particularly trawlers and purse-seiners, would severely impact human health than other shipping industries. To give an example, CO_2 emissions released from the industrial fishing vessels would reach the urban areas quicker and more intensively than other industries such as shipping. In other words, any improvement in CO_2 emission reduction released from the fisheries would make a direct and significant contribution to human health.

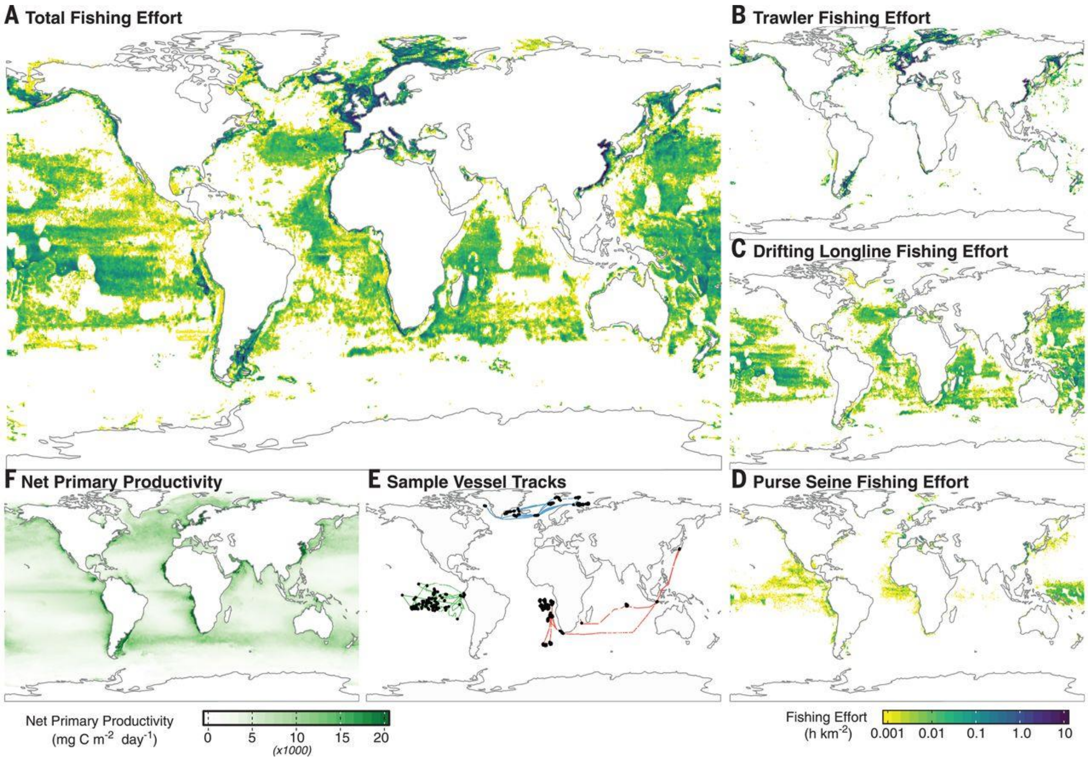


Figure 2-3: The spatial footprint of fishing. (A to D) Total fishing effort [hours fished per square kilometre (h km^{-2})] in 2016 by all vessels with AIS systems (A), trawlers (B), drifting longliners (C), and purse seiners (D). (E)Examples of individual tracks of a trawler (blue), a longliner (red), and a purse seiner (green). Black symbols show fishing locations for these vessels, as detected by the neural network, and coloured lines are AIS tracks. (F) Global patterns of average annual NPP [expressed as milligrams of carbon uptake per square meter per day (mg C m^{-2} day^{-1})] are shown for reference (Kroodsma et al., 2018).

Furthermore, as can be seen from Figure 2-3, different fishing gears are used in different areas. To detail, whilst longliners appeared to be active in transoceanic distances, purse seiners and trawlers fish mostly in regional areas. These statements are considered to comply with each other. As stated in previous sections in this thesis, trawlers, purse seiners, and longliners are considered the most effective fishing techniques and contributors to industrial fisheries among industrial fishing vessels.

2.2.4.1 Purse Seiners

Purse seiners are the fishing vessels that use seine nets and surrounding techniques for the fishing activity, ranging from small boats to open ocean-going vessels worldwide. The size ranges mostly depend on the target species, having larger storage capacities, and having larger gears aboard the vessel. Kroodsma et al. (2018) stated that the purse seiners use 17% of the ocean area with an average trip length of 750 km to conduct their fishing activities. That should also be kept in mind that most seiners are primarily used to catch pelagic or forage fish such as anchovies, sardines, mackerels etc.

Due to the purse seiners' working mechanism, high manoeuvrability is essential for a typical fishing operation. This is the reason why larger seiners have lateral thrusters. Furthermore, there are two key gear handling equipment types for purse seiners: purse gallows and purse winches. These types of equipment are used for hauling the purse lines to close the net after setting. In addition to that, a power block and net drums are used for hauling and stowing the net aboard (FAO, 1985; Marçalo et al., 2018).

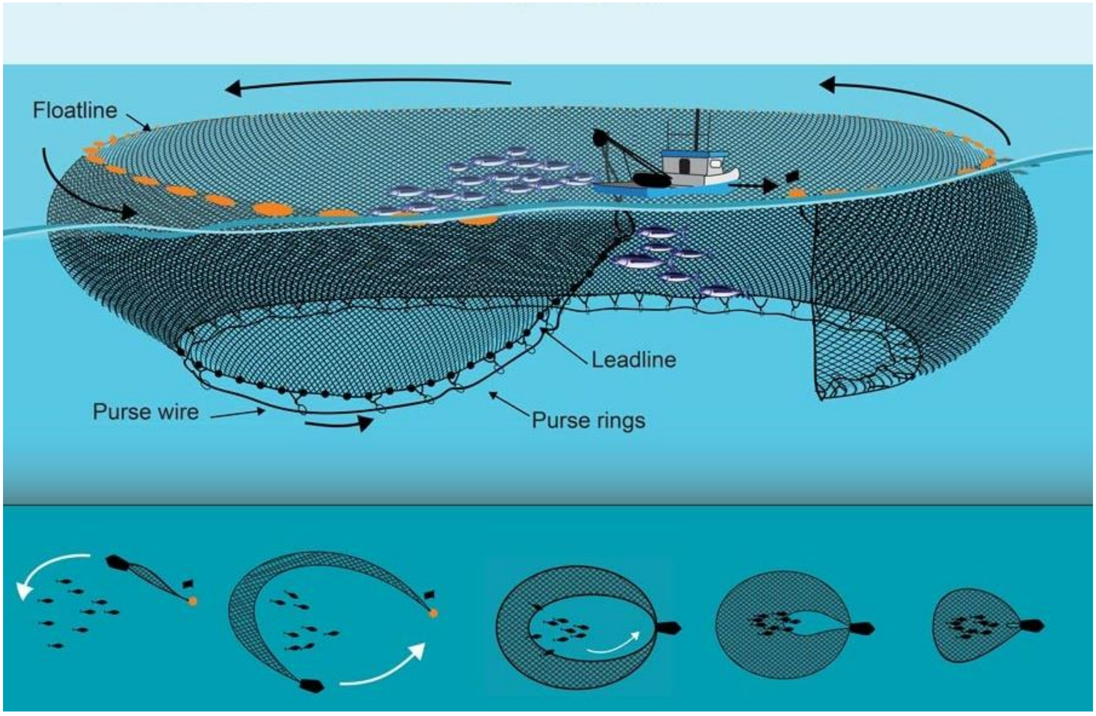


Figure 2-4: Schematic of a purse seining operation (AFMA, 2018a).

A typical purse seiner's fishing operation starts with the use of sonar or echo-sounder fish finders. Because target species shoal denser and swim near sea surface during the night, the majority of the purse seiner operations occur at night. After locating and reaching the fishing point, a wall of the net (seine net) surrounds the target shoal in a circle. The seine is placed on the surface with the help of a float-line, while the bottom of the seine is sunk quickly with the help of a leaded rope and heavy metal rings, which are also called purse rings. The next step is to close the seine under the target shoal by pursing the net with the help of the purse wire and purse rings. After this point, the target is trapped, and there is no way to escape from the shoal. Following that, the pursed seine is hauled gradually with the help of hydraulic winches.

It should be noted that purse seine is hauled from the vessel's starboard. This hauling process is done until the caught fish is brought to the edge of the seine net, called the bunt end. After it is visible to see and check what is in the catch, the process of transferring fish onboard starts. During this process, there are three options. The first is to use crewmen’s physical power. Crew members gather at the starboard side and start hauling the nets by hand. The second one is using brailing technique; a large dip net called brail is used. The third one is to use fish pumps (Dignan et al., 2009). A typical purse seiner operation can be seen in Figure 2-4 (AFMA, 2018a).

2.2.4.2 Trawlers

Trawlers are the fishing vessels that use trawl nets and towing techniques for the fishing activity at an appropriate trawling speed, ranging from small to large size vessels all around the world (FAO, 1985). Besides that, trawlers are accepted as one of the world's most essential and efficient fishing techniques. Kroodsma et al. (2018) stated that 9.4% of the ocean area is used by trawlers with an average trip length of 510 km to conduct their fishing activities. The target species for a trawler can vary from small pelagic fish such as mackerels, redbait to ground fishes, crabs, shrimp. The term trawler is mainly considered as an umbrella classification. According to FAO, there are several types of trawlers: beam trawlers, otter trawlers, pair trawlers, side trawlers, stern trawlers, outrigger trawlers, freezer trawlers, and wet-fish trawlers. However, bottom trawlers and midwater (pelagic) trawlers can be considered as two main groups for trawlers (AFMA, 2018b).

Depending on the target species, trawls can be used at various depths, and so the type of the nets changes by means of the mesh size. Trawl nets have a cone or funnel shape with a wide mouth to let the target enters a narrow, closed ‘cod-end’. Critical components of a trawl net are considered otter boards or trawl doors, which are used to keep the wide mouth of the net open. Furthermore, key components of the trawlers are considered to be gallows, winches, and equipment necessary to haul the net and lift cod-end on board. In addition to that, towing warps, a stern ramp, outriggers and net drums are also commonly found in a trawler (FAO, 1985). A typical midwater trawler operation can be seen in Figure 2-5.

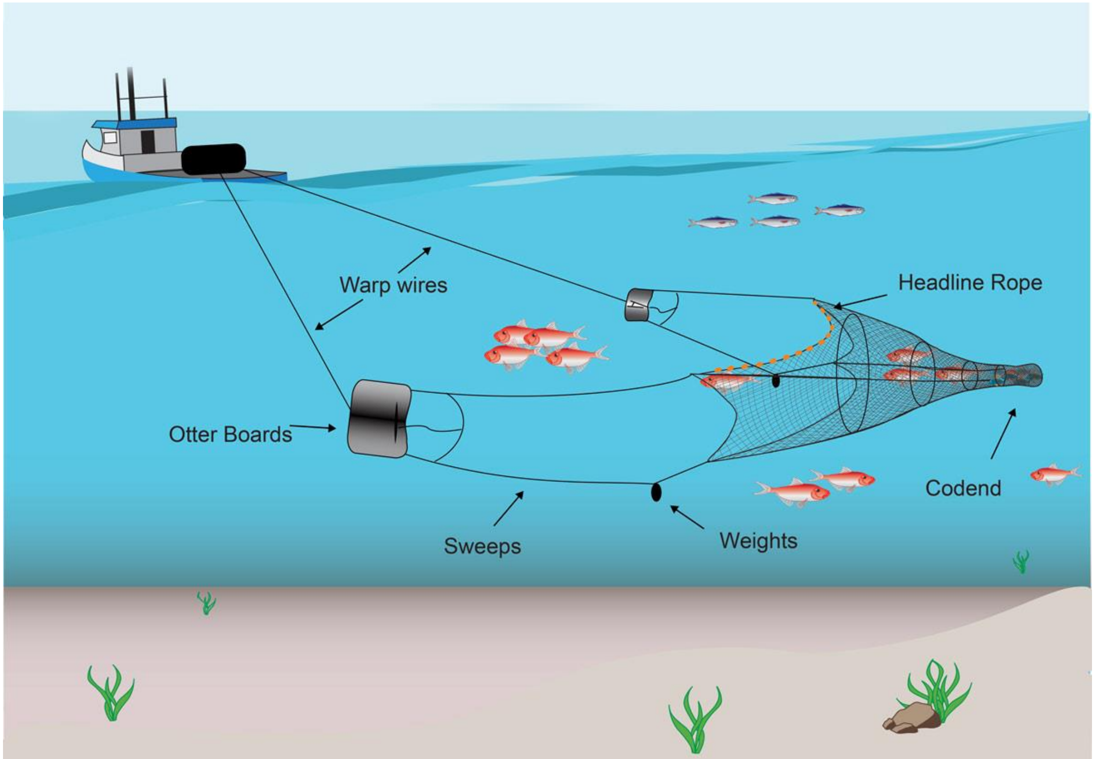


Figure 2-5: Schematic of a midwater trawler operation (AFMA, 2018b).

A typical pelagic trawler's fishing operation starts with the use of relevant fish finders. After locating and reaching the fishing point, the trawl is released to the water and pays out the required lengths of towing warp and streams towards the target shoal. Trawl nets are towed at the appropriate level in the water to set the trawl dept and catch the shoal. A net monitor or a sounder mounted on the net headline is used to determine the net's distance from the sea surface. Moreover, warp length and the towing speed becomes also determinants for the gear depth (Dignan et al., 2009). A typical purse seiner operation can be seen in Figure 2-5 (AFMA, 2018b).

2.2.4.3 Longliners

Longliners are the fishing vessels that use longlines nets for fishing activity ranging from small to large size vessels all around the world (FAO, 1985). Kroodsma et al. (2018) stated that the longliners use 45% of the ocean area with an average trip length of 7100 km to conduct their fishing activities. That should also be kept in mind that longliner was the most widespread fishing activity practised among the others. Target species for the longliners varies from bottom fish species to larger pelagic fish such as sailfish, swordfish, tuna etc. Additionally, the majority of the larger longliners aim to fish single species. For that reason, there are two types of longlining: pelagic and bottom longlining.

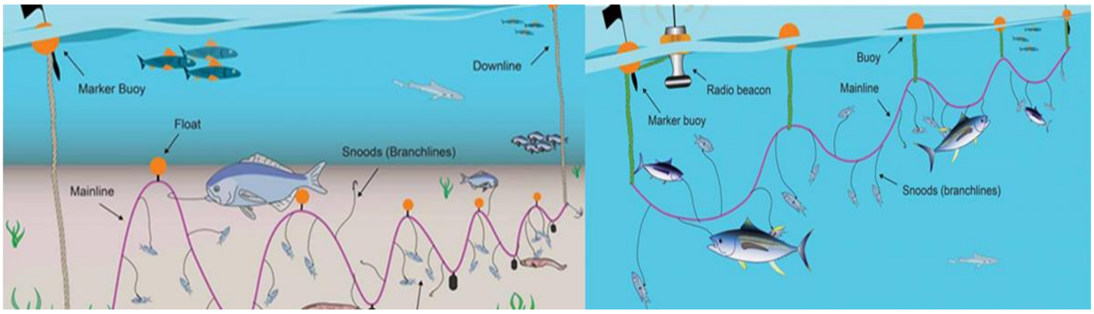


Figure 2-6: Schematic of a bottom (Left) and pelagic (Right) longlining operation

For the pelagic species, a typical longliner operation starts with baiting hooks attached to longlines by shorter lines (snood). In larger vessels, there are automated gears for the baiting process. The level of mechanisation becomes more technologically sophisticated in larger vessels. The long line goes up to kilometres long with thousands of hooks attached on, depending on the vessel size and storage capacity of the vessel. After the longlines are released into the water, they are not anchored and are set to be drifting with a radio transmitter. Radio transmitter gives a signal when the species are caught so that the vessel tracks and hacks the caught fish onboard. For bottom longlining, longlines lie on the ocean ground horizontally anchored. The target species for the bottom longlines are for the fish swimming just above the ground. Typical long liner operation pelagic and bottom long-liner operation can be seen in Figure 2-6.

In conclusion, each fishing vessel has a different operational profile due to having different fishing equipment on board, as stated above in previous sections. For that reason, any energy efficiency study concerning industrial fisheries must be investigated separately as different fishing techniques require different adjustments, particularly for industrial fishing vessels. In addition, it is important to consider regional differences in the selection of fishing vessels while carrying out such studies.

2.2.5 Fisheries in the Mediterranean and the Black Sea

From the early times of history, fisheries have always been an important activity in the Mediterranean and the Black Sea. For that reason, to encourage development, conservation, and the best management of marine living resources in the region, General Fisheries Commission for the Mediterranean (GFCM) was established as a regional authority regarding fisheries activities in the Black Sea and Mediterranean Sea by the United Nations' FAO.

According to GFCM, 87600 fishing vessels operate in the Black Sea and the Mediterranean Sea. However, only 12.9% of the fishing vessels are either purse seiners or trawlers, which constitute the second largest fishing vessels group after small-scale vessels in the Black Sea and the Mediterranean Sea. In addition, the number of small-scale fisheries consists of 83% of the total number of fishing fleets operating in the Black Sea and the Mediterranean Sea. Therefore 17% of the total number of fishing fleets make up the industrial fisheries. In other words, there are 15000 industrial fishing vessels operating in the Mediterranean and the Black Sea, according to FAO (2020). It can also be seen that the Mediterranean Sea is divided into subregions as the western Mediterranean Sea, central Mediterranean Sea, eastern Mediterranean Sea and the Adriatic Sea. Examining the relevant stats in detail, the eastern Mediterranean Sea and the western Mediterranean Sea have the highest fleet numbers with 30.6% and 23.2% of the total number of the fishing fleet in the GFCM area, respectively. GFCM's fishing areas can be seen in Figure 2-7.

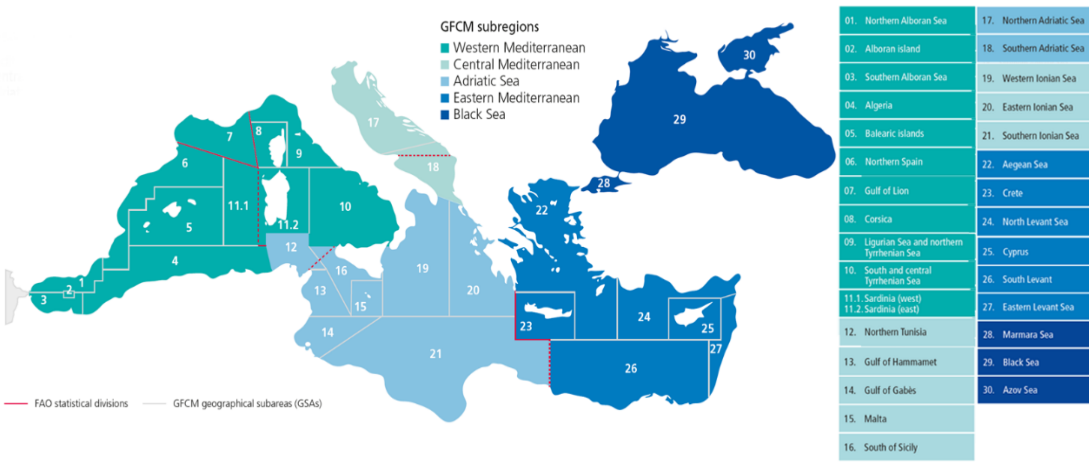


Figure 2-7: Fishing areas in the Mediterranean and the Black Sea according to GFCM, adapted from FAO (2020c)

In 2018, the total catch in the GFCM area was approximately 1.2 million tonnes. Moreover, purse seiners and pelagic trawlers targeting two significant species (anchovies and sardines) make up half of the total landings. Ongoing arrangements by the authorities in the region for sustainable fisheries have started showing their benefits. As an indication, it can be seen that although the number of landings from both the Mediterranean and the Black Sea showed a 2-3% increase, the number of fishing vessels has not increased since 2016. In addition, considering the total landings per country, there is a positive trend toward a balanced share between GFCM countries compared to previous years' total landings. It can be stated that the total landings by the major fishing countries decreased whilst the other countries' total landings increased. Morocco's 10.6% decrease and Romania's 73.4% increase in total landings can be given as an example.

There is an indisputable fact that the Black Sea and the Mediterranean Sea fisheries have direct links with many people's income. According to FAO (2020c), considering the whole GFCM area countries, 1 out of every 1000 people living near the coasts is a fisher who earn their living from fishing. Moreover, fisheries activities in the Mediterranean and the Black Sea provide approximately 785000 jobs for people. Considering the economics of the fisheries for the relevant countries, the estimated wider contribution of the fishing activities in the region is around USD 9.4 billion.

Overall, fishing activities in the Mediterranean and The Black Sea have vital importance for local people of the coastal areas. For that reason, any improvement in the fisheries, such as reducing the cost of fishing vessels in the region, would significantly contribute to fishermen's income. In parallel, It is a fact that lands almost wholly enclose the Mediterranean and the Black Sea, and both the Mediterranean and the Black Sea are surrounded by urban coastal areas. Thus, improving the energy efficiency in industrial fisheries in these regions would also help improve the air quality and hence the people's health.

2.3 Marine Biofouling

Although there have been many descriptions made for biofouling in the literature, one of the earliest definitions pointed out was as early as in 4th century B. C. by Plutarch's statement as to how beneficial it is to scrape weeds, ooze and filth from the ships (Woods Hole Oceanographic Institution, 1952). Biofouling, so fabled as ship-stopper, is a phenomenon that simply reflects a group of organism behaviours and tendencies to any given surface when the conditions occur. From micro to macro scale, waterborne organisms tend to attach to surfaces in the marine environment. Yet, this settlement gives birth to many problems in different industries, particularly in maritime.

2.3.1 Categorisation and Composition of Biofouling

As biofouling is accepted as a natural yet unwelcome accommodation of marine organisms, there have been a number of studies conducted identifying the types and species of the fouler organisms by many years. Starting from the earliest studies published, Woods Hole Oceanographic Institution (1952) conducted a comprehensive study regarding the principal fouling organisms and specified approximately 2000 species with fouling tendency. Another study stated that the type of fouler organisms is considered to be more than 2500 (Anderson et al., 2003). Nevertheless, Cao et al. (2011) pointed out that there are more than 4000 types of biofouling organisms. Besides the increase in the numbers, IMO (n.d.) stated that Asian Paddle Crab, Colonial Tunicate, North Pacific Seastar, Asian Green Mussel, Black Striped Mussel, European Fan Worm, Bay Barnacle, Wakame Seaweed, And European Shore Crab are considered to be some of the major fouler species besides other species.

In order to understand biofouling, it is better to understand what causes it. For that reason, the classification of fouler organisms is essential. Atlar (2008) made a simple but explanatory classification for marine fouling organisms. He divided fouling organisms into two segments as plants and animals. Next, he detailed the organisms for each segment. Plants are divided into microalgae (slime) and macroalgae (weeds). Furthermore, he stated that red, brown, and green algae are the subsegments of the macroalgae (weeds) segment.

On the other hand, the animal segment was classified into two subsegments as soft-bodied and hard-shelled organisms. Furthermore, whilst soft-bodied segments are divided into unlimited and limited organisms, he stated that barnacles, tubeworms, and mussels are accepted to be hard-shelled organisms as fouler organisms. Although there are different variations of biofouling classification, such as in Abarzua and Jakubowski (1995) and Atlar (2008), marine fouling is mainly categorised into two groups; microfouling and macrofouling.

2.3.1.1 Microfouling

Microfouling, also called slime fouling, plays a vital role in initiating the biofouling process in marine environments. As soon as a manmade material is immersed in the marine environment, adsorption of molecular substances and particles on the surfaces forms an organic film. This film, so-called conditional film, triggers a chain of commands that leads other organisms (microorganisms) to settle on the surface, which results in biofouling. With having proteins and carbohydrates in this film’s composition, surface structure changes and becomes an attraction for the first colonisers in microfouling, primarily bacteria (Bhosle et al., 2005). Subsequently, bacterial organisms produce natural polymers (extracellular polymeric substances), transforming the cells into the conditional film. Thus, a new form is constituted. This new form helps new colonisers hold on to the surface with its glue-alike behaviour (Stoodley et al., 2002).

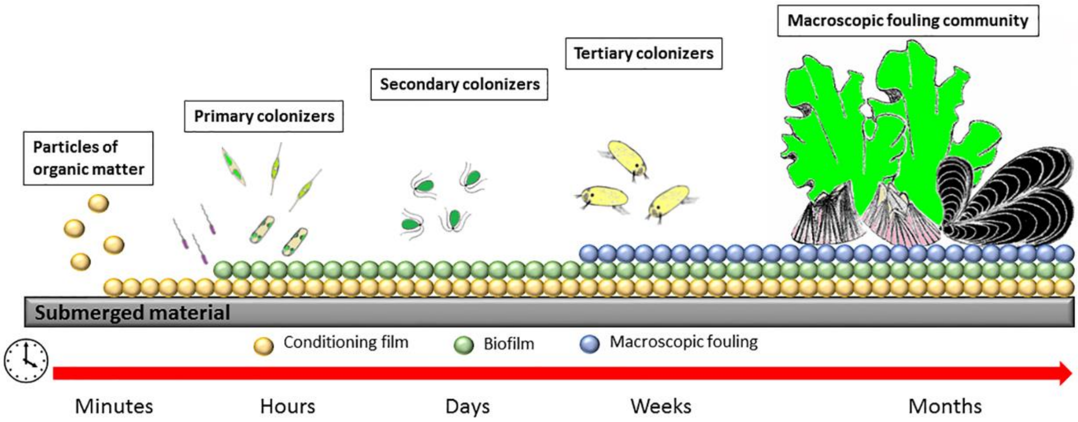


Figure 2-8: Schematic of Biofouling process over time adapted from Martín-Rodríguez et al. (2015)

After this, photosynthetic organisms that are capable of generating energy for the biofilms with the help of light starts appearing on the surfaces as secondary colonisers. Primary species for the secondary colonisers are considered as the diatoms (Anil et al., 2006). In addition to diatoms, spores of macroalgae and protozoa are accepted as the later secondary colonisers in microfouling. Although the limits of microfouling and macrofouling are not certain, and yet there is an overlap, at this point in the biofouling accumulation process, microfouling parts are accepted to be completed. A representative chart of the biofouling process can be seen in Figure 2-8.

2.3.1.2 Macrofouling

After microfouling organisms gathering on an immersed substrate or "served" as a rich nutrient of a plate in the marine environment, sessile larvae of the invertebrates such as mussel pediveliger, barnacle cyprid etc. begin settling on microfouling. This stage is accepted as the beginning of macrofouling. In detail, macrofouling organisms are divided into two segments whilst algae represent plants; invertebrates represent animals. Green, red, and brown algae are three subgroups of plants classified as soft fouling organisms.

On the other hand, there are four different subgroups for the animal fouling organisms, which are hard shell organisms (barnacles, Balanus, molluscs and fouling bryozoans, tubeworms, spirorbis etc.), grass type organisms (hydroids or bryozoans), small bush organisms (hydroids or bryozoans) and spineless organisms (ascidians, sponges, and anemones) (Almeida et al., 2007; Atlar et al., 2002; Breur, 2001; Lejars et al., 2012;

Martín-Rodríguez et al., 2015). That should also be kept in mind that although there is a variety of fouling organisms, the variety, density, size of these organisms depends on many other factors such as; depth, time, light, and location. A trawler's heavy growth of macrofouling after a year of fishing operation can be seen in Figure 2-9.

Figure 2-9: Heavy growth of macrofouling after a year of fishing operation on a trawler.

2.3.2 Parameters Affecting Biofouling

The longer a substrate stays in the seawater, the more advanced fouling accumulation occurs. As being dependent on chemical, physical, and biological events, many parameters influence biofouling due to its complex and multispecies structure. The parameters having a significant influence on biofouling can be listed as in following:

- **Water Temperature:** Seawater temperature is accepted as a trigger when considering the fouling organism growth. An upgoing trend is generally observed when the temperature increase. Many studies conducted in the literature show the difference in the growth rate in different sea surface temperatures. However, a note should be considered between temperate and tropical waters. Due to the reason that tropical sea surface temperatures are consistently at higher temperatures during a year, biofouling accumulation does not show remarkable differences when considering the growth rates over a year. On the other hand, in temperate waters, when considering the growth rate over a year, seasonal changes may change the biofouling growth rate (Hellio and Yebra, 2009). To give an example from the recent studies, Uzun et al. (2018, 2019) generated a time-dependant biofouling model by illustrating biofouling growth differences between 2 regions (2 separate seawater temperatures). From their results, it can be seen that biofouling growth is much faster in higher seawater temperatures. In addition to that, Dean and Hurd (1980), Koopmans and Wijffels (2008), Lord (2017), Stachowicz et al. (2002), and Villanueva et al. (2011) can be given as the other significant researches showing the positive relationship between temperature and biofouling growth rate.

- **Salinity:** Although it is fairly uniform with few exceptions, the world oceans' salinity levels are between 30-36‰ (Lindholdt, 2015). Therefore, Thiyagarajan et al. (2003) supported the idea that in comparison with the temperature's impacts on life forms, the effect of salinity is weaker than sea surface temperature. Besides that, a number of studies are conducted in the literature examining the fouling characteristics and survival behaviours of the fouler organisms (De Castro et al., 2018; Noor et al., 2021; Qiu and Qian, 1998). One of the good examples can be given to a study conducted for one of the most common fouler organisms; striped barnacle (*Balanus amphitrite*). Qiu and Qian (1998) investigated the relationship between salinity and tolerance of striped barnacles. Their study concluded that between 10‰ and 35‰ salinity levels are the critical limits where the adult striped barnacles are not affected in terms of growth rate and survivorship. In addition to that, De Castro et al. (2018) conducted immersion test panels at various salinity levels, and their results showed a good agreement with Qiu and Qian (1998)'s study. Elaborating further, a good example would be comparing two different seas with different salinity levels. Black Sea's average salinity level is 18‰, and it is 30‰ for the Mediterranean Sea. Therefore, *Balanus amphitrite*'s fouling characteristics on a surface immersed in the Black Sea and on a surface immersed in the Mediterranean Sea would not be different when salinity levels are concerned. Nevertheless, it is difficult to generalise the impacts of salinity on fouling organisms for two reasons. The first is because each species has different salinity tolerance, and the second one is due to world oceans salinity levels do not reach the levels that the impacts seen.

- **pH Level:** As a result of climate change, the amount of CO_2 does not only pollute the atmosphere but also cause many problems in marine oceans. For that reason, marine acidity will not go away in the near future (Elias, 2017). With the adsorption of CO_2 by world oceans, carbonic acid in the water forms due to a chemical reaction. There are only limited studies showing the impacts of pH on marine organisms. Michaelidis et al. (2005) examined pH and mussels' relation and showed that change in pH results in slow growth in mussels. In addition to that, similar results were obtained when a study was conducted on the growth and survival of gastropods and sea urchins by Shirayama and Thornton (2005). Another recent study showed the impacts of pH alteration on marine polychaete larval settlements (Espinel-Velasco et al., 2021). Although pH alteration has an essential impact on marine organisms, all of these studies showed that pH values never reach the levels that would affect the organisms in marine oceans.

- **Light:** Light is considered one of the vital elements needed for photosynthetic organisms. For that reason, light is an important figure for plants and algae in the biofouling community. However, it should be noted that the need for light for calcareous fouling organisms is less critical than food availability. Hence, calcareous fouling organisms are considered not the be affected by light as much as photosynthetic organisms (Lehaitre et al., 2008).

- **Depth:** Salinity, an abundance of nutrients, light and temperature can change significantly depending on the depth. For that reason, the diversity of the biofouling community is dependent on many parameters as well. Although there are limited research conducted showing the effects of depth on biofouling, a project called ANTARES showed that the difference between the deep sea and shallow sea is not significantly different from each other as far as the biofouling is concerned. In addition to that, as most of the macrofouling organisms are photosynthetic, so that they are dependent on the light, the amount of depth might affect the degree of biofouling due to lack of light (Amram et al., 2003; Luna et al., 2004; Venkatesan et al., 2003).

- **Nutrient Abundance:** Food and food availability are important parameters for fouler organisms. Moreover, the flow rate of the seawater and the closeness to the shore are the two key factors affecting nutrient abundance availability. Moreover, seawater flow rate plays a vital role in biofouling accumulation as it carries nutrients for the fouler organisms. Although slower flow rates support the biofilm accumulation at the early stages, fouling growth in later stages becomes slower due to lower nutrient abundance. On the other hand, if the flow rate is too high, it can slow down the primary colonisers' adherence, such as bacteria, due to the higher shear stress applied on the surface. However, it supplies an excellent environment for biofilm growth due to nutrient abundance. The other key point that can be regarded as significant is the site, whether accumulation occurs near shores or not. Sites close to the shores tend to have a more nutrient abundance due to domestic-based reasons. Thus, the closer it is to the shore, the greater the fouling accumulation on a ship’s hull is (Lehaitre et al., 2008).

- **Flow Velocity:** Because colonizer organisms position themselves perpendicularly to the flow of water currents, the flow rate directly influences biofilm growth due to the shear stress. Radu et al. (2012) conducted a study showing the effects of velocity flow on biofouling. Their study showed that biomass removal is inevitable when there is a sudden increase in flow velocity. However, they have also noticed that biomass re-growth happens when the velocity drops back to initial conditions. In addition to that, another study examining the biofouling growth rate when considering the flow velocity changes in a tubular heat exchanger showed similar results to that of Radu et al. (2012) (Trueba et al., 2015).

2.4 Antifouling Strategies

For the reasons aforementioned in previous sections, antifouling strategies is essential to mitigate marine biofouling. Due to its complex structure, being influenced by a large number of parameters, and the need for many disciplines and industries to overcome, biofouling prevention has been a difficult task to overcome over many years. For that reason, with developing technologies, various antifouling techniques and approaches have been trialled for antifouling technologies. A biofouling cleaning process via a water compressor after a year of fishing operation in drydock can be seen in Figure 2-10 for a trawler.

Figure 2-10: Biofouling cleaning process after a year of fishing operation in dry-dock

Starting from a historical perspective use of wax, tar, asphalt, pitch, copper sheathing, lead sheathing, and tallow can be given as the earliest examples of antifouling efforts taken into consideration to fight with biofouling by ancient civilizations (Callow, 1990; Lunn, 1974; Woods Hole Oceanographic Institution, 1952). Following events are considered the major events in antifouling history, respectively (Dafforn et al., 2011).

i. Use of heavy metals (copper, arsenic, mercury) in coatings,
ii. Copper dominance use in antifouling coatings,
iii. Discovery of TBT integrated conventional antifouling coatings,
iv. Development of Foul release antifouling coatings
v. Development of TBT-SPC coatings to control biocide release rates,
vi. Discovery of the deleterious impacts of TBT on the marine habitats via oyster farms,
vii. Copper release coating restrictions
viii. Research awareness for a more environmentally friendly antifouling coating
ix. Complete TBT ban across the world
x. IMO AFS Convention regulations

Considering the historical point of view, different methods and technologies have always been a part of the battle. Although antifouling technologies and/or methods are classified as modern and traditional in some cases, in general, antifouling strategies are categorised into three sections as biological, physical, and chemical methods (Cao et al., 2011).

2.4.1 Biological Antifouling Methods

Biological antifouling methods can be generalised as taking advantage of some of the enzymes secreted by some organisms as natural biofouling antagonists. Looking at it in detail, it can be seen that there are different enzymes that work in different mechanisms with fouling organisms. (i) Enzymes preventing fouler organisms from settling on surfaces by degrading their adhesion ability(Leroy et al., 2008), (ii) enzymes disturbing conditional biofilm matrix to prevent other organisms' growth in biofouling sequence (Xavier et al., 2005), (iii) enzymes generating deterrents and biocides by using the molecules secreted by other organisms (Johansen et al., 1997), and (iv) enzymes interfering with intercellular communication (Kristensen et al., 2008) are the four types of functions that biological antifouling mean. Although there are many advantages of using enzymes as antifouling methods, due to the lacking stability and disadvantages from environmental factors affecting the functionality of the enzymes, the application of enzymes is not accepted as successful or feasible yet.

2.4.2 Physical Antifouling Methods

There are several physical antifouling methods investigated to prevent biofouling, such as; electric use, acoustic use, electrolysis of seawater, changing surface characteristics (topography, wettability, and lubricity), radiation, magnetic fields, and radioactivity (Bertram, 2000; Callow, 1990; Dineshram et al., 2009; Scardino et al., 2006; Swain, 1998; Yebra et al., 2004). However, only a small number of the studies conducted in the aforementioned fields have been accepted as sufficient or enough to solve the problem. Riblet structured surfaces and Ultraviolet (UV) light treatment used in biofouling prevention can be given as recent examples from the literature (Kim et al., 2022; Ryan et al., 2020).

2.4.3 Chemical Antifouling Methods

As stated in previous sections, there have been many methods used in the battle with biofouling, from biological to physical antifouling strategies. However, none of them showed adequate effectiveness for preventing biofouling. Chemical antifouling strategies are divided into two groups as traditional and modern antifouling methods.

2.4.3.1 Traditional Chemical Antifouling Methods

In consideration of the historical point of view, it can be seen that antifouling coatings with toxins have played an essential role in preventing biofouling. Within this frame, the traditional antifouling method defines antifouling coatings with toxic biocides. By gradually releasing toxic particles into seawater, fouling organisms are prevented from settling on ship hulls, and yet this was one of the most efficient ways to get rid of fouler organisms from ship hulls up until the 1960s. With the developing technologies in the 20^{th} century, when tributyltin (TBT) based organotin compounds were implemented in antifouling coatings, a new era started; it solved the biofouling problem as it had never existed. After the discovery of TBT, it has been widely used due to its antifouling ability in the shipping industry all around the world. However, TBT-based antifouling coatings' dominance lasted only 40 years up until the 2000s. A French scientist discovered the anomalies in oyster growth, which later resulted in banning the use of TBT involving antifouling coatings all around the world by IMO (Alzieu et al., 1986;

IMO, 2001). As a result of the detrimental effects of TBT on marine organisms, a new trend started to replace TBT with so-called other 'more environmental toxic biocides'.

In addition, traditional chemical antifouling coatings are classified into two categories depending on their working metabolisms: insoluble matrix paints and soluble matrix paints, where both have their own drawbacks such as short life-times and inadequate performance in low speeds.

2.4.3.2 Modern Chemical Antifouling Methods

When it comes to modern chemical antifouling methods, biocides in antifouling coatings play an important role. Modern chemical antifouling coatings are categorised into two groups as biocidal and non-biocidal antifouling coatings. Whilst non-biocidal coatings are called foul release (FR) or non-stick coatings, and biocidal coatings are examined under three subgroups; Controlled Depletion Polymer (CDP), Self-Polishing Copolymer (SPC) and Hybrid SPC coatings.

- **Controlled Depletion Polymer (CDP) Coatings:** Controlled depletion polymer coatings use a technology that creates a layer around the ship hull for a specific time period. The formation of CDP coatings is similar to traditional soluble matrix coatings. The hydration process, which is a chemical reaction where water reacts with compounds to form another compound, is used to let the biocides leach into seawater. However, due to its working metabolism and insufficient biocide release after a specific time, CPD coatings become useless for the intended purpose. For that reason, CDP coatings are mainly used for the vessels that drydock more often than the other ships (Atlar, 2008). In detail, it can also be seen that the CDP coatings are rosin and biocide based and applied in thick layers.

- **Self-Polishing Copolymer (SPC) Coatings:** Self-polishing copolymer coatings use a technology that releases biocides into the water with the help of hydrolysis, which is a chemical reaction whereby chemical bonds are broken in contact with water. SPC coatings are considered in 2 groups as TBT-SPC and tin free SPC coatings. After the complete ban of TBT use in antifouling coatings, a new trend started to discover a similar antifouling mechanism as

TBT has been highly efficient to prevent marine biofouling. For that reason, TBT was changed with biocides (Zinc acrylate, Silyl acrylate, Zinc acrylate, etc.), and tin free SPC coatings were developed. Looking at in detail, in comparison with the CDP coatings, tin-free SPC coatings are considered as highly efficient as SPC coatings have a longer lifetime, relatively cheaper maintenance, and smoother surface due to more efficient self-polishing ability (Cao et al., 2011). A simplified working scheme of a CDP coating can be seen in Figure 2-11.

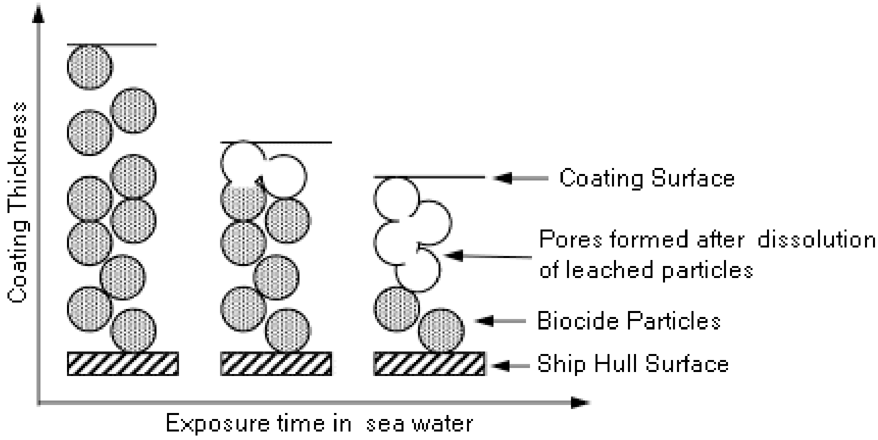


Figure 2-11: Simple working Scheme of SPC-Coatings similar to traditional soluble coatings adapted from Yebra et al. (2004)

- **Hybrid SPC coatings:** Hybrid SPC coatings use hydrolysis and hydration as biocide releasing methods with rosin and acrylic-based compounds.

- **Foul Release (FR) Coatings:** Although SPC coatings are considered to be efficient ways to prevent biofouling, due to their toxic impacts on the environment by releasing biocides in the marine environment, a possible ban of these biocides in the near future can be expected. For that reason, biocide-free foul release coatings offer a great opportunity for more environmentally friendly solutions. FR coatings offer a smooth surface, and the working mechanism is designed to degrade the adhesion strengths of the colonisers. When a fouler organism settles on a ship hull, together with its weight, whilst the ship is moving, relevant shear forces cause detachment of the organisms(Champ, 2003; Yebra et al., 2004). This mechanism is also called a self-cleaning mechanism. However, the shear force needed to detach an organism, for foul release coatings, becomes less effective on slow speed moving vessels, which is one of the biggest drawbacks of this paint.

A further comparison between different antifouling coatings by means of performance and costs is presented by Lejars et al. (2012).

2.4.4 Antifouling Coating Performance Tests

As stated in the previous section, antifouling coatings play the most critical role in the fight with the penalties caused by biofouling. The chemical compounds of the antifouling coatings lead to the effectiveness of the coatings so that small changes in the chemical formulation can result in different biofouling organisms attaching to the surfaces. For that reason, several testing and experiments have to be conducted before antifouling coatings become industrially available. Although there are many factors affecting the duration of these experiments/tests, such as experiment types, most of them take more than a year. That should also be noted that these tests are conducted to measure the performance of the coatings so that further upgrades on the relevant coatings can be done if required. After a coating is successfully applied and performed as expected, further experiments are conducted on real ship hulls to test it in a real operational environment. Therefore, all of this procedure takes from 1 to 5 years in total as the antifouling coating's lifetime depends on the frequency of the dry-docking, which typically ranges from 1 to 5 years.

Looking into the details, ageing tests are divided into two main categories as field tests and laboratory ageing tests (Sánchez and Yebra, 2009).

2.4.4.1 Field Tests

Field tests are conducted to test and experience a coating's performance in seawater and in real conditions. Although the best method would ideally be coating full-scale ship hulls with the relevant coatings and collecting performance data over time with regular inspections, the economic and time-based limitations are considered as major problems within this approach. Ship tests and sea testing stations are considered two subcategories within field tests.

2.4.4.1.1 Sea Testing Stations

There are many factors affecting the intensity of the fouling accumulation, as detailed in previous sections. When antifouling coatings are tested in sea sites, there are many parameters that are not controlled. For that reason, antifouling coatings are observed and analysed in one or more sea testing stations, and the experiment start day varies as a quicker biofouling formation is expected in warmer sea temperatures. However, it should also be noted that although seasonal changes are monitored when considering antifouling coating performances, there are only small changes in different long ageing sea testing stations in different locations and seawater temperatures (Sánchez and Yebra, 2009). Sea testing station tests are conducted in two ways: static and dynamic.

Static tests are conducted through coating panels with the relevant antifouling coatings and immersing them into the natural seawater. Panels are regularly checked and observed to understand the efficacy of antifouling coatings. Static tests are especially useful to get the relevant antifouling performances of offshore structures and ships with long idle periods, such as coastal fishing vessels. In other words, static tests represent the exposure conditions of slow currents and low tides on antifouling coatings whilst a ship is in an idle position. In addition, relevant standards were released by the formerly known American Society for Testing and Materials, ASTM International. Within these standards, a procedure to specify testing antifouling compositions in the shallow marine environment was described clearly (ASTM, 2012).

On the other hand, dynamic tests consist of rotating drums immersed in seawater. Dynamic tests represent the cruising conditions of ships by provoking the friction between antifouling coatings and seawater. These tests are helpful for both self-polishing or eroding coatings and foul release coatings. Whilst biocide release rate is measured for the biocidal antifouling coatings, it is the adhesion strength of the fouler organisms which is measured for the foul-release coatings.

2.4.4.1.2 Ship Tests

As a result of ageing tests, all the coatings are supposed to be used in real working conditions so that on ship hulls. For that reason, the best performance test results would be obtained by coating ship hulls and monitoring antifouling coating performances regularly over a long duration. Ship tests can be accounted as coating the entire hull of the ships or coating a small area of the hulls. However, there are many limitations that make full-scale ship tests impracticable such as (i) the amount of the antifouling coating applied is expensive, (ii) operation profiles of the ships take longer times, (iii) convincing the shipowner or company to get the permissions are difficult, (iv) uncontrolled environmental conditions. For that reason, the application of coatings on small parts of ship hull areas is more practical. Atlar et al. (2018) stated that small coating areas of the ship hulls could be considered as a step between laboratory/field tests and full ship tests. Another important point that should be pointed out is that small coating areas of the ship hulls make antifouling coating comparisons available (Sánchez and Yebra, 2009).

Uzun (2019) stated that he developed a novel time-based biofouling growth model based on three parameters: antifouling coating field tests, roughness functions and ship operational data. Additionally, assuming that idle conditions dominate the dynamic fouling growth in his model, he also stated the need for the data representing the biofouling growth under cruising conditions. For that reason, the author found the motivation to complete this task by cooperating with a representative fishing vessel owner and applying several types of coatings on the vessel to generate fouling growth data for the dynamic conditions.

2.4.4.2 Laboratory Tests

As stated in the previous sections, most of the field tests take long seawater exposures for both static and dynamic setups. For that reason, controlling ageing tests in laboratory setups is designed to speed up this process compared to the field tests. That should be noted that in laboratory tests, most of the factors affecting biofouling growth can directly be controlled, such as temperature and nutrient abundance. There are several laboratory setups that have been used such as in Couette-type laboratory setups, turbo-eroder type, slime farms, Multipurpose flume facility, ASTM D4938 highspeed water channel (Atlar et al., 2015; Lindholdt, 2015; Sánchez and Yebra, 2009; Swain and Touzot, 2008; Yebra et al., 2006; Yeginbayeva et al., 2019).

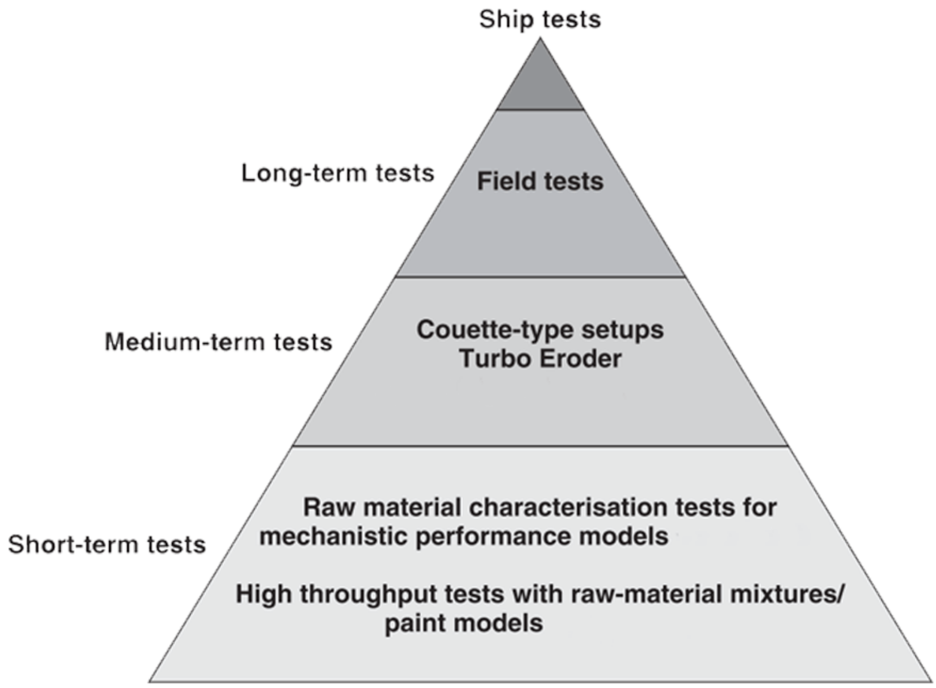


Figure 2-12: Efficient antifouling coating design and optimisation work-flow (Sánchez and Yebra, 2009)

To summarise, looking at the pyramid representing the workflow of antifouling coating tests given in Figure 2-12, it can be seen that whilst the laboratory tests take a shorter time to perform, field tests and particularly ship tests take a longer time. Each step in the pyramid is followed by the "next step", from the bottom to the top of the pyramid illustrated in Figure 2-12. Short term lab tests are conducted to estimate a given formulation/raw material to be suggested as medium-term tests for polishing and biocide leaching tests. After having successful test results from medium-term tests, long-term optimisation tests are conducted in the field. Following that, the final method used is ship tests, as it provides the real results for an antifouling coating.

2.5 Impacts of Biofouling

As stated in previous sections, biofouling has been an issue for marine-based activities for over 2 thousand years. Ship fuel systems, ship hulls, marine propellers, underwater turbines, piping, sea chests, water tanks, fuel and hydrodynamic systems, marine sensors, and marine aquaculture are some of the many fields among marine-based industries that biofouling affected (Flemming, 2020). Among these, the effect of biofouling on ship hulls is substantial. Although there are many impacts of biofouling, such as environmental problems (increasing emissions and invasive species), biofouling on ship hull not only deteriorates ship hull surface but also increases drag resistance of the vessel, increases corrosion rate, and cause breakdown of the coatings applied. Furthermore, an increase in ships' frictional resistance causes significant problems such as an increase in fuel consumption and an increase in CO_2 emissions for the ships.

Since the beginning of the 20th century, a number of research studies have been conducted indicating the impacts of biofouling and hull surface conditions on ships' hydrodynamic performance and resistance in the shipping industry. Effects of biofouling on a ship's frictional resistance were first extensively conducted by McEntee (1916). What he did was coating flat plates with anti-corrosive paints and keeping them in the water in the Chesapeake Bay over 12 months to observe the biofouling's impact on frictional resistance. He pulled the flat plates out of the water every month and towed the fouled plates for each month over 12 months. Later, he compared the frictional resistance change on the fouled plates in comparison to clean plates at different velocities. As a result of his extensive research, he estimated that the fouled plates' frictional resistance values were four times higher than the clean flat plates after 12 months of immersion in seawater (Woods Hole Oceanographic Institution, 1952).

Besides flat plate tests, another method to quantify the roughness effects in the forms of biofouling is to monitor the fouling accumulation before (representing clean hull), and after (representing a fouled hull) a trial ship hull is coated. Izubuchi (1934) conducted ship tests with a Japanese destroyer Yudachi by measuring the increase in frictional resistance coefficients between clean and fouled hulls. After coating the destroyer's hull with the relevant coatings, the vessel was put back to the sea, and the top speed was measured. After 375 days of operation, the top speed that the destroyer could go was measured. Results showed that there was a 4.6 knots decrease in the ship speed, from 20 knots to 15.4 knots precisely. Although the method used was not satisfactorily explained, his test results indicated a 100% increase in frictional resistance after 300 days due to severe fouling conditions on the hull surface. Hiraga (1934) conducted towing test experiments with brass plates in order to show the impact of the early stage of micro fouling accumulation on the surface. He immersed coated plates in seawater for just over three weeks and towed the plates. His results indicated a significant increase in total drag under initiative microfouling conditions.

Kempf (1937) also conducted experiments on pontoons known as classic pontoon tests under shell fouling, and his results showed a significant increase in ship resistance even with lower surface coverages. Another study showing the impacts of biofouling in forms of slime accumulation on frictional resistance was conducted by Benson et al. 1938). In addition to that, Conn et al. (1953) conducted a study with a trial ship hull over 40 days whilst cruising between 5 to 15 knots in seawater. After 40 days of accumulation, results showed biofouling caused a 5% increase in frictional resistance. Slime accumulation was on the headlines when Watanabe et al. (1969) conducted research showing biofouling's impacts on frictional resistance. Their results reported that there is an increase in frictional resistance between 8% and 14% when slime accumulation is in question. Another tool used to measure the slime accumulation's impact on the frictional resistance was rotating disks. Loeb et al. (1984) measured the frictional resistance of the rotating disks before and after fouling accumulation. Their results showed that slime accumulation increased the frictional resistance 10%.

One of the earlier full-scale trials was conducted by Haslbeck and Bohlander (1992). In their study, they examined a frigate and reported the increase in delivered power. The frigate was moored in a harbour in Hawaii over 22 months, and then ship speed and the delivered power was measured. Their results showed an 18% increase in delivered power compared to a clean hull. Schultz and Swain (1999) and Schultz (2000) investigated laminar and turbulent boundary layer velocity characteristics under biofilm covered and clean surfaces using a Doppler velocimeter in a recirculating water tunnel. Results showed an average increase from 33% to 187% in skin friction under fouled conditions. Schultz (2004) conducted extensive towing tank experiments (using flat plates) to compare frictional resistance values among several antifouling coatings for freshly applied, fouled and cleaned conditions. The most important outcome from his study was that the calcareous fouler organisms' heights play an important role in impact on frictional resistance on the plates. In other words, the higher the calcareous fouler organism's height is, the severer the impact on the frictional resistance is.

Schultz (2007) predicted full-scale ship resistance and powering penalties under different roughness and fouling conditions for antifouling coatings. He stated that from slime to calcareous (macro) fouling accumulation, ships face severe penalties that might require between 21% and 86% additional power to operate the vessel at the same speed. Furthermore, Hellio and Yebra (2009) illustrated the additional emission numbers resulting from fouling accumulation depending on Schultz (2007)'s calculations. It can be seen that even at early stages of biofouling, in the forms of thin slime accumulation, causes 134 million tonnes of CO_2 emission released into the atmosphere annually. These numbers increase up to 1238 million tonnes per year, depending on the severity of the biofouling. In the same study, potential savings due to biofouling were put in numbers and similarly, it is demonstrated that the most negligible biofouling accumulation causes approximately $22 billion and goes up to $204 billion a year. In addition, Schultz et al. (2011) investigated the economic impact of biofouling on a midsize naval ship hull to raise awareness for the amount of money that biofouling causes. Several costs, including fuel, hull coatings, coating application and removal, and hull cleaning, were considered. The results showed that the primary cost due to biofouling is the fuel consumption as a result of the increase in frictional resistance.

As can be seen from the studies conducted in the literature, there have been many studies focusing on the systematic measurement of the penalties caused by biofouling through added frictional resistance, required power increase to maintain cruising speed, financial penalties, and detrimental impacts on the environment including several ship tests for a number of ship types. However, in addition to the studies reported in Section 2.2.3, it would have been incomplete if the studies showing the impacts of biofouling on fisheries, together with the efforts put for more energy-efficient and sustainable fisheries, would not be reported.

Furthermore, one of the initial studies related to biofouling and the fishing boat ship hulls was conducted by Ravindran & Balasubramanyan (1974). Although such studies focus on the wooden hulls due to early advancements in fisheries, it is a good representative of how the fishing vessels' fight against biofouling and corrosion was neglected at that time. The paper suggests a final contribution to the literature as the cathodic hull protection would solve this ever-eluding problem, biofouling and so the corrosion, for the fishing vessels. Another study showing the impacts of biofouling on fishing vessels was conducted by Gulbrandsen (1986). He stated that hull fouling causes significant penalties for a small-scale fishing vessel. To be more specific, he calculated that one month, six months and twelve months of biofouling accumulation on a small-scale fishing vessel hull would cause a 7%, 44% and 88% increase in fuel consumption, respectively. In addition, Sato et al. (1989) conducted an experimental study examining the prevention of the hull and the propeller fouling for energy saving.

Hamaguchi et al. (1996) also investigated a small fishing vessel's NOx emission and fuel consumption change when underwater hull, propeller and rudder cleaning was conducted. According to this study, there was a significant reduction in fuel consumption (kg/l) and NOx emission (kg/l). Moreover, the fishing vessel's sailing speed was observed, reaching more than 10 knots as an increase.

Boopendranath (2000) conducted a PhD research, and as a part of his PhD, he surveyed the fishermen/stakeholders of mechanised fishing vessels to see the knowledge, awareness, and adoption of practices in energy saving. Several topics were discussed in the survey, including; alternative low energy fishing, optimum economic vessel speed, advanced technology, propeller nozzle, antifouling performance and sail-assisted propulsion. Survey results showed that the fishermen's awareness of antifouling usage and hull cleaning was poor. He also concluded that the antifouling measures are largely neglected and underestimated by the commercial fishing industry. Therefore, he highlighted the need to increase awareness to understand the penalties caused by biofouling among the fishing communities.

On the other hand, Notti et al. (2019) conducted one of few experimental assessments examining fouling and its impacts on fuel consumption rates for industrial fishing vessels. Their study compared fuel consumption rates of a Mediterranean trawler before and after a foul release coating application. Their results showed that 13,213 litre/year fuel-saving and 35.3 tons/year of CO_2 emission reduction is possible for an industrial fishing vessel.

Overall, these studies present an excellent range of signs for indicating penalties caused by biofouling. Furthermore, these studies can be accepted as proof of the continuous efforts taken by the researchers to fight against biofouling for both the shipping and fisheries industries. However, although there have been experimental studies investigating the impacts of biofouling in terms of an increase in frictional resistance, fuel consumption, GHG emission, and financial penalties, there is no systematic study conducted focusing on the improvements for the fight with biofouling in terms of hull protection and its impacts on industrial fisheries. Further research could fill this gap by (i) conducting field tests of different antifouling coatings, (ii) determining the fouling characteristics of the fishing vessels at the end of their fishing operation, (iii) determining the fouler organisms in the selected regions, (iv) comparing different antifouling strategies performances over time, and (v) conducting case studies with the selected antifouling coatings for the selected fishing vessels using different fishing techniques. In addition, although there are studies conducted for small-scale fisheries, there is no study conducted to determine and increase the awareness in the industrial fisheries regarding biofouling's deleterious impacts. This gap could be filled by carrying out a survey with the relevant fishermen/stakeholders to determine current knowledge on biofouling, antifouling strategies, preferences, and behaviours as social science research relevant to the biofouling phenomenon.

2.6 Theoretical Backgrounds – Roughness and Turbulent Boundary Layer

2.6.1 Ship Resistance and Powering

Ship resistance is defined as the force required to tow a ship at a constant speed in calm water. Due to the reason that full-scale ship resistance trials are expensive and complex in practice, towing test tanks with models or flat plates, which are similar to the actual ships, are used. A comprehensive review of proposed methods to model the roughness on ship hulls was investigated by Andersson et al. (2020). In addition to that, it is important to point out that the form factor effects on ship resistance due to biofouling are neglected. Furthermore, a recent study's conclusions, by Oliveira et al.

(2018), can be regarded as confirmation for the discouragements of the application of a form factor's effect into flat plate predictions on hull roughness penalties.

Once the total resistance (R_T) of the flat plates is determined by the towing tank tests for both smooth and rough surfaces, due to the scale differences, Granville's similarity law is used to calculate resistance values in full scale for the ship. R_T value is then employed in Equation 1 to calculate the effective power of a ship. Effective power is the necessary power to tow the ship's hull through the water at a given speed. Therefore, the effective power of the ship, P_E, is calculated with the multiplication of the total resistance, R_T, and ship speed, V, defined by Equation 1.

$$P_E = R_T V \tag{1}$$

The total resistance (R_T) decomposition formula is given by Equation 2.

$$R_T = \frac{1}{2}\rho S C_T V^2 \tag{2}$$

Where ρ is the density of the water, S is the wetted surface area, C_T is the total resistance coefficient. To re-define the effective power, the total resistance formula is integrated into the effective power formula. Then Equation 1 and Equation 2 are combined and rewritten as in Equation 3.

$$P_E = \frac{1}{2}\rho S C_T V^3 \tag{3}$$

A variety of forces are applied on the ship, which ends up as resistance components for the ships. These components are confined as frictional resistance, R_F, residual resistance, R_R, and air resistance R_{AA} as defined by Equation 4.

$$R_T = R_F + R_R + R_{AA} \tag{4}$$

As mentioned above, resistance calculations of ships are traditionally calculated through towing tank tests with model ships geometrically similar to full-scale ships. Because most of the models do not have superstructures or fully immersed flat plates are used in towing tank tests, air resistance is not thus included in the total resistance calculation formula for the model ships. William Froude's total drag components theory is given as in Equation 5.

$$R_T = R_F + R_R \tag{5}$$

Once the total drag, R_T, values were calculated for each plate and related speeds, they were customarily non-dimensionalised by dividing by dynamic pressure ($\frac{1}{2}\rho V^2$), and the wetted area of the ship model hull (S) as defined by Equation 6.

$$\frac{R_T}{\frac{1}{2}\rho V^2 S} = \frac{R_F}{\frac{1}{2}\rho V^2 S} + \frac{R_R}{\frac{1}{2}\rho V^2 S} \quad (6)$$

As a result, the total resistance coefficient of the model, C_T, is the sum of the residuary resistance coefficient of the model, C_R, and the frictional resistance coefficient, C_F. Schultz (2007) stated that whilst the residuary resistance coefficient is a function of Froude number, the frictional resistance coefficient is a function of Reynolds number. Therefore, the total resistance coefficient can be defined as in Equation 7.

$$C_T = C_F(Re) + C_R(Fr) \quad (7)$$

Once the resistance is calculated in a towing test, the total resistance coefficient (C_T) is calculated using Equation 2. As a next step, the frictional resistance coefficient (C_F) is taken into consideration. Although there are several studies conducted to calculate the frictional resistance coefficient, The Karman-Schoenherr friction line (Schoenherr, 1932) given by Equation 8 for a smooth plate can be used to predict the frictional resistance coefficients of a smooth flat plate.

$$\frac{0.242}{\sqrt{C_F}} = \log(Re \cdot C_F) \quad (8)$$

As the two components of Equation 7 are determined for the smooth plate surfaces, the third component, the residual coefficient of the smooth plate (C_{R_S}), can be calculated as in Equation 9.

$$C_{R_S} = C_{T_S} - C_{F_S} \quad (9)$$

As the flat plates are towed to get resistance values, the change in the total resistance due to the biofouling accumulation is accepted to be only due to frictional resistance (Schultz, 2007). For this reason, rough and smooth plate's residuary resistant coefficients are assumed to be equal, as shown in Equation 10.

$$C_{R_S} = C_{R_r} \quad (10)$$

Finally, frictional resistance coefficient values of the rough plate surfaces (C_{F_r}) were computed by subtracting the smooth plate's residuary resistant coefficient values from the total resistance coefficients of rough flat plate surfaces as shown in Equation 11.

$$C_{F_r} = C_{T_r} - C_{R_r} \tag{11}$$

The increase in P_E due to the effect of fouling can be expressed by Equation 12 similar to that used by Tezdogan et al. (2015).

$$\%\Delta P_E = \frac{C_{T,rough} - C_{T,smooth}}{C_{T,smooth}} \text{ x } 100 = \frac{\Delta C_F}{C_{T,smooth}} \text{ x } 100 \tag{12}$$

2.6.2 Boundary Layer

The boundary layer concept was firstly presented by German physicist Ludwig Prandtl in a conference held in 1904 (Schlichting, 1979). Furthermore, the term Boundary layer defines the layer which forms around any submerged object under interaction with the fluid flow. Moreover, boundary layer theory helps us understand and calculate the impacts of roughness effects, as in the form of biofouling, on ship resistance. Therefore, to understand the calculations, firstly, velocity change in the boundary layer has to be analysed and well understood. Prandtl stated that where the fluid flow meets the substrate, the velocity of the fluid particles become equal to zero (no-slip condition), and fluid velocity increases exponentially with distance from the object until the fluid flow reaches to free stream velocity of the fluid. This velocity gradient near a submerged substrate gives us the definition of a boundary layer.

Figure 2-13 illustrates the velocity changes in the boundary layer and the growing distance from the object as the fluid moves downstream. Considering a flat plate, when the fluid flow meets the plate surface, it is exposed to three states as laminar, transition and turbulent flow patterns of the boundary layer, respectively.

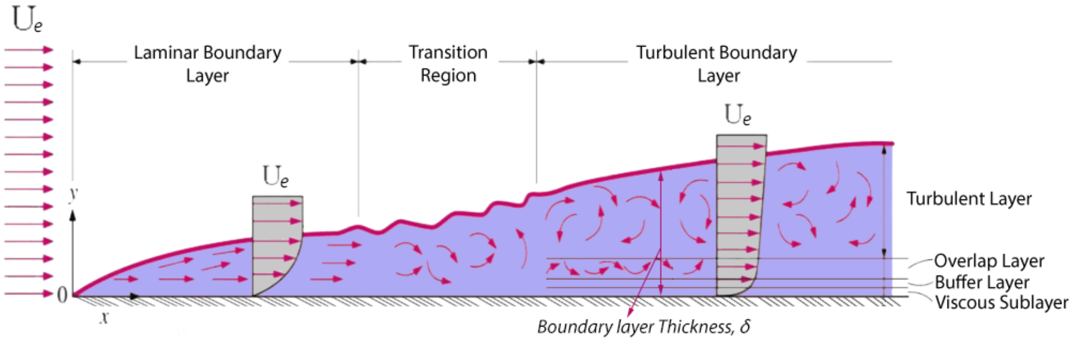


Figure 2-13: Boundary layer development over a flat plate adapted from Alaoui (2016)

Firstly, a laminar flow is observed for a distance from the point where the first contact occurs. This also means that the velocity of the flow does not fluctuate in the so-called laminar boundary layer. In the laminar boundary layer, skin friction is the smallest in comparison with the following states as the flow is in stable condition. After a certain point, the fluid flow enters the transition region, where the velocity fluctuations begin, and instabilities arise. Finally, the flow becomes turbulent where the velocity profile is fully fluctuating. The length of the laminar boundary layer and the transition region depends on several factors such as roughness, pressure, and velocity fluctuations. In addition, the transition region highly depends on Reynolds number (*Re*), which is defined as:

$$Re = \frac{U_e x}{\nu} \tag{13}$$

Where U_e is freestream velocity, x is the distance from the downstream distance, and ν is the kinematic viscosity of the fluid, respectively.

Furthermore, it should be noted that the laminar boundary layer and the transition region covers the smallest portion of the hull surface whilst the majority of the hull is covered with the turbulent boundary layer area of a sailing ship. For example, when 230 m-long ships cruising at 24 knots is considered and Re = 5×10^5 is used, it can be seen that only the first 5 cm in length from the leading edge is defined as a laminar boundary layer (Song, 2020).

2.6.3 The Velocity Profile in the Turbulent Boundary Layer

After briefly introducing the boundary layer and its downstream behaviours, the turbulent boundary layer is detailed in this section. The turbulent boundary layer is divided into two layers as an inner and outer layer. Figure 2-14 shows the velocity profile in a turbulent boundary layer. In Figure 2-14, U is mean velocity, U_τ is friction velocity, U^+ is non-dimensional mean velocity, y is the normal distance from the wall, y^+ is the non-dimensional distance from the wall, and ν is kinematic viscosity. Furthermore, friction velocity (U_τ) is defined as $\sqrt{\tau_w/\rho}$, where, τ_w is the wall shear stress, and kinematic viscosity (ν) is defined as μ/ρ, where μ is dynamic viscosity, and ρ is the fluid density.

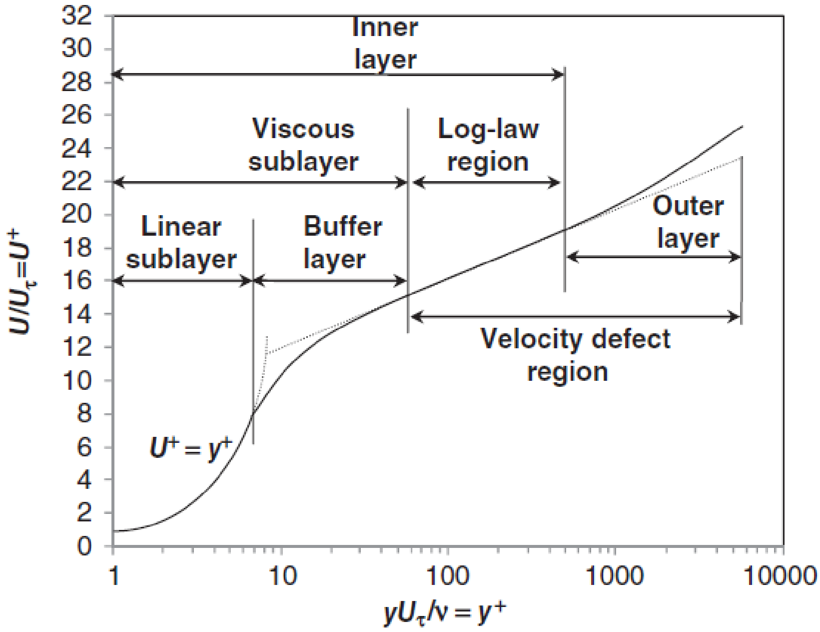


Figure 2-14 Law of the wall plot for a turbulent boundary layer (Schultz and Swain, 2000).

The important point for the inner layer is that although it only consists of a small portion of the boundary layer (from 10% to 20%), the majority of the velocity variations (approximately 70%) occur in this part of the boundary layer. And yet, whilst the flow in the inner region is affected by surface roughness, flow is not affected by the surface roughness in the outer layer. The mean velocity profile in this region is defined with a function including wall shear stress, fluid density, kinematic viscosity, and the distance from the wall. For that reason, the velocity profile of the inner layer, the so-called law of the wall, can be defined as in Equation 14.

$$\frac{U}{U_\tau} = f\left(\frac{yU_\tau}{v}\right) \quad \rightarrow \quad U^+ = f(y^+) \tag{14}$$

The inner layer consists of two sublayers, a viscous sublayer and a log-law region. Considering Figure 2-14, it can be further seen that the linear sublayer and buffer layer are two parts of the viscous sublayer. As can be understood from its name, the flow velocity is in the linear state in the linear sub-layer. The velocity profile of the linear sublayer can be seen as given in Equation 15.

$$U^+ = y^+ \tag{15}$$

Another point that should be noticed is that total shear stress is stable and equal to the wall shear stress (τ_0). Therefore, when the wall shear stress is normalised, skin friction coefficient C_F can be defined as given in Equation 16.

$$C_F = \frac{\tau_0}{\frac{1}{2}\rho U_e^2} \tag{16}$$

Additionally, the region where the velocity profile starts losing its linearity is called the buffer region. That should be noted that the highest turbulence takes place in this region.

The Log-law region starts after the viscous layer ends. Because the total shear stress is stable and velocity fluctuations exist in this region, the flow is also highly turbulent in this log-law region. As can be understood from its name, the velocity profile in this region is called log-law, which is expressed as in the following Equation 17 for a smooth wall.

$$U^+ = \frac{1}{\kappa}\, log(y^+) + C \tag{17}$$

Where, κ is the von Karman constant and *C* is the log-law intercept. Looking at the literature, there have been several studies conducted confirming the log-law region of the boundary layer (Clauser, 1954; Klebanoff and Diehl, 1951). However, it can also be seen that κ and *C* values vary among different studies, as there is still a conflict when defining these values (George, 2007). Different values for C and κ values can be seen in Table 2-2.

Table 2-2: Different κ and C values among different studies

Authors	*van Korman* constant (κ)	*C* intercept
(Clauser, 1954)	0.41	4.9
(Coles, 1956)	0.4	5
(Cebeci and Bradshaw, 1977; Cebeci and Chang, 1978)	0.41	5.2
(Zagarola and Smits, 1998)	0.436	6.15
(Mckeon et al., 2004)	0.421	5.60

As stated previously in this section, the inner region consists of 10% - 20% of the total boundary layer; however, most of the velocity fluctuations occur in this region. For the outer region, the flow velocity is accepted to be not affected by surface conditions such as roughness and or viscous effects (Townsend, 1980; Yaglom, 1979). In addition to that, velocity defect starts from the log-law region and advances in the outer layer. In other words, as it can be seen from Figure 2-14, the velocity profile does not follow the preceding log-law trend, which is called the wake characteristic of the outer layer for a turbulent boundary layer. Velocity defect law can be seen in Equation 18.

$$\frac{U_e - U}{U_\tau} = f\left(\frac{y}{\delta}\right) \tag{18}$$

On the other hand, Coles (1956) correlated the log-law and the velocity defect law as the wake function, as shown in Equation 19.

$$U^+ = \frac{1}{\kappa} ln(y^+) + C + \frac{2\Pi}{\kappa} sin^2\left(\frac{\pi}{2}\frac{y}{\delta}\right) \tag{19}$$

Where, Π is the wake parameter assumed to equal 0.055 for zero pressure gradient and lo free -stream turbulence.

2.6.4 The Effect of Surface Roughness on Boundary Layer

A simple definition of roughness can be made as the irregularities on a surface texture or surface geometry. Besides that, hydrodynamic roughness is defined as a critical parameter for describing the bottom drag in the boundary layer (Lacy et al., 2005). Furthermore, roughness is presented with numeric values representing the roughness profile. Before detailing the effects of roughness on the boundary layer, roughness types have to be stated briefly. Although there are many parameters used, the most common roughness parameter can be regarded as the average roughness height (Ra). In addition to that, mean peak-to-valley height (Rz) and root mean square roughness (Rq, RMS) are some of the parameters of roughness. In the marine industry, standard hull roughness measure has been accepted as average hull roughness (Rt_{50}), which is a measure of maximum peak-to-valley height over 50 mm lengths of the hull surface. To give an example from the literature, Schultz (2008) used the Rt_{50} in equivalent sand roughness heights (k_s) conversion table when converting the NSTM fouling ratings into k_s. Furthermore, there are two types of roughness: *k*-type and *d*-type roughness. This categorisation is made as they represent different scales used in roughness functions. The *d*-type roughness stands for the pipe diameter roughness scale, while the *k*-type roughness stands for the roughness height scale. As the roughness scale on the ship hull surface is *k*-type roughness, *k*-type roughness is used in this thesis. Therefore, the roughness term used in this thesis stands for *k*-type roughness from this time forth.

Surface roughness term is a parameter that can be defined with the roughness Reynolds number (k^+), which is formulated as in the following Equation 20

$$k^+ = \frac{kU_\tau}{v} \tag{20}$$

There have been many studies conducted related to k-type roughness in the forms of sand grain roughness (Demirel et al., 2019, 2017; Flack and Schultz, 2010; Musker, 1977; Schultz, 2004, 2002; Schultz and Flack, 2013, 2007; Sezen et al., 2021; Shockling et al., 2006; Turan et al., 2016; Ünal, 2015; Uzun et al., 2021, 2020, 2019). In addition to that, Jiménez (2004) conducted a comprehensive review on the turbulent flows over rough surfaces where further research can be found. Considering the effects of surface roughness on the boundary layer, one particular condition must be checked. Depending on whether the roughness scale on a surface is covered by the linear sublayer of the boundary layer or not, three flow regimes have to be taken into account as smooth, transitional regime and fully rough regime.

To start with the first flow pattern, firstly, a hydrodynamically-smooth surface term has to be explained. When the roughness scale on a surface is so small that it can be covered by the linear sublayer of the boundary layer, relevant roughness has no effect on the surface shear stress. This surface is termed a hydrodynamically smooth surface, and therefore the flow over that surface is termed as smooth regime flow. Next, transitional or intermediate regime occurs when the roughness elements partially go beyond the linear sublayer of the boundary layer. Due to the roughness scale, eddy shedding and drag formation can be observed in this regime. Finally, a fully rough flow regime occurs when most of the roughness elements go beyond the boundary layer's linear sublayer. Furthermore, that should be noted that the shear stress varies quadratically with the velocity (Allen et al., 2007).

Looking at the literature, it can be seen that there is comprehensive roughness research conducted by using artificially roughened surfaces with sand grains on either surfaces or pipes. By using the sand grains, sand grain height is used as a roughness character which is defined as the equivalent sand grain height (k_s). As stated by Schlichting (1979), equivalent sand roughness grain height can be used as of the same roughness function with any roughness geometry. Turan et al. (2016) conducted extensive towing tests at the Kelvin Hydrodynamics Laboratory at the University of Strathclyde. In their study, flat plates covered 3D printed artificial barnacles were towed at the laboratory to investigate the effect of coverage percentage of the barnacle accumulation on ship resistance with various Reynolds numbers. In addition, Uzun et al. (2017) investigated the impacts of calcareous fouling on added resistance and power requirements of the ships by attaching 3D printed barnacles on flat plates. Flat plates were covered with varying coverage areas, then towed over different Reynolds numbers at Kelvin Hydrodynamics Laboratory at the University of Strathclyde. Similarly, Demirel et al. (2017) examined the impacts of different barnacle heights and coverage areas on the ships' resistance and effective power. Another good and practical example that can be given is Uzun et al. (2020)'s research examining the different barnacle fouling settlement configurations by using 3D printed barnacle patterns.

Furthermore, Uzun et al. (2019) investigated fouling growth and developed a model to predict the daily fouling accumulation over time. In their study, a time-dependent model was developed with the help of an SPC type antifouling field test data provided by the company with operational profile and shipping route. Following that, they converted biofouling growth over time into equivalent sand roughness heights and roughness functions. Next, they used Granville's scaling-up procedure to investigate the effect of roughness on full-scale ship resistance. Finally, their results were validated with a tanker's operation data where the increase in frictional resistance was measured with onboard devices over a year and a case study where the noon reports of a crude oil carrier were examined to predict the increase in the effective power.

In addition, Demirel et al. (2019) presented frictional resistance diagrams data of varying ship lengths, ship speeds and fouling conditions for practical use for further studies. These figures provide the added resistance values for any ship ranging from 10 m to 400 m LOA under varying ship speeds. To give an example, from typical as applied antifouling coating condition to heavy calcareous fouling condition, ΔC_F value of a 20 m ship cruising at 10 m/s can go from 1.625 x 10^{-4} up to 4.55 x 10^{-3} as can be seen in Figure 2-15. Furthermore, a keynote has to be taken for the definition of the added resistance here. The term "added resistance" is used for defining the increase in the frictional resistance due to biofouling accumulation for a ship operating in calm water at a given speed.

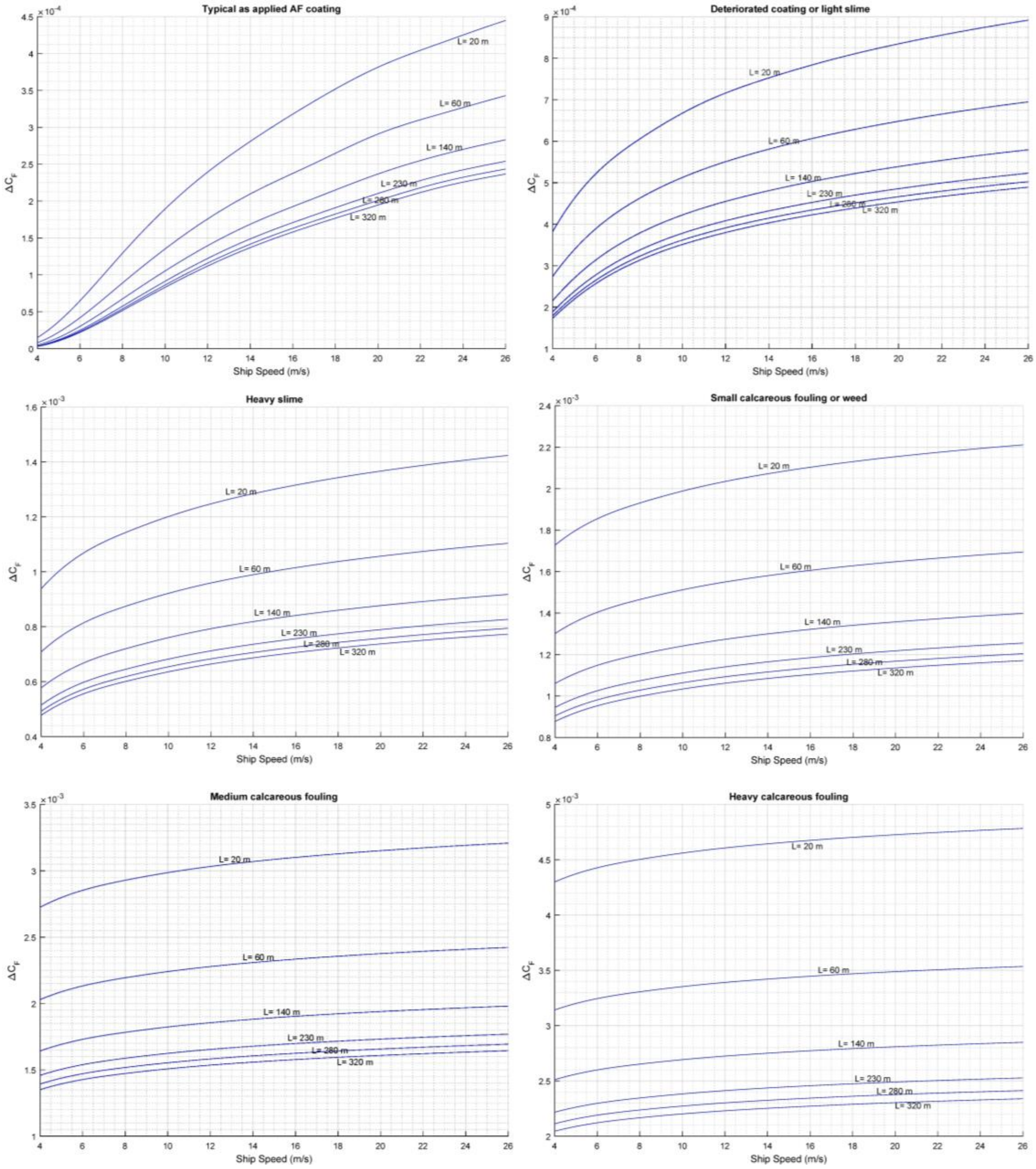


Figure 2-15: Practical added resistance diagrams for ships under a variety of fouling conditions with different LOA cruising at different ship speeds as adapted from Demirel et al. (2019).

In Schlichting (1979), definition roughness Reynolds number of a flow can be used to identify the flow regimes detailed previously in this section. Furthermore, he identified the relevant ranges of roughness Reynolds number for the equivalent sand roughness k_s^+ for different flow regimes as shown in Table 2-3.

Table 2-3: Flow regime characteristics according to Schlichting (1979) and Cebeci and Chang (1978)

k_s^+ Range (Schlichting, 1979)	Flow Regimes	k_s^+ Range (Cebeci and Chang, 1978)
$5 > k_s^+$	Smooth	$2.25 > k_s^+$
$70 > k_s^+ > 5$	Intermediate	$90 > k_s^+ > 2.25$
$k_s^+ > 70$	Fully rough	$k_s^+ > 90$

Within this context, which should be noted that for different types of surface roughness, this k_s^+ range may change depending on the nature of the surface roughness, as Schlichting (1979) used a uniform sand roughness. As stated by Bandyopadhyay (1987), Schlichting (1979)'s flow regime limits for k_s^+ values are lower for a wire mesh roughness and for spanwise grooves. In addition, Cebeci and Chang (1978)'s limits can be given as another example of different values range shown in Table 2-2.

The first experimental studies conducted on the effects of roughness can be seen in Nikuradse (1933)'s research. He used uniform-sand-grain coated pipes by characterising the roughness elements with sand grain height, k_s.

Depending on the sublinear sublayer thickness (δ') and roughness height in forms of k_s relation, the flow regime is determined. If the roughness height in the form of k_s is smaller than $\frac{\delta'}{3}$, flow is in a smooth regime, and the roughness height does not go beyond the linear sublayer. For that reason, a log-law velocity profile is used for the law of the wall region. Equation 21 is the updated statement of the log-law velocity profile, as in Equation 19 with A= 5.62 (Schultz, 1998).

$$U^+ = A\,log(y^+) + C \quad (21)$$

Furthermore, if the height of the sand roughness elements is greater than seven times the thickness of the sublayer, or simply $k_s > 7\text{x}\delta'$, the flow becomes not affected by viscous effects. In other words, this regime is fully rough condition. The velocity profile of this relation is given by Equation 22 with B=8.5 for fully rough flow regime according to Schlichting (1979).

$$U^+ = A\,log\left(\frac{y}{k_s}\right) + B \quad (22)$$

After obtaining both the velocity profile equations for rough and smooth surfaces, Equation 24 is subtracted from Equation 23, and a downward shift as a result of roughness elements is calculated. For that reason, roughness defect, or so-called roughness function, is defined in Equation 23.

$$\frac{\Delta U}{U_\tau} = \Delta U^+ = C - B_1 \tag{23}$$

Where C is smooth wall log-law, B_1 is actual log-law intercept.

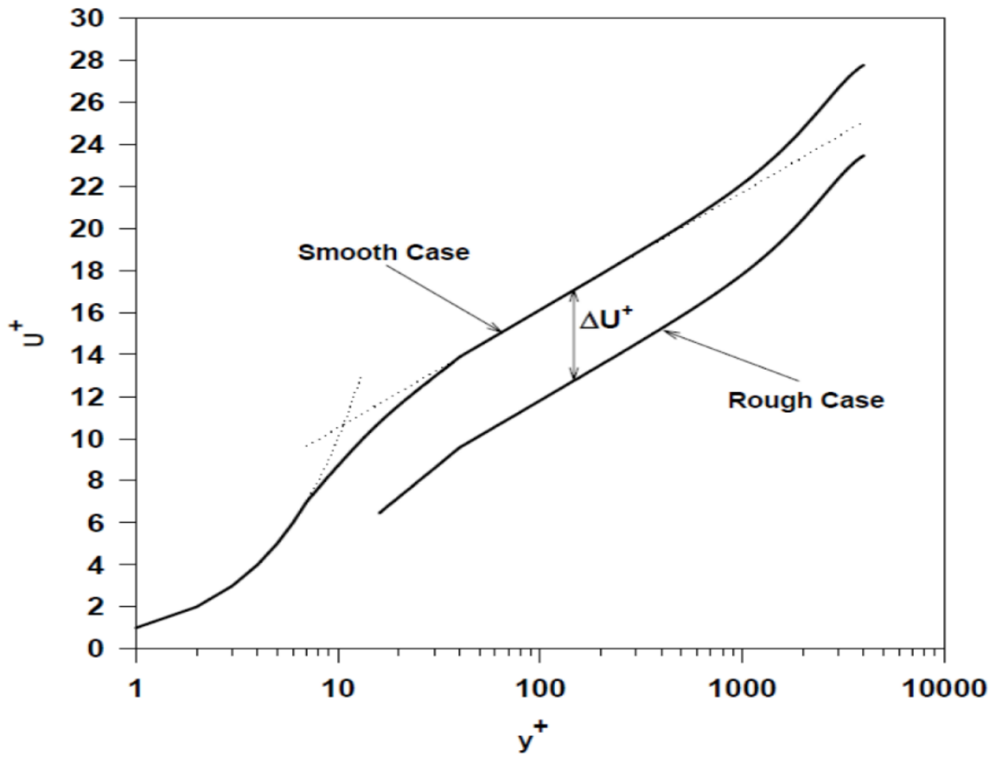


Figure 2-16: Roughness Effect on the law of the wall (Schultz and Swain, 2000)

Next, when the U^+ and log y^+ is plotted, the aforementioned roughness defect can be seen as a downward shift in the velocity profile. This downward shift can be seen in Figure 2-16. Therefore, the log-law region of the boundary layer for all regimes can be expressed as in the following Equation 24 (Schultz, 1998).

$$U^{+} = A\,log(y^{+}) + B_1 = A\,log(y^{+}) + C - \Delta U^{+} \tag{24}$$

Where, C=B_1 and ΔU^{+} in smooth flow regime due to the reason that roughness should not affect the log-law intercept. On the other hand, the roughness function for a fully rough regime can be written in terms of roughness Reynold number, as shown in Equation 25.

$$\Delta U^{+} = A \log\left({k_s}^{+}\right) + C - B \tag{25}$$

2.6.5 Determinations of Roughness Functions

As stated before in this chapter, biofouling on ship hulls increases the ship's frictional resistance, which triggers a number of actions resulting in problems such as air pollution, economic penalties, etc. For that reason, prediction of the increase in frictional resistance of any immersed object covered by fouler organisms is important. Furthermore, according to Granville (1985, 1987), once the roughness function is known, an increase in frictional resistance can be calculated with a boundary layer method. Within this context, that should be noted that each roughness element has different roughness characteristics and roughness functions. For that reason, each roughness type and so that the roughness function has to be determined experimentally.

In the determination of the roughness function, there are two methods used, namely direct and indirect methods. Whilst direct methods measure the velocity profile in the boundary layer to determine the roughness functions, simpler and generally more economical methods are called indirect methods, such as measuring the pressure drops in pipe flow (Nikuradse 1933), total drag of flat plates (Granville 1978) or torque on rotating disks (Granville 1982). Because the towed plate method is used in this thesis, further discussion is conducted with regard to this approach.

After the calculation of the total resistance coefficient (C_T), frictional resistance coefficient (C_F) and residuary resistance coefficient (C_R) values of both rough and smooth flat plates as stated in Section 2.5.1, Granville's similarity law is used in order to extrapolate the roughness effects of particular fouling condition from model scale to the full-scale ship, which is based on the flat-plate assumption (Granville, 1958, 1987). In order to predict the effect of roughness on frictional resistance of flat plates of ship lengths, roughness Reynolds numbers, k^+, and roughness function values, ΔU^+, must be calculated for all of the surfaces to be employed in Granville's similarity law (Schultz, 2007). Therefore, roughness Reynolds numbers, k^+, and roughness function values, ΔU^+, for all surfaces are obtained iteratively using Equation 26 and Equation 27 following the overall procedure of Granville (1987).

$$k^+ = \left(\frac{k}{L}\right)\left(\frac{Re_L C_F}{2}\right)\left(\sqrt{\frac{2}{C_F}}\right)_R \left[1 - \frac{1}{\kappa}\left(\sqrt{\frac{C_F}{2}}\right)_R + \frac{1}{\kappa}\left(\frac{3}{2\kappa} - \Delta U^{+\prime}\right)\left(\frac{C_F}{2}\right)_R\right] \tag{26}$$

$$\Delta U^+ = \left(\sqrt{\frac{2}{C_F}}\right)_S - \left(\sqrt{\frac{2}{C_F}}\right)_R - 19.7\left[\left(\sqrt{\frac{C_F}{2}}\right)_S - \left(\sqrt{\frac{C_F}{2}}\right)_R\right] - \frac{1}{\kappa}\Delta U^{+\prime}\left(\sqrt{\frac{C_F}{2}}\right)_R \tag{27}$$

Where L is the plate length, Re_L is the plate Reynolds number, C_F is the frictional drag coefficient, $\Delta U^{+\prime}$ is the roughness function slope, which is the slope of ΔU^+ as a function of $ln(k^+)$, and the subscript *S* indicates a smooth condition whereas the subscript *R* indicates a rough condition.

2.6.6 Granville's Similarity Law Scaling Procedure

Biofouling accumulation on ship hulls impacts the velocity profile in the turbulent boundary layer. This deformation causes a downward shift which gives the roughness function (ΔU^+) definition with given roughness Reynolds number (k^+), as shown in Figure 2-16. Moreover, once the roughness Reynolds number (k^+) is known for any immersed surface, increase in the frictional resistance due to biofouling accumulation can be calculated through following the steps given in Section 2.5 in this chapter. For that reason, many experiments have been conducted in towing tests to obtain relevant added resistance values for flat plates covered with relevant biofouling conditions (Demirel et al., 2017; Schultz, 2004, 2002; Turan et al., 2016; Uzun et al., 2017). However, it has never been easy, and so that a practical task to conduct these experiments for full-scale ships in terms of towing tests. For that reason, Granville's similarity law scaling procedure is accepted to be one of the most practical ways to calculate the changes in frictional resistance due to biofouling effects on full-scale ships (Granville, 1958).

Granville's similarity law scaling procedure is completed in 3 steps. In order to conduct the scaling procedure, roughness height (*k*), roughness Reynolds numbers (k^+), roughness functions (ΔU^+), corresponding flat plate and the ship's length are required to be known. The first step starts with the calculation of the frictional coefficient of a smooth flat plate (C_{F_S}) using Equation 8. Following that, C_{F_S} against $log(Re_L)$ curve is plotted. In the second step, the roughness function is used for shifting the plotted C_{F_S} curve by a distance of $\Delta U^+/ (ln(10)/\kappa)$ in $log(Re_L)$ direction. This new curve represents the frictional coefficient of a rough flat plate (C_{F_r}). Moreover, the third step is plotting the line of constant L_{plate}^+ satisfying the Equation 28.

$$Re_L = \frac{{L_{plate}}^+}{\sqrt{\frac{C_F}{2}}\left(1 - \frac{1}{\kappa}\sqrt{\frac{C_F}{2}}\right)} \tag{28}$$

Where L_{plate}^+ is the non-dimensional length of the plate defined as the length of the plate (L_{plate}) divided by viscous length scale as shown in Equation 29.

$$L_{plate}{}^+ = \frac{L_{plate}}{viscous\ length\ scale} \tag{29}$$

That should be noted that the viscous length scale (ν/U_τ) can be calculated using Equation 20. The fourth step is to shift the line of constant L_{plate}^+ by $\log(L_{ship}/L_{plate})$ in $\log(Re_L)$ direction. The new line is defined as L_{ship}^+. The intersection point of this new line with the C_{F_r} curve gives the C_{F_r} value for the ship. Hence, subtracting C_{F_r}value from C_{F_S} gives the increase in the frictional resistance (ΔC_F) of the ship due to the roughness. The schematic of this procedure is illustrated in Figure 2-17.

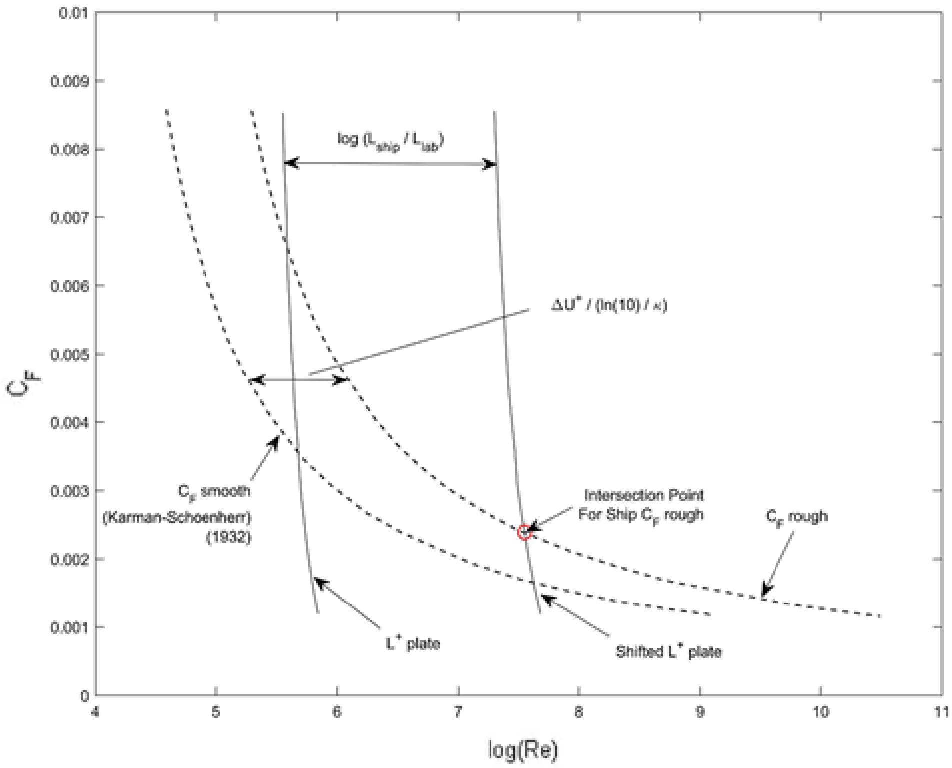


Figure 2-17: Granville's scale-up procedure adapted from Schultz (2007, 1998) and Shapiro (2004) (Uzun, 2019).

2.7 Financial and Environmental Analysis Calculations

In order to take the impacts of biofouling into the end-user's point of view, financial and environmental penalties have to be stated. For that reason, fuel consumption increase due to biofouling must be calculated. To do that, power output of the engine (brake horsepower) with the service allowance and the main engine fuel consumption (MEFC) at design speed have to be determined.

Effective power is equal to the brake horsepower minus losses due to the gearbox, shafting and propeller, as well as interaction between the propeller and the hull (USNA, 2020). For that reason, after calculating the total resistance and the effective power with Equation 3, several parameters have to be considered, such as propulsive efficiency, engine condition, weather conditions, and distance cruised. Withing this in mind, the distance cruised for each fishing vessel can be obtained using AIS. Moreover, it can be assumed that the ships operating in calm water and have the same engine conditions. However, due to the difficulties of obtaining each parameter for every ship, a simple approach is used by taking propulsive efficiency into account for each fishing vessel.

As stated before in this chapter, effective power is the necessary power to tow the ship's hull through the water at a given speed, and it can be obtained using Equation 3. However, due to the energy losses in a typical propulsion system of a ship, ship powering requirement is impacted by the gear, shaft, propeller, and hull efficiencies. Therefore, to be able to calculate the brake horsepower from effective power, efficiencies are required to be assumed for each portion of the drivetrain. Nevertheless, instead of deducing all of the separate efficiencies for each component, the separate efficiencies are frequently combined into a single efficiency, which is called propulsive efficiency. That is to say, after obtaining the effective power for each fishing vessel, transmission and propulsive efficiency losses are taken into account and then brake horsepower is calculated for the fuel consumption. Furthermore, common values of propulsive efficiency range from 55% to 75% (USNA, 2020). In addition to that, Theotokatos and Tzelepis (2013) examined propulsive efficiency values ranging from 67% to 77%. What is more, the majority of the fishing vessels' propulsive efficiencies are considered as 70% by Oliveira et al. (2021).

Following the calculation of the energy losses in the propulsion systems, service allowance is added to the brake horsepower. Furthermore, service allowance is determined depending on the expected service area. Consequently, relevant engine's fuel consumption, in litres per hour, can be determined with the help of the relevant engine's technical manual with the calculated brake horsepower. Once the fuel consumption is calculated, the cruising time data is determined with the help of AIS. After that, cruising time, brake horsepower and engine fuel consumption are multiplied, and the total fuel consumption for the ship's operation is calculated in litres. Finally, the recent marine diesel oil price is determined from the market for the fuel consumed; therefore, the total fuel consumption cost can be calculated.

Furthermore, fossil fuel combustion causes the release of Green House Gases such as CO_2 into the atmosphere. Considering the thousands of industrial fishing vessels, the impact of fishing vessels on climate change is one factor that should be considered. For that reason, CO_2 emission from the fuel consumption of the fishing vessels is calculated as diesel oil is the primary fossil fuel used among industrial fishing vessels. Marine diesel oil is known to emit 3206 kg CO_2 per tonnes of marine diesel oil (IMO, 2005). Moreover, the density of marine diesel oil is 900 kg/m^3 (IMO, 2016). Therefore, for a litre of diesel oil, 2.8854 kg of CO_2 is emitted into the atmosphere. Thus, the fuel consumption of the fishing vessels can be converted into CO_2 emissions emitted into the air from the fishing vessels by multiplication.

2.8 Gaps in the Literature

After a thorough literature review, the following gaps in the literature were determined:

- There is no systematic study showing the benefits of the fouling control systems (hull protection) focusing on industrial fisheries,

- There is no systematic study conducted showing and comparing the impacts of biofouling on fishing vessels operating with different fishing techniques.

- ITTC (2011)' recommendations pointed out the need for addressing the lack of databases of the roughness on the surfaces invaded by different fouler organisms for different antifouling coatings. To the author's best of knowledge, there is no biofouling database over time available from field tests, including static field tests and ship tests with different antifouling coatings conducted in the margins of the Atlantic Ocean between Asia, Europe, and Africa.

- There is no available biofouling data over time linking ship tests and static sea station tests.

- There is no social science research relevant to the biofouling phenomenon conducted about Fishermen and their thoughts for antifouling strategies, preferences, and behaviours in a systematic manner.

- There is limited data on the shear stress data of the fouler organisms.

2.9 Chapter Summary

In this chapter, a comprehensive literature review on fisheries, marine biofouling, antifouling strategies, boundary layer, the effect of biofouling on a ship, and determination of roughness functions is presented.

3 Survey And Hull Inspections

3.1 Chapter Introduction

This chapter presents the results of a survey conducted with the fishermen and hull underwater inspections of the selected industrial fishing vessels.

3.2 Survey Conducted with Fishermen

Categorisation of the fisheries is still a complex task because there are no specific limits when classifying fishing activities. However, it can be said that fishing activities vary between region, species, technology, investment, boat type, gear type and purpose of fishing activity (O'Farrell et al., 2019, Cooke & Cowx, 2006). In the literature, industrial fisheries or commercial fisheries, artisanal fisheries, small-scale fisheries and recreational fisheries can be named as the most popular categories among the fishing activities (MMO, 2017, Charles W. & Makowski, 2015, Jafarzadeh et al., 2016, Watson & Tidd, 2018). In addition, the Food and Agriculture Organisation (FAO) of The United Nations classifies fishing vessels into two categories as motorised and non-motorised vessels. Additionally, motorised vessels are divided into three categories depending on the vessel length overall (LOA): vessels smaller than 12 m, vessels between 12 - 24 m, and vessels above 24 m LOA.

Motorized vessels constitute the majority (63%) of the global fleet, and the majority of the motorised vessels consist of smaller vessels (FAO, 2020b). However, Rousseau et al. (2019) conducted a study linking the LOA and engine powers of the marine fishing vessels in the motorised category. The results showed that although smaller fishing fleets dominate the global marine fishing fleet, small fishing vessels contribute only 27% of the global engine power.

Watson & Tidd (2018) demonstrated industrial fisheries statistics in terms of global catch and landings between 1950 and 2015. What can clearly be seen in this study is the dominance of industrial fisheries. Additionally, in this study, taking only the amount of principal species caught into account, it can be said that trawl and seine catches constitute the majority of the caught fish in industrial fisheries. Similarly, examining the worldwide capture amount of principal species, it can be seen that the majority of the caught species are pelagic fish such as anchovy, pollock, tuna, sardine, cod and mackerel (FAO, 2019). Hence, this evidence presents and supports the idea that seines and trawls are the most commonly used gear types of modern-day in commercial/industrial fisheries.

That is to say, this section aims to investigate the knowledge of stakeholders, characteristics of the fishing vessels as well as common coating applications, in terms of biofouling and how to avoid penalties caused by it in industrial fisheries. To do that, the first step was taken as preparation of a survey. A survey was prepared in consultation with four experts from academia and the corresponding author's experience as part of the MSc thesis (Ozyurt, 2013). The relevant questionnaire can be found in Appendix A. After that, a face-to-face survey with 34 open- and closed-ended questions were prepared and conducted among 64 fishermen/stakeholders of 64 different fishing vessels. Furthermore, target of the survey is to consider and reveal "in-real" conditions for the industrial fishing vessel rather than suggested antifouling practices used among the industrial fishing vessels. More specifically, the targets of the survey are to determine the common knowledge, awareness and the practices used among industrial fishing vessels in regards to antifouling strategies.

That should be noted that the survey was conducted with the stakeholders of the fishing vessels operating in the southern Black Sea region. The reason behind southern Black Sea choice is one of the major capture species; anchovy's migration routes. Guraslan et al. (2017) stated that when the anchovy schools migrate to the southern regions of the Black Sea, a valuable source of fishery becomes available. In addition, as it is detailed in the FAO (2020c), anchovy and sardines constitute just over half of the total landings in the Mediterranean and the Black Sea. For that reason, considering the fact that the majority of the fisheries relies on the anchovy fisheries in the Black Sea and anchovy is one of the major capture species in the General Fisheries Council for the Mediterranean and Black Sea (GFCM) regions, therefore, conducting a survey with the fishermen in the Southern Black Sea regions would show a good representation of the industrial fisheries in GFCM regions.

What is more, majority of the fishing vessels are smaller than 12 m LOA, and the fishermen drydock their fishing vessels monthly for protection and cleaning purposes. Therefore, the subject of this thesis comprises only industrial fisheries, and the survey focuses on the industrial fishing vessels, which are considered as 12 m and above in LOA. The surveyed fishing vessels were chosen in accordance with the aforementioned reasons in this chapter. Questions in the surveys can be classified into four different sections:

- Technical info of the vessel
- Operation profile of the vessel
- Coating application process
- Fishermen's experience

3.2.1 Survey Results Industrial Fishing Vessels (Vessels Greater than 12m LOA)

41 owners of 64 industrial fishing vessels were contacted, and the results of the surveys are presented in this section in order to put the stakeholders' knowledge about the issue. Fishing vessels are grouped into four subgroups depending on their LOA as; 12 - 19.9 metres, 20 - 29.9 metres, 30 - 49.9 metres and 50+ metres for the industrial fishing vessels.

3.2.2 Positions of the Attendees in the Survey Concerning the Vessels

In order to determine the relationship between the attendees and the related fishing vessel, a question was added to the survey and asked the attendees. The additional question in the survey is communicated to the participants as "Do you own the vessel? If your answer is NO, please specify your position.". Among the 41 attendees, 23 of the attendees stated that they are the ship owners whilst 6 stated that they are the captains, 4 stated they are the family members, 2 stated that they are the person in charge, 4 stated they are seaman, and 2 stated that they are stakeholders.

3.2.3 LOA and Total Main Engine Power Relation

Considering the number of engines each vessel used, it can clearly be seen that although the highest percentage of the industrial fishing vessels use only one main engine, a significant number of vessels use 2 or 3 main engines starting from 135 HP to 4400 HP in total. A regression analysis between LOA (m) and total main engine power (HP) can be seen in Figure 3-1. In addition, what can additionally be seen from Figure 3-1 is that the main engine power and LOA increases in correlation.

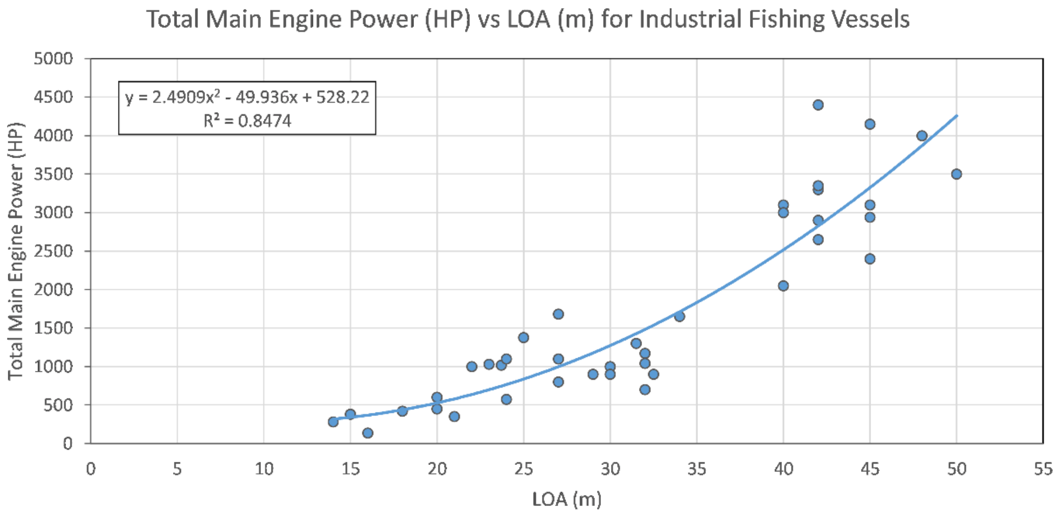
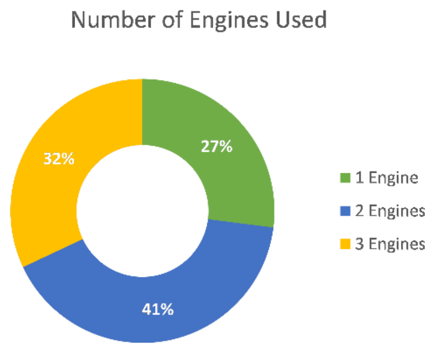


Figure 3-1: Distribution of Total Main Engine Powers (HP) Regarding LOA (m) for Industrial Fishing Vessels

3.2.4 Main Engine Age Groups and the Number of Engines Used in the Vessel

What is interesting in this data is that, although the main engine's age range varies from 0 to 30 years, 44% of the main engines are less than 10 years old, whilst 39% is between 10 and 20 years old, and 17% is between 20 and 30 years old. Figure 3-2 illustrates distributions of the number of engines and engine age groups obtained from the survey data.



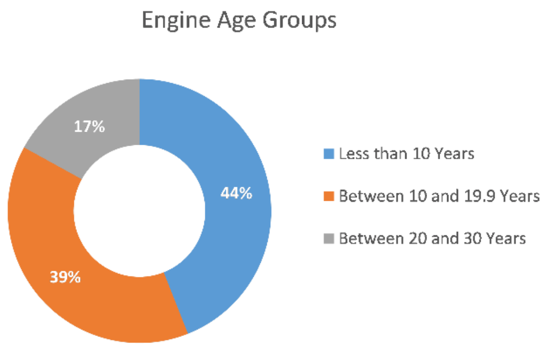


Figure 3-2: Distributions of the Number of Engines and Engine Age Groups

3.2.5 Hull Material

It is a fact that in the modern world, hull material for industrial fishing vessels is commonly steel; however, due to tradition, wooden vessels are still in use in the sector. For this reason, a question was included in the survey as to what hull material was used in your fishing vessel's hull. Results confirmed that the majority (90%) of the fishing vessel hulls are made of steel, and the number of the fishing vessels using wooden hulls are seen only in lower LOA groups.

3.2.6 Distribution of Fishing Vessel Age Groups

A question related to vessels' ages was included in the survey as to how old your vessel is. What can be seen from the survey results is that the oldest vessel is 34 years old, and 22% of the vessels are under 10 years old. Figure 3-3 illustrates the distribution of fishing vessels according to vessel age groups. In addition to that, the majority of the industrial fishing vessels are between 10 and 30 years old.

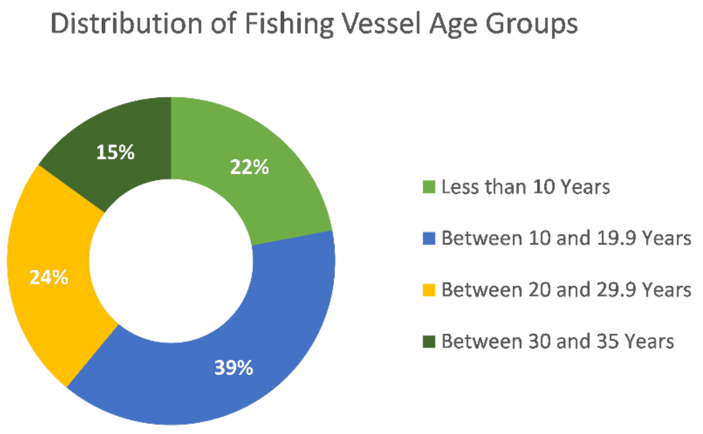


Figure 3-3: Distribution of Industrial Fishing Vessels' Ages

3.2.7 Experience of the Fishermen

A question was asked to the attendees in order to determine the fishermen's experience in the industrial fisheries. Results showed that fishermen involved with industrial fisheries have experience varying between 9 and 55 years. To go further in detail, more than half of the fishermen have experience of 30 years of fishing, or in other words, it indicates that experienced people perform the majority of the industrial fisheries.

3.2.8 Fishing Activity Frequency

When a question asked about fishing activity frequency as "How many days does your vessel go fishing in a year?", results showed that the day spent in fishing activity varies from 75 to 225 days for an industrial fishing vessel in a calendar year. Fishermen's answers have also been analysed, and results showed that fishing activities are conducted in official fishing seasons, which is between 1st September and 15th April for each calendar year. An additional question was asked to the fishermen in order to understand the reason why they do not go fishing for a full year. All of the fishermen stated that there are time-based regulations and restrictions put into force by the government. For that reason, an evaluation can be done as that the authorities keep fishing bans strict and push industrial fishermen to go fishing in the legal fishing seasons.

3.2.9 Fuel Consumption

A question was asked to the fishermen to determine the daily fuel usage of the relevant fishing vessels. Results showed that daily fuel consumption ranges from 100 to 5500 litres for an industrial fishing vessel. In addition, a scatter plot between fishing vessels' LOA (m) and daily fuel consumption in litres was added and illustrated in Figure 3-4. As it can be seen from the graph, the LOA of the industrial fishing vessels and daily fuel consumption shows an exponential agreement with the daily fuel consumption in litres.

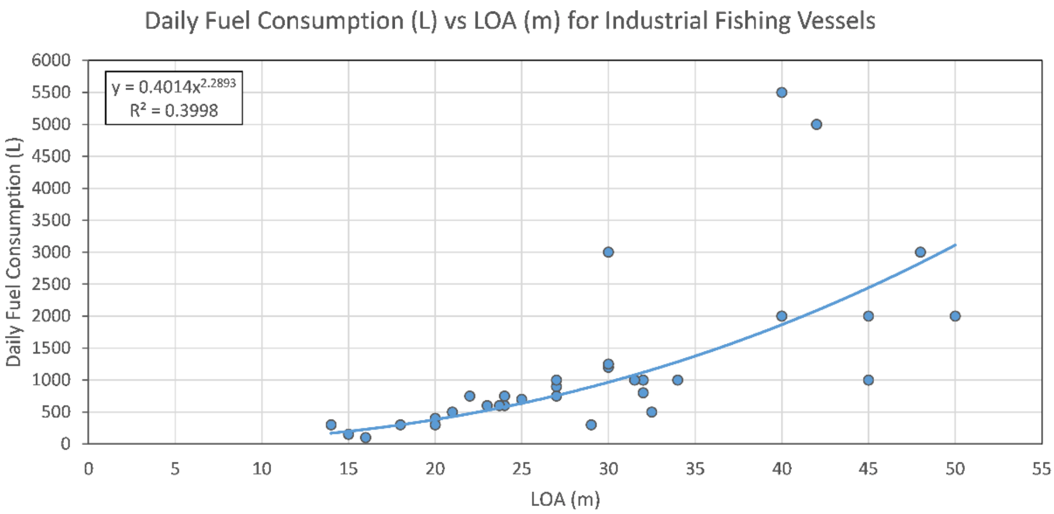


Figure 3-4: Distribution of Fishing Vessels' LOA (m) and Daily Fuel Consumption in Litres

3.2.10 Fishermen's Knowledge about the Penalties Caused by Biofouling

As one of the main purposes of this survey was to capture fishermen's awareness regarding biofouling, several questions were posed to the attendees. When a question was asked as "Are you aware of the penalties posed by biofouling? If Your answer is YES, please specify.", 95% of the attendees stated that they are aware of the penalties caused by biofouling. What is more, there is more than one disadvantage of biofouling accumulation, according to the given answers by the fishermen. The distribution of the specified penalties caused, as in the given answers, are presented in Figure 3-5.

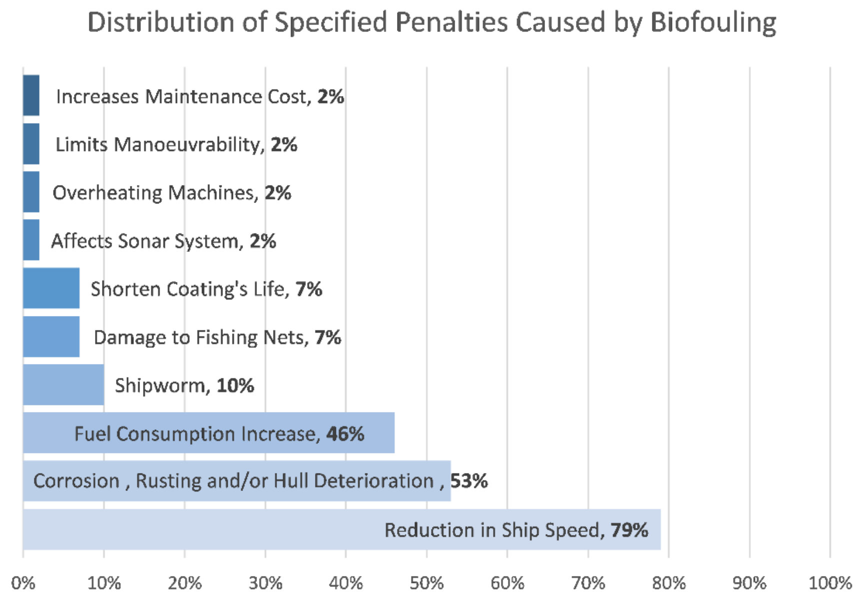


Figure 3-5: Distribution of Specified Penalties caused by Biofouling for the Fishermen

As seen from Figure 3-5, the penalties specified by the fishermen vary. Furthermore, 79% of the fishermen stated that biofouling causes a reduction in ship speed, and 53% of fishermen stated that biofouling causes corrosion, rusting and/or hull deterioration. Also, 46% of fishermen stated that biofouling increases fuel consumption. On the other hand, only 2% of the fishermen stated that biofouling causes an increase in maintenance cost, manoeuvrability, overheating machines and affected sonar systems which were the least mentioned by the fishermen.

3.2.11 Fishermen’s Training for Fighting with Biofouling

Another question posed to the fishermen was whether they had received any training/ information from any organisation/institution to minimise the biofouling accumulation. As shown in Figure 3-6, the results confirmed a lack of information and guidance available to fishermen about biofouling and its detrimental effects. 88% of the fishermen stated that they had not been given any information or training by any organisation. On the other hand, a few fishermen stated that they were somehow either supplied or trained by different organisations and authorities. 3% of the fishermen stated that they were given circulars by a public institution, 5% stated that they were informed by coating companies, 2% of the fishermen stated that they were given information by the painters and or paint sellers, 2% of the fishermen stated that they were given training by the local directorates of fisheries.

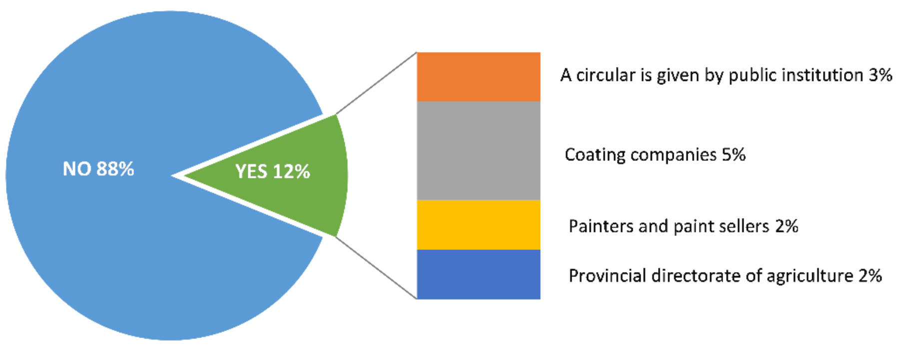


Figure 3-6: Distribution of the Given Information/Training by any Organisation

3.2.12 Fishing Activity Profile

In order to understand the operational profile of the fishing vessels, several questions were asked to the fishermen. Average time spent and average speed for the specified activities listed below were determined;

- Navigation to fishing zone,
- Multiple hauling and back to the next line,
- Navigation back to the port,
- Discharging caught fish in port/ to tender ship

When a question was asked as “What is the average time spent in hours for navigation to the fishing zone?” , fishermen's answers varied from 0.25 to 26 hours. Variety of the time spent in the navigation to the fishing zone can be related to many factors such as fishfinder technology availability, amount of fish spotted, the distance of the fish and amount of the stock etc. In addition, another question was subjected as “What is the average speed in knots for navigation to the fishing zone?” and fishermen's answers vary from 5 knots to 12 knots.

When a question was asked as “What is the average time spent in hours for multiple hauling and back to the next line?”, fishermen stated that it takes between 1 to 16 hours. In addition, another question posed was “What is the average speed in knots for multiple hauling and back to the next line?” and fishermen's answers vary from 0 to 15 knots. The reason for the difference between average speed for the navigation to the fishing zone and hauling and back to the next line confirms the urge to keep the fish in the net and/or to use a tender ship while catching the fish.

After that, similar questions were asked to the fishermen for navigation back to the port as “What is the average time spent in hours for navigation back to the port?” and “What is the average speed in knots for navigation back to the port?”. Fishermen stated that it takes from 10 minutes to 6 hours, with speed varying between 6 and 13 knots.

Finally, questions were posed to the fishermen for discharging the caught fish as “What is the average time spent in hours for discharging the caught fish?” and “What is the average speed in knots for navigation back to the port?”. Fishermen stated that it takes from 20 minutes to 5 hours with no speed.

3.2.13 Hull Cleaning Operation

In order to determine the methods fishermen deploy to prevent biofouling, several questions were included in the survey. When a question is posed to the fishermen whether they conduct the hull cleaning or not, all of the attendees stated that they regularly clean their vessel’s hull. To elaborate this point in detail, an additional question was asked to the fishermen as “Where and by whom is your hull cleaning process conducted for biofouling”. Results indicated that the majority of the fishermen gave multiple answers to this question, including: by a diver, in a shipyard or in a fishing boatyard. Among the given answers, 24% of the fishermen stated that they conduct the hull cleaning themselves in a fishing boat yard, 76% of the fishermen stated that they have the hull cleaning conducted by the skilled workmen in a shipyard, and 29% of the fishermen stated that they conduct the hull cleaning with a skilled diver as well.

In addition to that, it is noticed that the fishermen who included "divers" in their answers to this question also stated that they do not conduct the hull cleaning themselves in fishing boat yards. Instead, they have the hull cleaning conducted by the skilled workmen in shipyards. This means that majority of the fishermen (76%) have their biofouling cleaning conducted by professional workmen, either by skilled divers or skilled workmen in a shipyard. There might be several reasons behind this "using divers" and "having the hull cleaning process conducted in the shipyards" relation such as "drydocking the vessel biyearly". Nevertheless, it is inevitable to state that the fishermen who ask divers' help for conducting the hull cleaning for the biofouling get professional care when the fouled hull cleaning is required.

3.2.13.1 Drydocking and Hull Cleaning

At this point, two questions are required to be formulated for a better understanding of this section. A question (i) posed to the fishermen was, "how often do you drydock your vessel?". 63% of the fishermen stated that they dry dock their vessel annually whilst 37% of the fishermen stated that they dry dock their vessel biyearly. Another question (ii) posed to the fishermen was, "How often do you conduct the hull cleaning for biofouling?". 93% of the fishermen stated that they conduct the hull cleaning for biofouling annually, and 7% of them stated that they conduct the hull cleaning biyearly. Moreover, a further step was taken to examine differences between the answers given to (i) and (ii) questions. Therefore, the fishermen who answered "biyearly" to question (i) were taken into consideration. The answers given to question (ii) were further investigated for these fishermen (among the ones who answered the question (i) as "biyearly"). Finally, 80% of the fishermen who answered the question (i) as "biyearly" stated that they conduct the hull cleaning annually. In other words, some of the fishermen do not prefer to conduct the biofouling cleaning even if the vessel is drydocked.

The following question in the survey asked the fishermen was, "What is the main reason behind drydocking your vessel? Please specify". Results showed that there are multiple reasons for the drydocking process; hence the majority of the fishermen gave multiple reasons. Looking at it in detail, more than half of the fishermen (61%) stated the maintenance and repair as a reason for drydocking their fishing vessels. Following that, underwater hull cleaning for biofouling comes as the second important reason given for the drydocking with a proportion of 41%. The majority of industrial fishing activities are controlled and inspected by the authorities. To give an example, in order to prevent extra fuel consumption, industrial fishing vessels are obliged to be dry-docked biyearly. The reason behind this is to let authorities to investigate the antifouling coating applications and check, inspect and prevent the relevant issues that might occur during fishing activities. Nevertheless, an interesting result statistics from the survey indicate that although there are regulations, so the legal obligatory, only 37% of the fishermen stated that one of the main reasons for the drydocking is legal obligations. In addition to these, whilst 24% of the attendees stated that coating application is one of the main reasons for drydocking, 12% of the fishermen stated that the cleaning is one of the main reasons for the drydocking.

3.2.13.2 Methods Used to Conduct the Hull Cleaning

A further question posed to the fishermen was, “What kind of methods do you use to conduct the hull cleaning (docking) process for biofouling?”. Results showed that there are several methods and tools used to conduct the hull cleaning. In other words, fishermen prefer to conduct the hull cleaning with more than one method. Although there are 8 methods specified in survey results, most of the fishermen (78%) stated that the hull cleaning is conducted with a freshwater compressor. Following that, grinding machines and scraping with a spatula were used by 29% of the fishermen as the second most common tools for underwater hull cleaning. In accordance to survey results, other tools that were used by the fishermen during the hull cleaning are sandpaper (15%), sandblasting machines (17%), bristle brush (7%) and, bleach (2%). That should be noted that the tools mentioned above in this paragraph were used by either fishermen or skilled workmen while the ship was drydocked. The distribution of the methods used to conduct the hull cleaning for biofouling is presented in Figure 3-7.

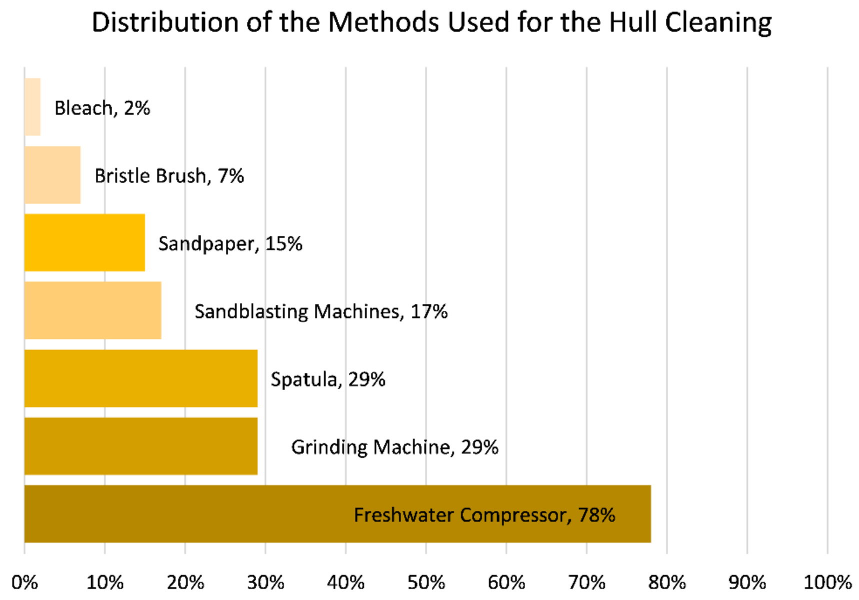


Figure 3-7: Distribution Of The Methods Used To Conduct The Hull Cleaning For Biofouling

When it comes to the tools/methods that are used to clean underwater hulls by divers, survey attendees stated that all of the divers use spatula, 8% use grinding machines, 8% use fishing nets, 25% use compressors. That should be noted that survey attendees stated that divers use more than one tool to conduct the underwater hull cleaning.

3.2.13.3 Time Spent on Hull Cleaning Process for Biofouling

In order to understand the duration of the biofouling cleaning process, a question was subjected to the fishermen as "How long does it take to conduct the hull cleaning process for biofouling?". Results showed that the days spent in biofouling cleaning ranges from 1 day up to 20 days. In order to show the relevance between biofouling cleaning time in days with vessel's LOA (m), vessel's age in years and vessel's total main engine power (HP), relevant linear regression analyses were conducted. However, results showed that there is not a correlation between hull cleaning for biofouling time and LOA, vessel's age or total main engine power. Regression analyses are presented in Figure 3-8, Figure 3-9 and Figure 3-10.

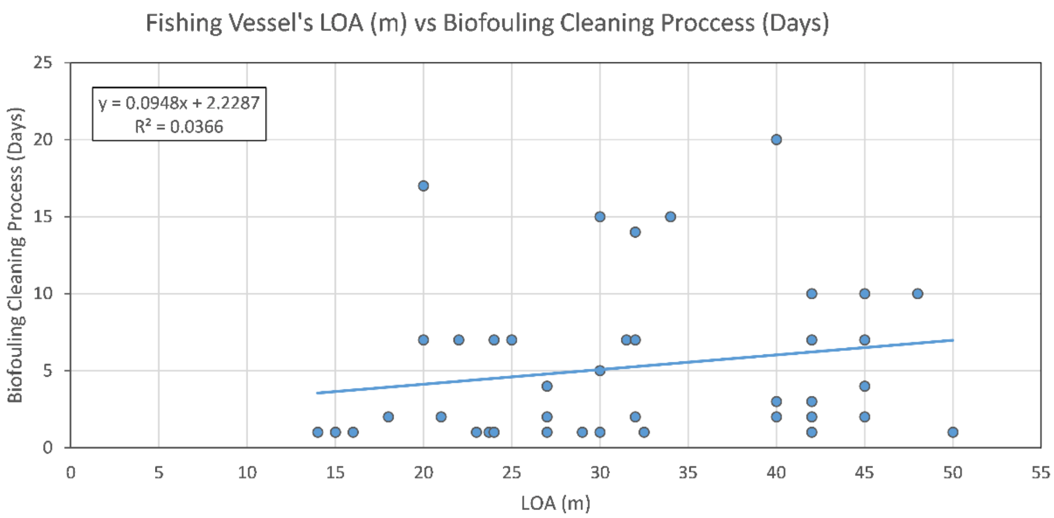


Figure 3-8: Fishing Vessel's LOA in Comparison with Biofouling Cleaning Time in Days

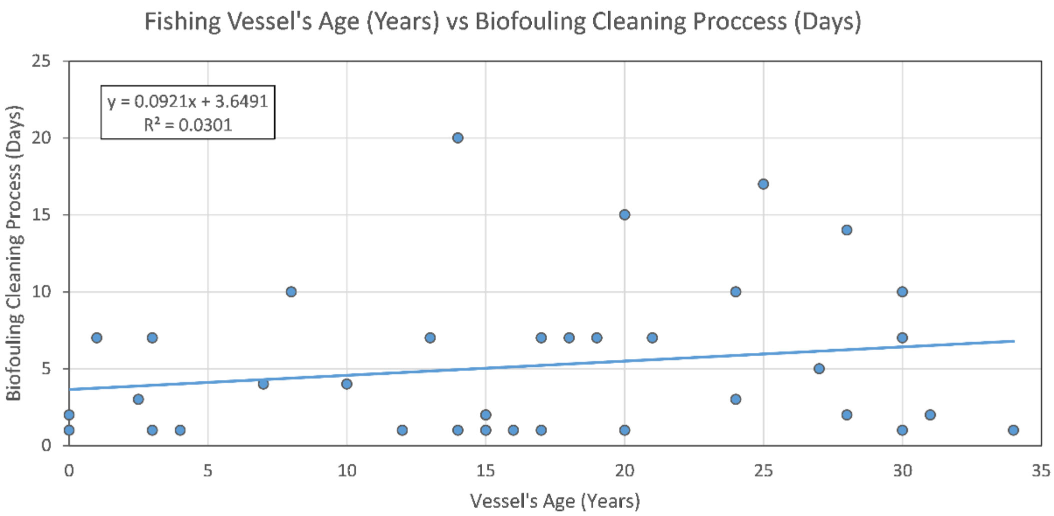


Figure 3-9: Fishing Vessel's age in Comparison with Biofouling Cleaning Time in Days

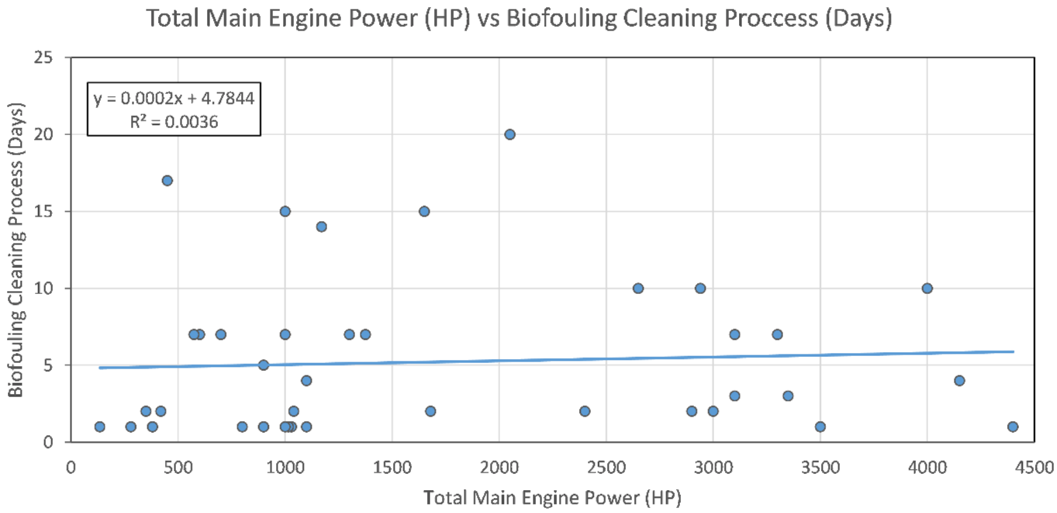


Figure 3-10: Fishing Vessel's Total Main Engine (HP) in Comparison with Biofouling Cleaning Time in Days

3.2.13.4 Selection of the Method to Conduct Hull Cleaning

In accordance with the hull cleaning method, a question was posed to the fishermen about how they chose the cleaning method for the biofouling. As illustrated in Figure 3-11, results indicated that 69% of the fishermen stated that they chose the hull cleaning method for biofouling from their personal observations and copying from the other fishermen, 20% of the fishermen stated that they chose their method with trial and error methods, 7% of the fishermen stated that they choose their method with the recommendations, only 2% of the fishermen stated that the cost is the major factor when choosing hull cleaning method and 2% of the fishermen stated that maritime regulations and rules determine their hull cleaning methods.

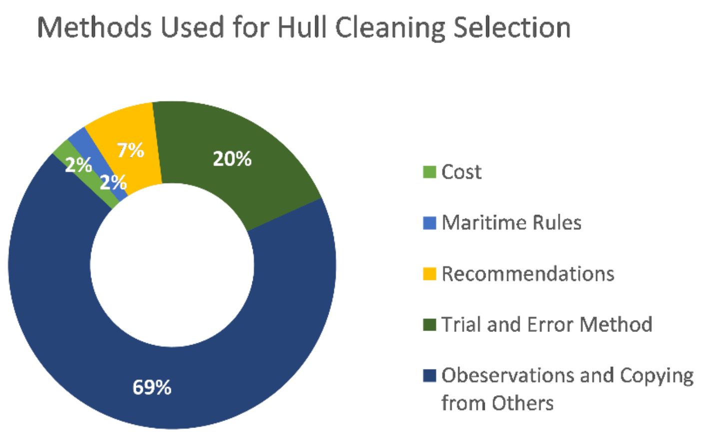


Figure 3-11: Distribution of the Methods about How the Fishermen Choose Hull Cleaning for Biofouling

3.2.14 Antifouling Coating Preferences

3.2.14.1 Antifouling Coating Application Process

Not surprisingly, when a question was asked to the fishermen whether they use hull coating or not, all of the fishermen stated that they paint their vessel's underwater hull with a coating. In accordance with that, a question was subjected to the fishermen as "How often do you coat your vessel?". Results showed that 63% of the fishermen stated that they coat their underwater hull annually and 37% of them biyearly.

3.2.14.2 Antifouling Coating Brands

For the reason that it was considered to be complicated to ask the type of coating the fishermen chose, another question was posed to the fishermen as to which brand they use for the underwater hull. Survey results showed that the majority of the fishermen do not have any tendency on a specific brand; hence, their answers stated that there was more than one brand name given by a fisherman that they are using. To be more specific, whilst 49% of the fishermen gave one coating brand name, 34% gave two brand names, 12% gave three brand names and 5% gave four brand names. After the examination of the results, two categorizations can be made as to the coatings that are available in the international market and the coatings that are available only in the local markets. To be more specific, as can be seen from Table 3-1, 54% and 51% of the fishermen stated that they use internationally available coatings A and B, respectively. Furthermore, the least preferred coatings are the local paints with 2% and 5% respectively.

Table 3-1: Distribution of the Fishermen's Coating Selection for the Underwater Hull

Internationally Available Coatings	% Of Fishermen Stated That They Use The Coating	Locally Available Coatings	% Of Fishermen Stated That They Use The Coating
PAINT A	54%	Local Paint A	37%
PAINT B	51%	Local Paint B	7%
PAINT C	17%	Local Paint C	5%
		Local Paint D	2%

3.2.14.3 Antifouling Coating Selection Method

In order to understand who supply the coatings to the fishermen, a question posed to the fishermen was, “Where do you buy the hull coating from?”. 78% of the participants stated that they buy the coating from the dealer, 15% of the fishermen stated that they buy their underwater hull coating from the hardware store and 7% of the fishermen stated that they buy the coating from the supplier as presented in Figure 3-12.

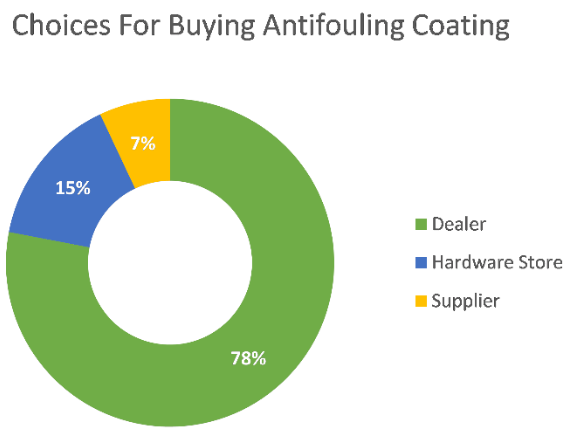


Figure 3-12: Distribution Of The Fishermen’s Choices For Buying Coatings

At this point, definitions of the dealers, hardware stores and suppliers have to be clarified. Hardware stores are the local shops selling handy materials for the fishermen and small-scale fishing vessels. On the other hand, dealers refer to the representatives of the larger paint companies. Dealers are preferred mainly by the large scale fishing vessel owners as a larger amount of antifouling coatings can only be provided by dealers locally with the help of their representing antifouling companies. To compare with the hardware stores, dealers sell antifouling coatings of a particular brand, and the majority of the products that the dealers sell are antifouling coatings. However, any small craft needed for a fisherman, such as smaller amounts of antifouling coatings or gears, can be found in hardware stores. Suppliers are the people hired either by a group of industrial fishermen or privately, and their duties are to take the antifouling coating prices down for the fishermen. In other words, suppliers are the key people acting as a mediator between the antifouling companies and the fishermen.

Another question asked to the fishermen was, “How do you choose the coating applied on the hull?”. Results showed that the majority of the fishermen gave multiple answers to this question. To be more specific, whilst 63% of fishermen stated that they consider three factors, 30% of fishermen stated that they consider two factors, and only 7% of the fishermen stated that they consider one factor when choosing the antifouling coating applied on the ship hull. Giving an example would make it clear to understand this situation. For example, whilst one of the fishermen stated that “coating-price” and “experience” influence their decision (two factors), another fisherman stated that “experience”, “coating-price”, and “recommendations” influence their decision (three factors) when choosing the coating applied on the hull. Furthermore, a conclusion can be drawn as the majority of the fishermen (93%) stated that there is more than one factor when deciding which antifouling coating is applied on the ship. To be more specific, seven separate choices were stated by the fishermen given to this question.

- The first choice was “trial and error method”. Furthermore, 39% of the fishermen stated that “trial-and-error-method” is one of the factors influencing their decision when choosing the coating applied on the hull.

- The second choice was “ quality-of-the-coating”. Furthermore, 39% of the fishermen stated that “quality-of-the-coating” is one of the factors influencing their decision when choosing the coating applied on the hull.

- The third choice was “recommendations”. Furthermore, 22% of the fishermen stated that “recommendations” is one of the factors influencing their decision when choosing the coating applied on the hull.

- The fourth choice was “coating-price”. Furthermore, 22% of the fishermen stated that “coating-price” is one of the factors influencing their decision when choosing the coating applied on the hull.

- The fifth choice was "experience". Furthermore, 15% of the fishermen stated that "experience" is one of the factors influencing their decision when choosing the coating applied on the hull.

- The sixth choice was "Coating's lasting-time". Furthermore, 5% of the fishermen stated that "Coating's lasting time" is one of the factors influencing their decision when choosing the coating applied on the hull.

- The seventh choice was "legal obligations". Furthermore, 2% of the fishermen stated that "legal obligations" is one of the factors influencing their decision when choosing the coating applied on the hull.

Choices effecting antifouling coating selection for the fishermen and the distribution of the answers given by the fishermen are presented in Figure 3-13.

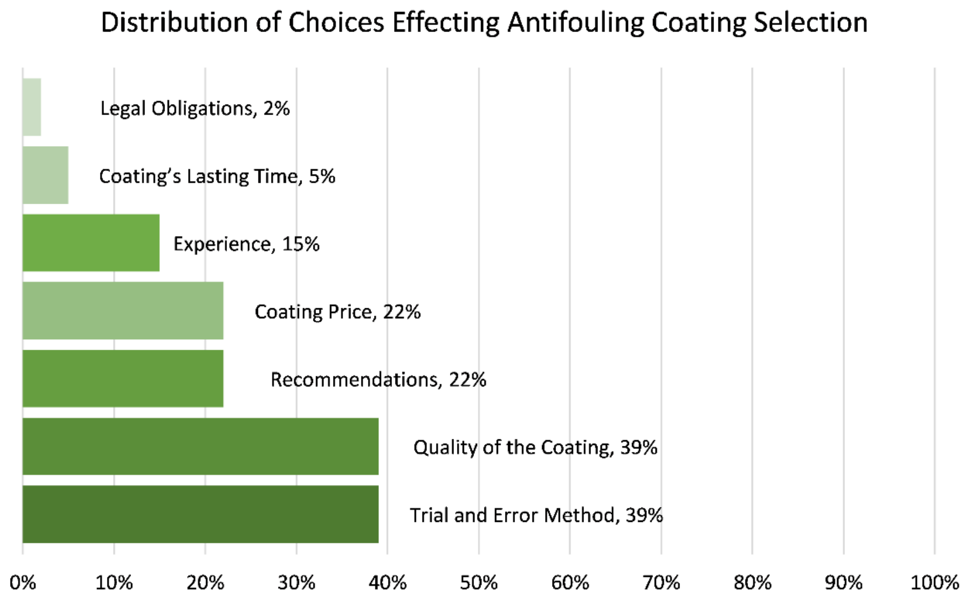


Figure 3-13: Distribution of Choices Effecting Antifouling Coating Selection

3.2.14.4 Antifouling Coating Application and Manpower Relation

A question was asked to the fishermen for the person who applies the hull coating. Results showed that the fishermen either conduct the painting themselves, dedicated painters or labours. Looking at it in detail, it can be seen that only 22% of the fishermen have underwater hull coating conducted by dedicated professional painters. The distribution of the given answers in detail to this question can be seen in Figure 3-14.

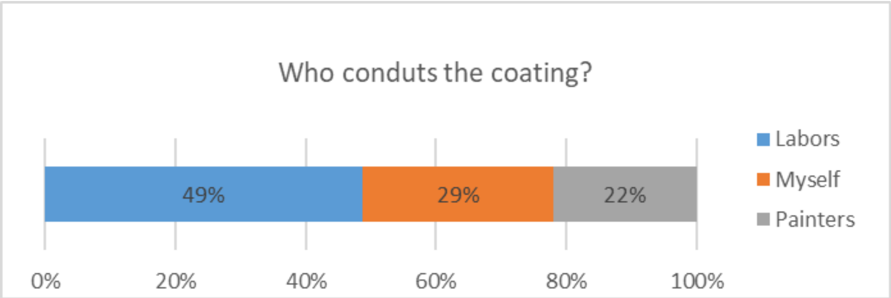


Figure 3-14: Distribution of the Fishermen's answer to the question about who conducts the coating

When it comes to the question about the place where the fishermen conduct the hull coating, fishermen stated that they either coat their vessels in professional shipyards (78%) or fishing ports (22%). In addition to that, another question was asked to the fishermen as "What is the common paint application practice amongst typical fishermen communities?". Results showed that, according to the fishermen, although the most common practice is conducted with paint guns, a considerable number of fishermen stated that roller brush is still used in practice.

3.2.14.5 Time Spent in Antifouling Coating Application

A question was posed to the fishermen in order to determine the duration of how long it takes to apply the hull coating. Interestingly, results showed that coating application duration varies from 1 day to a month. With the aim of understanding the distribution of the days spent for conducting the hull coating application process, a regression analysis was conducted between the LOA of the surveyed fishermen's vessel and the days spent to apply hull coating. Surprisingly, the trend between LOA and the days spent in hull coating is not presenting a good match as expected due to the hull surface area. Regression analysis can be seen in Figure 3-15.

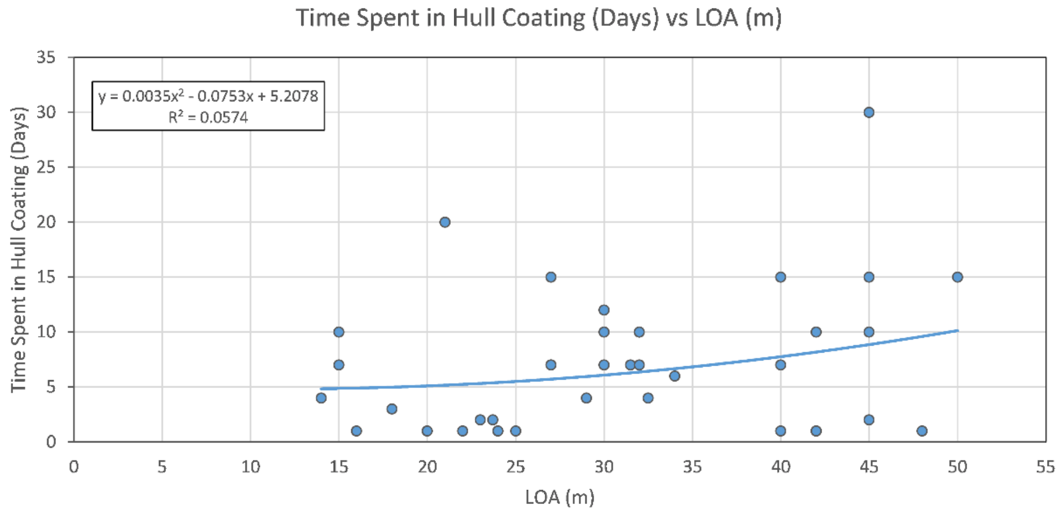


Figure 3-15:LOA and Days Spent in hull coating relation

Within this point, it should be ideal to state that there are several possible reasons for this "no-rush" situation when considering antifouling coating application. Because the official fishing season ends on 15th April and lasts until 1st September, there is plenty of time when considering the antifouling coating application. Furthermore, when the vessels drydocked, the antifouling coating application is not the only problem that the fishing vessels have to deal with. Fishing vessel's maintenance procedure, legal paper works, availability of the shipyards relevant personal, availability of the desired antifouling coating in the market, negotiation process with the antifouling coating dealers, the desire to put the fishing vessel back to the sea close to the beginning of the fishing season might be many of the possible reasons for why the trend between LOA and the days spent in hull coating is not presenting a good match as in Figure 3-15.

3.2.14.6 Amount of the Antifouling Coating Applied per Vessel

Another question subjected to the fishermen was, "How many litres of antifouling coatings do you use to coat your vessel?". Results show that fishermen use from 10 litres to 1500 litres of antifouling coating. A regression analysis conducted between Fishing vessels' LOA (m) and used antifouling coating in litres can be seen in Figure 3-16.

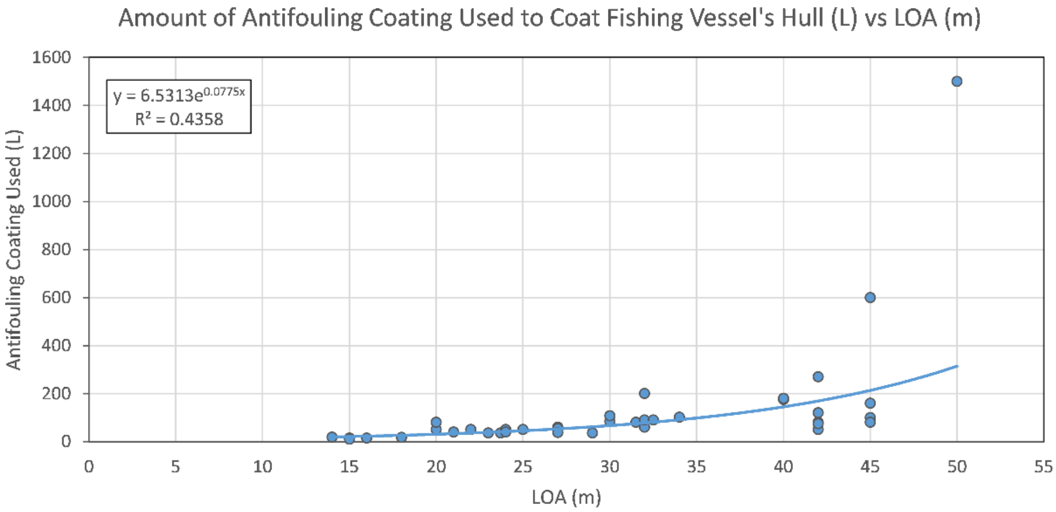


Figure 3-16: Regression Analysis of LOA and Used Antifouling Coating (Litres) Relation for Fishing Vessels

3.2.15 Propeller and Biofouling

In addition to the questions asked regarding the fishing vessels' hull, a question was posed to the fishermen as "Does your propeller get fouled?" and 90% of the fishermen stated that their vessel's propellers are fouled whilst 10% stated that their vessel's propeller is not fouled. Furthermore, another question was asked to the fishermen to understand whether they coat the vessel's propeller or not. In contrast to the answers given to a similar question for the hulls, whilst 61% of the fishermen stated that they coat their propeller, 39% of the fishermen stated that they do not coat their propeller. Answers given by the fishermen who do not prefer coating their vessel's propellers can be seen below:

- 19% of the fishermen stated that they do not coat the propeller because its colour is yellow
- 44% of the fishermen stated that they do not coat the propeller because we do not believe that it makes a difference
- 19% of the fishermen stated that they do not coat the propeller because it decelerates vessel speed
- 6% of the fishermen stated that they do not coat the propeller because it is made of brass
- 12% of the fishermen stated that they do not have a reason

A pie chart showing the distribution of the preferences stated by the fishermen is illustrated in Figure 3-17.

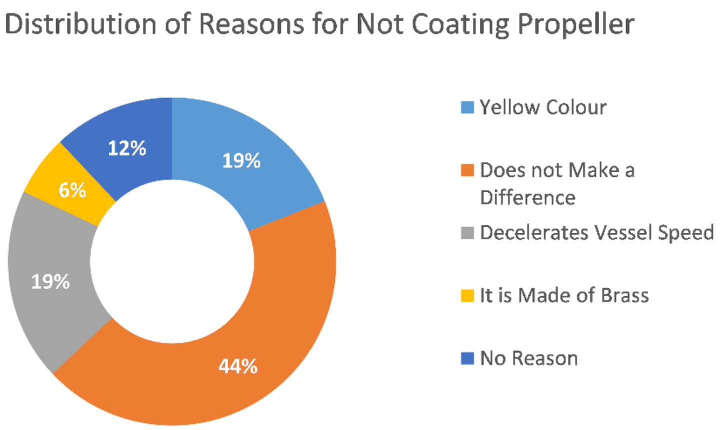


Figure 3-17: Distribution of the Reasons for Not Coating Propeller

3.3 Underwater Hull Inspections of Fishing Vessels in the Region

In order to determine the biofouling accumulation results for the various coatings applied on the fishing vessel and test panels, several fishing vessels' biofouling accumulations were investigated, and the results were presented in the section below.

3.3.1 Data for Fishing Vessel UW1

Fishing Vessel UW1 is a 15 years old trawler vessel, which goes fishing in the Black Sea region. The vessel's LOA is 32 metres, and the vessel's hull material is steel. There are two main diesel engines with 720 and 720 HP. After conducting a survey with the vessel owner, the vessel's dry-docking frequency is determined as bi-yearly, however; underwater hull cleaning is conducted every year. When the vessel is in the port, the underwater cleaning process is conducted via a diver. Diver scrapes biofouling using a spatula. Hence, fouling accumulated on the vessel represents biofouling, which occurred as a result of one year of fishing activity. Figure 3-18 illustrates various underwater hull sections and biofouling accumulation on Fishing Vessel UW1.

Figure 3-18: Biofouling Accumulation on Various Hull Sections for UW1 Fishing Vessel

The owner of the fishing vessel indicated that the underwater hull was painted with an antifouling coating. Due to the owner's limited knowledge of the antifouling coating process, the type of antifouling coating applied on the vessel is unknown. However, when the shipyard's painter investigated, he mentioned that approximately 90% of the fishing vessels are coated with Self Polishing Paint. Hence, an assumption was made as Fishing Vessel UW1 is coated with SPC with a high degree of probability. As indicated by the survey, recommendations and trial/error methods play an important role in choosing antifouling coating. Additionally, internationally available two major antifouling coatings are two brands that they prefer. To conduct the coating process, the owner indicated that firstly rubbing down with sandpaper and then scraping process is done. Following that, washing with a freshwater compressor is done. After waiting for the surface to dry, primer paint is applied and finally, one or two days before relaunching the vessel, an antifouling coat is applied. Although antifouling coating takes only 1 day, the whole underwater coating process takes 1 week by professionals hired by the owner.

With regards to the operation profile of the vessel, although the owner indicated that it has a 300 Nm operation range on average in the Black Sea, it is difficult to make an assumption for how far the vessel's operational range from the coast is. Moreover, the vessels operate every day for 6 months within the legal fishing season. Table 3-2 shows the average time spent on each operation type and the average speed for each operation type.

Table 3-2: Operation Profile of Fishing Vessel UW1

Operation Type	Average Time	Average Speed (Knot)
Navigation to fishing zone:	10 hours	10 Knot
Multiple hauling and back to the next line	2 hours	12 Knot (releasing the net), 0 Knot (gathering the net)
Navigation back to port	1 hour	12 Knot
Discharging fish in the port	45 minutes	0 Knot

Due to the cleaning process that was conducted approximately one hour after dry-docking, the researcher had limited time to do the measurements. Slime measurements were done in 4 different parts of the ship: port bow, starboard bow, port stern and starboard stern just after dry-docking. Table 3-3 illustrates the data gathered with wet film thickness gauge from slime measurements.

Table 3-3: Slime measurements taken from various sections of the underwater hull

Port Bow	800 µm
Starboard Bow	750 µm
Port Stern	650 µm
Starboard Stern	800 µm

After the observations, some of the most common species were examined due to the limited time. Because of the limited knowledge of the classification of the species, the researcher named the species with common names of its kind. However, after making a short literature review of the species, the researcher deduced that several species are the ones accumulated on the underwater hull of fishing vessels in the region. This research was also confirmed by a Marine biologist identifying the species within the academia. These species are Mussels such as *Mytilus edulis* (Linnaeus), *Mytilus galloprovincialis*, and Barnacles such as *Balanus amphitrite*, Oysters such as *Ostrea edulis*, Bryozoans and Shipworms.

Figure 3-19: Pictures of a barnacle before and after the adhesion strength measurement test

Figure 3-19 illustrates the surface area of a barnacle, which is one of the common species observed on the ship's underwater hull, before and after the adhesion strength measurement test. A reference coin was used with the aim of standard measurement. The coin's diameter equals 2.615 cm. The mentioned species could resist a maximum 7.18 kg force applied on them, and so the adhesion strength was calculated as 0.485 MPa.

Figure 3-20: Pictures of a barnacle before and after the adhesion strength measurement test

Figure 3-20 illustrates the surface area of a mussel which is the second common species observed on the ship's underwater hull before and after the adhesion strength measurement test. A reference coin was used with the aim of standard measurement. The coin's diameter equals 2.615 cm. The mentioned species could resist a maximum 2.06 kg force applied on the mentioned species. However, due to the complexity of the fouling structure, mentioned species' attachment area could not be estimated; hence, adhesion strength could not be calculated.

3.3.2 Data for Fishing Vessel UW2

Fishing Vessel UW2 is a ship's tender vessel in the Black Sea. The vessel was inspected 15 hours after the dry-docking. Hence, slime measurements could not be measured due to the dry surface. However, the adhesion strengths of some of the most common species were measured. Table 3-4 illustrates adhesion strengths values of the species on Fishing Vessel UW2.

Table 3-4. Adhesion strengths Values of the species on Fishing Vessel UW2

No.	Species	Peak Applied Force on Species	Species Adhesion Surface Area	Adhesion strengths values (MPa)
1	*Balanus amphitrite*	3.39 kg	a= 1 cm b= 1.2 cm	0.353
2	N/A	1.04 kg	a= 0.8 cm b= 1 cm	0.162
3	*Balanus amphitrite*	1.87 kg	a= 0.8 cm b= 1.1 cm	0.265
4	*Balanus amphitrite*	4.32 kg	a= 1.2 cm b= 1 cm	0.450
5	*Balanus amphitrite*	6.42 kg	a= 1.4 cm b= 1.1 cm	0.521
6	*Balanus amphitrite*	6.74 kg	a= 1.4 cm b= 1.2 cm	0.501
7	*Balanus amphitrite*	2.35 kg	a= 1.3 cm b= 1 cm	0.226
8	*Balanus amphitrite*	2.82 kg	a= 1.4 cm b= 1.4 cm	0.180
9	*Mytilus galloprovincialis*	0.51 kg	a= 1.5 cm b= 2.3 cm	0.018
10	*Balanus amphitrite*	7.39 kg	a= 1.6 cm b= 1.3 cm	0.444
11	*Balanus amphitrite*	7.68 kg	a= 1.6 cm b= 1.4 cm	0.428

3.3.3 Data for Fishing Vessel UW3

Fishing Vessel UW3 is an active fishing vessel fishing in the Black Sea that did not undergo dry-docking for 3 years. Hence, the accumulation on this vessel was at higher levels compared to the rest of the vessels examined. The vessel was dry-docked in the fishing port, and the researcher had the opportunity to examine the vessel approximately 12 hours later than dry-docking. Several adhesion strengths were taken due to the biofouling abundance on underwater hull using a force gauge.

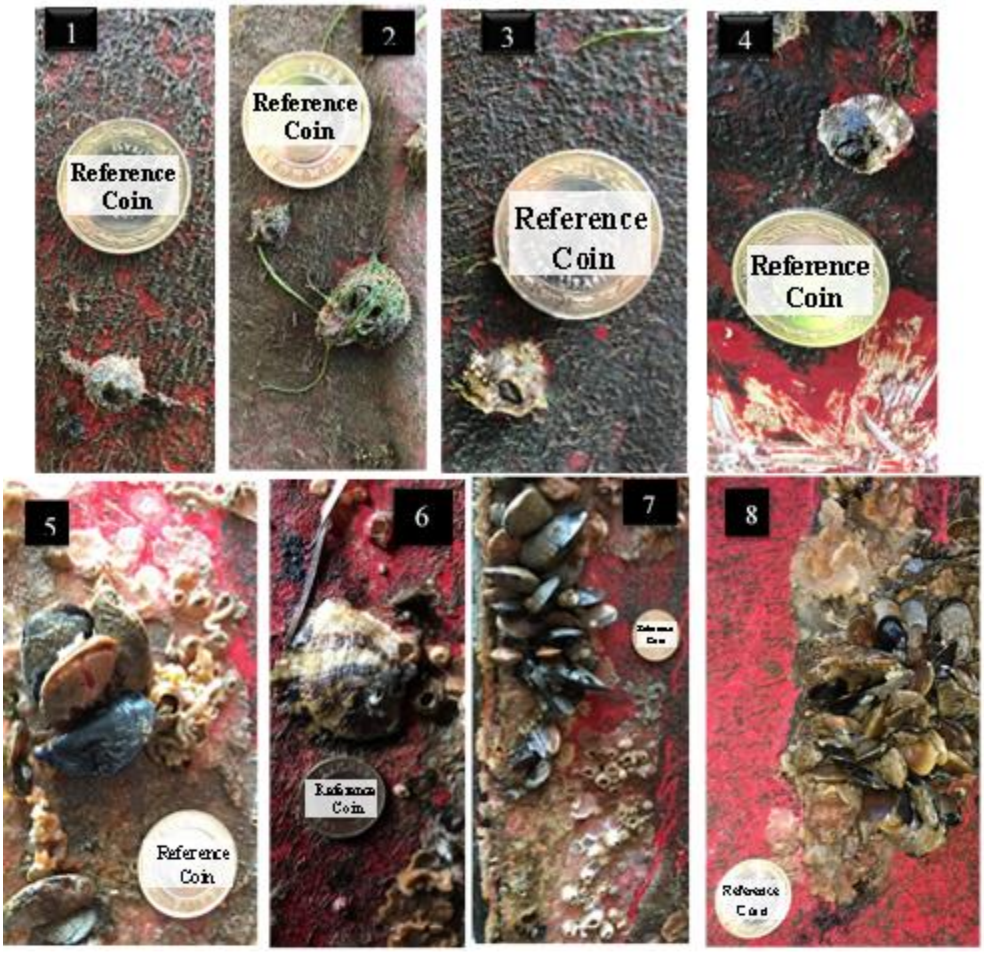


Figure 3-21: Species used for measuring the adhesion strengths in Fishing Vessel UW3

Figure 3-21 shows the numbering of the related species that the adhesion strengths were measured on Fishing Vessel UW3. Due to the incomplete dry-docking process, most of the measurements were taken from the Port Bow and Starboard Bow sections of the underwater hull. Most of the common fouling species were *Balanus amphitrite*, *Mytilus galloprovincialis*, and *Ostrea edulis*.

Table 3-5: Adhesion strength values of measured species in Fishing Vessel UW3

No.	Species	Peak Applied Force on Species	Species Adhesion Surface Area	Adhesion strengths values (MPa)
1	*Balanus amphitrite*	4.10 kg	2r=1.16 cm	0.381
2	*Balanus amphitrite*	12.32 kg	2r=1.61 cm	0.594
3	*Balanus amphitrite*	4.39 kg	2r=1.19 cm	0.387
4	*Balanus amphitrite*	3.48 kg	2r=1.32 cm	0.249
5	*Mytilus galloprovincialis*	2.30 kg	N/A	N/A
6	*Ostrea edulis*	8.84 kg	a= 2.37 cm r= 1.84 cm	0.079
7	*Mytilus galloprovincialis*	2.73 kg	N/A	N/A
8	*Mytilus galloprovincialis*	1.47 kg	N/A	N/A

Table 3-5 illustrates the adhesion strengths values of measured species on Fishing Vessel UW3. After closer examination, it can be noticed that although barnacles and oyster adhesion strengths are shown clearly; due to the complex accumulation of muscles' adhesion surface area could not be calculated; hence adhesion strengths values could be calculated. Additionally, slime measurements were taken using a wet film thickness gauge. Table 3-6 illustrates the data gathered with wet film thickness gauge from slime measurements.

Table 3-6: Slime measurements taken from various sections of the underwater hull

Port Bow	600 µm
Starboard Bow	450 µm
Port	275 µm
Starboard	500 µm

3.4 Chapter Summary and Conclusions

In this chapter, survey results and underwater hull inspections of industrial fishing vessels are presented. Furthermore, 41 industrial fishing vessels from 14 m to 50 m LOA were taken into consideration. Firstly, LOA (m) and the industrial fishing vessels' total engine powers (HP) were correlated, and the results showed a good agreement. In addition, the total main engine power ranged from 135 HP to 4400 HP. Secondly, the number of the main engines that the fishing vessels have was presented. It was learnt that there might be up to three main engines installed in the industrial fishing vessels. Furthermore, when the engine ages were investigated, it was learnt that more than half of the fishing vessel's engines were over ten years old.

Although wood and steel are the two most common types of hull materials used in fishing vessels, results confirmed that the most common hull material is steel with 90%. Moreover, fishing vessels with wooden hulls were only seen in lower LOA groups. Next, fishing vessel age groups were determined. Results showed that only 22% of the fishing vessels were younger than ten years old, whilst 78% of the industrial fishing vessels were between 10 and 34 years old. These results should be considered as an indication of the need for the new fishing vessels as the new fishing vessels are built under more energy-efficient regulations set by IMO. Another key finding to state as a result of the survey is that more than half of the fishermen have experience of 30 years of fishing activities. Within this manner, a comment can be made that industrial fisheries are under experienced fishermen control; thus, industrial fishing activities are traditionally conducted.

One of the other findings obtained from the survey results was related to the time spent on fishing activities. Industrial fishing vessels conduct their fishing activities from 75 to 225 days. As the official fishing season lasts seven and a half months, it indicates that the industrial fishing activities are conducted within the legal limits, and authorities keep controlling the fishing activities. After that, industrial fishing vessels' daily fuel consumption was considered, and results showed that LOA (m) and the daily fuel consumption (Litres) correlate and show an exponential agreement. In addition to that daily fuel consumption of the industrial fishing vessels varies from 100 to 5500 litres per day. Following that, the fishing activity profile of the industrial fishing vessels was determined.

Another finding obtained from the survey results was related to the fishermen's knowledge of the penalties caused by the biofouling. What is surprising is that although 95% of the fishermen stated that they are aware of the penalties caused by biofouling, there are 5% who are not aware of the penalties caused by the biofouling phenomenon. After that, a further question was asked to the fishermen whether they are trained to minimise the biofouling accumulation. Although the importance and the penalties caused by marine biofouling are significant problems for the ships, 88% of the fishermen stated that they did not get any training, circular, or information regarding minimising biofouling accumulation.

Although each industrial fishing has its own fishing activity profile, an average fishing activity profile was presented in terms of; navigation to the fishing zone, multiple hauling and back to the next line, navigation back to the port and discharging caught fish in port/ to tender ship. The time spent on each activity and the relevant speed of each activity was also determined. Results showed that the time spent on the relevant activities varies from a minimum of 0.2 hours to a maximum of 26 hours. Moreover, the average speed for each activity starts from 0 to 16 knots maximum.

Next, it was revealed that industrial fishing vessels' hull cleaning operation for the biofouling is conducted under three categories: by a diver, in a shipyard by professional workmen or in a fishing boatyard by the fishermen themselves. In addition to that, most of the fishermen (76%) stated that their industrial fishing vessel's hull cleaning operation is conducted in a shipyard by professional workmen. In addition to that, asking divers' help might mean that the hull cleaning process of the fishing vessel in the topic is conducted professionally.

After that, two questions were asked to the fishermen as "how often do you drydock your vessel?" and "How often do you conduct the hull cleaning for the biofouling". The majority of the fisherman stated that they (63% of the fishermen) drydock their vessel biyearly, and they (93%) conduct the hull cleaning annually. However, the fishermen's responses to these two questions indicate that there are fishing vessels that do not have the hull cleaning conducted even if the vessel is drydocked. A further question was posed to the fishermen regarding the reason behind drydocking. Interestingly, besides the most common answer being maintenance and repair, only 37% of the fishermen stated that one of the main reasons behind the drydocking is legal obligations, although every fishing vessel must be drydocked and investigated by the authorities biyearly in the Mediterranean and the Black Sea.

When the time spent on the hull cleaning process for biofouling was on the topic, fishermen stated that it varies between 1 and 20 days. The more interesting thing is that when a correlation between hull cleaning time for biofouling and LOA, vessel's age or total main engine power is studied, results showed no link among them. In addition, when it comes to how the fishermen chose the hull cleaning method for the biofouling, 68% of the fishermen stated that "their personal observations" and "copying from the other fishermen" play an essential role.

After that, a question was posed to the fishermen regarding antifouling coating brands. Results indicated that almost half of the fishermen do not tend to use a specific antifouling coating brand. Another critical finding from this question was related to the availability of antifouling coatings on a local or international scale. Results showed that the two most common antifouling brands (that of 54% and 51% of the fishermen use), respectively) are the coatings available internationally, whilst the most popular locally available coating was selected only by 37% of the fishermen. Another question was posed related to where the fishermen buy the antifouling coatings from; the majority (78%) stated that they get the coatings from the dealer, 15% of them from the hardware store and 7% of them from the supplier. When it comes to how the fishermen choose the coating applied on the hull, most of the fishermen stated that they have multiple criteria when choosing the coating. Furthermore, the fishermen stated seven different reasons, and the most common reason was given as the "trial and error method" with 39%.

Another question that was posed to fishermen was related to who conducts the coatings. Nearly half of the fishermen stated that labourers conduct the coatings, whilst 29% of them conducts themselves, and 22% stated that painters coat their vessels' hull. Another key finding is that although a significant proportion of the fishing vessel hulls are coated with paint guns, many fishermen stated that roller brush is still used in practice.

When the time spent in antifouling coating application is considered, results showed that this process would take up to 30 days. What is surprising is that when LOA and the days spent in hull coating correlated, there is no good match. Although there might be many reasons behind this "no-rush" situation in the days spent in hull coating, four and a half months lasting off-season for the fishing activities can be given as one of the possible reasons. Survey results also showed that the amount of the antifouling coating varies from 10 to 1500 litres depending on the LOA(m) size due to a correlation made between LOA and the antifouling coating used in litres.

When it comes to the propeller and the antifouling coating relation, 39% of the fishermen stated that they do not coat their propeller. Interestingly, nearly half of the fishermen stated that coating propellers would not make any difference in their beliefs.

Underwater hull inspections were conducted to obtain fouling characteristics of the fishing vessels fishing with different fishing activities. The first fishing vessel that the underwater hull was investigated was a trawler fishing in the Black Sea. Before conducting underwater investigations, a brief survey was conducted with the owner of the fishing vessel. After obtaining the relevant information about the fishing vessel, underwater inspections were conducted. Firstly slime thickness was measured from different points around the vessel's hull using a film thickness gauge. Results showed that slime thickness varies from 650 to 800 µm maximum. Next, a force gauge was used to measure the peak applied force required for the calcareous fouler organism to release itself from the adhered surface. The reason behind this measurement was to calculate the adhesion strength (MPa) of each fouler organism.

Next, the second fishing vessel UW2's underwater hull inspection, was conducted. Although the slime measurements could not be conducted, peak applied force to release each fouler organism was measured with the help of a force gauge. Furthermore, fouler organisms' adhesion strength areas were measured after removing the organism from the hull surface with the force gauge. As a result, adhesion strengths values of each fouler organism were calculated and then presented.

For the underwater inspections of the fishing vessel UW3, the same measurement process was repeated from the UW1. Slime measurements were conducted with a wet thickness gauge. Following that force gauge was used to determine the adhesion strength values of each species adhered on the ship's hull. It can be seen from the hull inspections is that the *Balanus amphitrite, Mytilus galloprovincialis*, and *Ostrea edulis* are the three most common species of calcareous fouler organisms were found on the ship hulls. In addition, slime thickness on a fishing vessel varies between 275 µm and 800 µm after one fishing season.

4 Field and Ship Tests

4.1 Introduction

This Chapter presents the design, data collection, and analysis of field tests using the static immersion test panels and coated patches on a fishing vessel with different types of antifouling paints. Following this introductory section (5.1), the field and ship tests' justification is described in Section 4.2. Following that, the subject field test and ship test preparations are described in Section 4.3. Firstly, SPC Immersion test panels, then FR immersion test panels, and finally ship test preparations are detailed respectively in this section. Following that, a rating system that is used to quantify the biofouling growth is introduced in Section 4.4. Next, Field and ship test results are presented in Section 4.5 in three subsections to give detailed results separately for each field test and ship test. In addition, the ship test and SPC immersion test panel comparison is presented in the same section. The field test data generation for the Mediterranean Sea is explained in detail in Section 4.6. Also, SPC immersion test panels' assessment results for the Black Sea and the Mediterranean Sea are given in terms of logistic growth constants within Section 4.6. Finally, a summary and the main conclusions of the Chapter is presented in Section 4.7.

4.2 Justification of Field and Ship Tests

After obtaining the relevant statistics (such as fleet size, LOA, fishing activity, etc.) officially released by the countries bordering the Black Sea, a pre-prepared survey was conducted with the relevant people who are engaged with fishing vessels representing industrial fisheries. Fisheries statistics are published bi-yearly by the Food and Agriculture Organisation (FAO) of the United Nations. Yet, the survey was prepared with the help of experts within the academy. Survey results were used to characterise industrial fisheries in the Black Sea. Furthermore, the most common antifouling coatings were determined via survey results, and these coatings were applied in both ship tests and field tests. In addition to FAO's bi-yearly published statistics, word of mouth information was also taken into account after getting in contact with the officials of local authorities to determine local exceptions regarding fishing vessels. Word of mouth information and the official statistics confirmed the most typical fishing vessel characteristics. As a result, a purse seiner fishing vessel with 30 m LOA was selected to represent the most common fishing vessels, and so pre-determined antifouling coatings were applied in the selected ship hull. Field and the ship tests showed that the results are cohering with each other with negligible fouling conditions when the idle time of the selected fishing vessel's one-year fishing activity was taken into consideration. In other words, ship tests cross-validated the field tests conducted in the same region, as detailed in Section 4.5.3.

During the ship test's antifouling coating application process, the fishing vessel's owner's help and the experience were captured. Following the discussions made with the fishing vessel's owner, antifouling coatings were applied on the port side of the fishing vessels. The main reason behind this was to avoid self-grooming from the fishing net hauling during the fishing activity. The self-grooming was confirmed by the time when the fishing vessel was drydocked after completing its fishing activities. While the fishing vessel's starboard side was partially foul free due to the interaction with the fishing nets, the port side of the fishing vessel was not affected by self-grooming by the fishing nets.

Moreover, coatings applied on the ship test area were extended toward the fishing vessel's maximum depth—the reason behind this was to see the light's effect in terms of fouling growth. Ship test results showed no difference between the shallow and the deepest paint area on the ship hull. Results can be related to the insignificant depth difference where the coatings applied so that the amount of light that the coatings' deepest and the shallowest points exposed were similar.

Before the examination of the fouling conditions on the field test panels, the underwater hull inspections were conducted. As a result, fouling organisms observed within the assessments appeared to be the same species observed in the field and ship tests. That should be stated that fouling organisms were examined and identified with the help of a marine biologist.

The most typical fishing vessel with the most common fishing activity type was chosen for the ship tests to comply with a realistic perspective. The experiment procedure to test the antifouling coatings was followed within the guidance of NSTM and ASTM standards. During the rating process, observations were conducted with the help of in-detail investigations. Following the definitions given in NSTM standards, hands were used to identify the calcareous and soft fouling. Pictures of each fouling condition, together with the descriptive notes, were also taken. The photos and the notes were used to get help from the marine biologist to confirm the fouling conditioning when necessary. In the field test, panels were chosen to be painted with a roller brush as suggested by the survey results proving that a substantial portion of the fishing vessels uses the roller brush to conduct the antifouling coatings. Field test panels were immersed in a safe place in a fishing port. Furthermore, panels were submerged 117 cm beneath the seawater surface to replicate the average draft of a purse seiner with a similar LOA following the immersion dept limits given in (ASTM, 2012) standards.

As stated in the literature review chapter in this thesis, different antifouling strategies perform with both advantages and disadvantages in their way. After completing the field tests in the Black Sea, a comparison between two antifouling coating strategies (Self Polishing Copolymer and Foul Release coatings) was made. To elaborate, following the fouling ratings of the field tests conducted between two different types of antifouling strategies, foul release coatings showed a poor performance in comparison with the self-polishing copolymer coatings under static conditions. Hence, comparison results showed an excellent agreement with the performance characteristics of the SPC and FR coatings when the static conditions are in concern. However, it should be noted that ship tests might show different results due to the SPC and FR antifouling coatings' working mechanisms, as discussed in Section 2.4.3.

As stated in many studies before, one of the primary triggers for fouling growth rate is the seawater temperature. In other words, the higher the seawater temperature is, the faster the fouling growth rate is. While the average Black Sea surface temperature has been statistically considered as 16 degrees Celsius, the average SST for the Mediterranean Sea has been regarded as 22 degrees Celsius for the last ten years. Furthermore, this SST difference and its effect on the biofouling growth can be seen from the curves fitted in the logistic growth model of the field test data for the Black Sea and the generated field test data for the Mediterranean Sea. That is to say, due to higher seawater temperatures, the fouling organisms colonise quicker in the Mediterranean Sea in comparison to the Black Sea.

Salinity also plays an essential role in fouling organisms' growth. Due to the reason that many rivers are feeding the Black Sea, the average salinity of the Black Sea is lower than the Mediterranean Sea salinity levels. The impacts of salinity levels are seen when the salinity levels are around 10‰, and the average surface salinity level for the oceans is around 30-36‰. Furthermore, it is essential to state that the ratios of the salinity levels where the field tests occur are within limits; the impacts of salinity on fouling organisms are not seen in this study. The generalisation for the salinity is similar to pH levels where the field and the ship tests are conducted as both the Black Sea and Mediterranean Sea surface water pH levels never reach the limits that would affect the fouler organisms.

Field tests were immersed statically in seawater where the selected fishing operations were conducted. One of the reasons behind this was to replicate the idle time of fishing vessels during fishing activities. Selected fishing vessel's fishing activities were conducted entirely in the Black Sea, which was confirmed with the automatic Identification System (AIS). For that reason, the temperature, pH, and salinity values were considered for the Black Sea. Furthermore, the effects of flow velocity on biofouling were confirmed with the relevant field test and ship test results comparison. During this analysis, the idle time of the selected fishing vessel's one-year operation profile was taken into account with the help of AIS data. Also, equivalent idle time and the fouling condition from the field tests were taken and compared with the ship test results. This indicated that the fouling condition rating according to NSTM standards on the ship hull was lower than the field test data. Also, waves and currents can groom the organisms adhered. These conditions can be confirmed within the field test results.

Finally, as the nutrient availability depends on the flow velocity around the fouler organisms and whether the area where the accumulation occurs is close to the shore, the experiment location for the field test was selected as one of the most suitable and natural environments for fouling organisms.

4.3 Field and Ship Test Preparations

In this section, immersed test panels and ship tests are introduced, details of the test preparation are presented together with the results.

4.3.1 Immersion Test Panels

Immersion test panels were used to test the antifouling coating performance over time immersed in the Black Sea in a fishing port located within a university's campus borders. Two different immersion test panels were set for two different antifouling coating technologies to represent the SPC and FR type coatings.

4.3.1.1 SPC Immersion Test Panels

The survey conducted in Chapter 3 was the initial work done for the immersion test panels. As a result of the survey, the most common antifouling technologies and application processes were determined. As a result, five different antifouling coatings were selected and applied on the test panels to immerse in the Black Sea with the help of the local shipyards and the fishermen. The American Society for Testing and Material (ASTM)'s Standard Test Method for Testing Antifouling Panels in Shallow Submergence was used as a guide when preparing and conducting the immersion test panel (ASTM, 2012).

After investigations and discussions with the shipyards owners and the constructors, steel was chosen as the panel materials. The selected panels were used from the same steel material which the yards used when constructing a ship's hull. This operation was led by the shipyard owner/craftsman. The reason behind this selection was to replicate the fishing vessels' hull surface realistically. In order to comply with the standards, 4 mm thick 350 mm x 150 mm steel panels with 525 cm^2 surface area were prepared for the immersion test setup. In addition, 8 mm diameter holes were drilled and centred from 22.5 mm away from the top to stabilize the panels in the rack. Finally, the test panels were sandblasted.

Furthermore, a rack was prepared to keep the panels firmly in a vertical position against currents and the waves. For this reason, an iron frame with 50 cm width and 150 cm length was prepared, and four of 30 cm length iron legs were welded in the frame corners. Frame legs were added to the tool to avoid any possible contact with the concrete while pulling the immersion test apparatus out of the water and examining the panels. In addition, panels were insulated to prevent metallic contact with the rack. The panels in the rack were mounted side by side, leaving a 30-50 mm distance between the adjacent panels. To do that, 5 mm holes were drilled within the rack to secure the drilled panels. Plastic self-locking strap ties were used in order to keep the panels firmly in the rack. Panels and the exposure rack pictures can be seen in Figure 4-1.

Figure 4-1: Immersion test tool pre-setup

Next, the antifouling coatings were applied using the pre-selected coatings as aforementioned in this chapter. It should be noted that the coating application was conducted by the shipyard's painter, who is responsible for maintaining the coating application process of the largest shipyard for the fishing vessels in the region. The professional painter was chosen to represent a realistic perspective and follow the routines of antifouling coating applications. The coating was applied with roller brushes as a result of the survey results. A layer of epoxy coating was first applied as a pre-treatment coating before the final antifouling coating was applied on each side of the panels. In addition to that, a panel was left blank intentionally as the reference panel. After the coating application process was completed, all the test panels and the reference panel were labelled as: Paint 1, Paint 2, Paint 3 (Ref. Panel), Paint 4, Paint 5, and Paint 6. Paint 3 refers to the reference panel for the SPC immersion test apparatus, and there was no coating applied on the reference. A general look for the immersion test rack is presented in Figure 4-2.

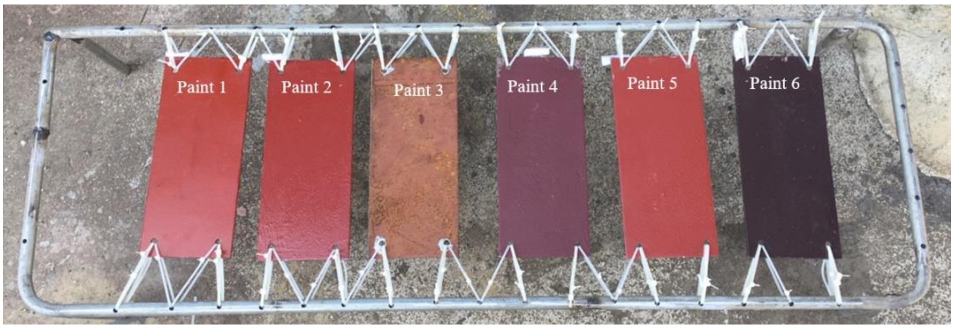


Figure 4-2: A General Look of the SPC Immersion Test Apparatus

Furthermore, biocide contents of the SPC coatings were obtained from Lloyd's Register (2018). Investigating in detail revealed that no information was available on the biocide content of Paint'5 since a start-up company produced this coating, and they could not share the contents due to their policy. Details of the coatings applied on the immersion test panels can be seen in Table 4-1.

Table 4-1: Antifouling coatings applied on immersion test panels (where CO: Cuprous Oxide, Di: Diuron, CY: N-cyclopropyl-N'-(1,1- dimethylethyl)-6- (methylthio)-1,3,5- Triazine-2,4-diamine, ZP: Zinc Pyrithione)

Coating Labels	*Locally / Internationally Availability*	*Antifouling Type*	*Biocide Contents*
Paint 1	Locally available	Biocidal - SPC	CO, Di, CY
Paint 2	Locally available	Biocidal - SPC	CO, Di, CY
Paint 3 (Ref. Panel)	N/A	N/A	N/A
Paint 4	Internationally available	Biocidal - SPC	CO, ZP
Paint 5	Locally available	Biocidal - SPC	N/A
Paint 6	Internationally available	Biocidal - SPC	CO, CP

After the coating application process, roughness measurements were taken for each paint using the TQC Surface Roughness Gauge and the mean roughness (R_a) presented as shown in Table 4.2.

Table 4-2: Mean Roughness (R_a) Measurement Results for Each Applied Coating on the SPC Test Panels. (μm)

	Paint 1	*Paint 2*	*Paint 3 (Ref. Panel)*	*Paint 4*	*Paint 5*	*Paint 6*
R_a	110	117	N/A	234	195	279

The immersion test panel apparatus was submerged at 117 cm depth from the surface on 4th September 2018 in a determined location, and it was observed weekly for the first month and then biweekly until the 52nd week in one year period. The site where the immersion took place can be seen in Figure 4-3. The panels were left in the seawater for a further period, and the accumulation was checked two more times in week 74 and week 78. Fouling accumulation results are presented in Section 4.5.1 of this chapter.

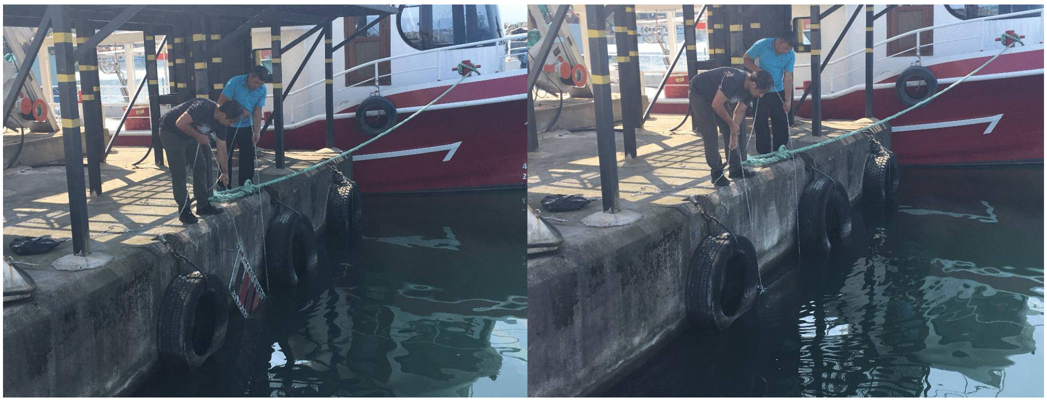


Figure 4-3: Field test immersion Site

4.3.1.2 Foul Release (FR) Immersion Test Panels

Survey results in Chapter 3 showed that the only type of antifouling coatings used was biocide based SPC coatings among fishing vessels. However, as stated in the previous chapters, with stricter regulations, a trend towards the use of less toxic antifouling technologies is inevitable. For that reason, foul release (FR) coatings were included in the field tests to make a comparison between SPC and FR coatings performance. To do that, one of the leading antifouling coating companies' help was asked. After discussions with the relevant company's representatives and managers, three FR coatings were determined to be immersed in the Black Sea as part of seat tests. Due to the company’s privacy policies, selected foul release coating brands were labelled as A, B, C by the company. Furthermore, because each coating was applied on two different test panels, the author made the final labelling as; Paint A1, Paint A2, Paint B1, Paint B2, Paint C1, and Paint C2.

Similar to the SPC coating immersion test tool, the American Society for Testing and Material (ASTM)’s Standard Test Method for Testing Antifouling Panels in Shallow Submergence was used as a guide when preparing and conducting the FR immersion test panel (ASTM, 2012). Therefore, to comply with the standards, 6 copies of 4 mm thick 350 mm x 150 mm steel panels, with 525 cm^2 surface area each were prepared for the FR immersion test setup in the Mechanical Engineering department of the University of Strathclyde. In addition, 10 mm diameter holes were drilled and centred from 22.5 mm away from the top in order to stabilize the panels in the rack. Panel dimensions can be seen in Figure 4-4.

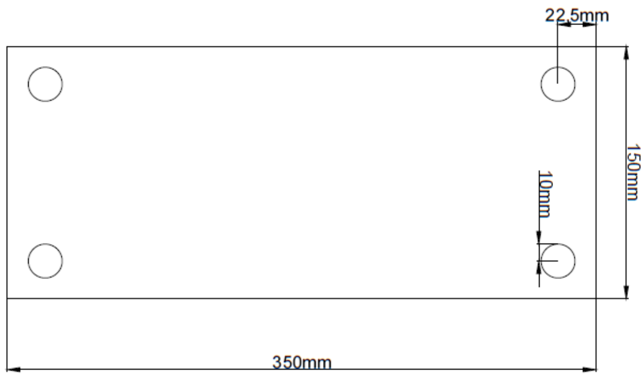


Figure 4-4: Dimensions of the Panels prepared

After preparing, 6 steel panels were sent to the antifouling coating company to be firstly blasted and then coated. At this point, it should be noted that although the SPC coatings were applied by the shipyard’s painter, FR coatings were applied by the company’s professional team due to the working mechanism of FR coatings. Test panels with the labels can be seen in Figure 4-5.

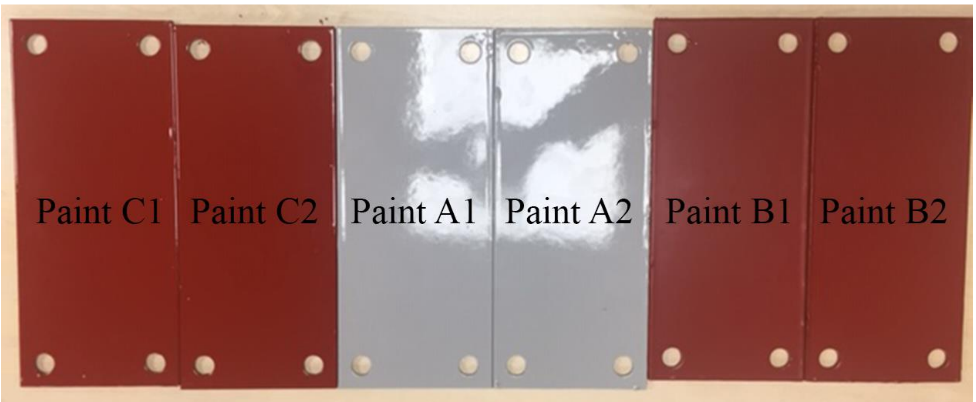


Figure 4-5: Foul Release coatings to be immersed in Black Sea where A, B, C representing the coating brands, 1 and 2 represents the same coating's replica numbers.

After the company's professional team conducted the coating application of the panels, roughness measurements were taken with the Taylor Hobson Surtronic 25 roughness tester. However, due to an unforeseen incident, the measurement for Paint C1 could not be taken. Relevant roughness measurements for the mean roughness (R_a) can be seen in Table 4-3.

Table 4-3: Mean Roughness (R_a) Measurement Results for Each Applied Coating on the FR Test Panels. (μm)

	Paint A1	Paint A2	Paint B1	Paint B2	Paint C1	Paint C2
R_a	0.52	0.65	0.8	0.6	N/A	0.2

After panel preparation, coating application and the mean roughness measurements, panels were sent to the Black Sea region, where the immersion tests took place. Next, another rack was prepared similar to the rack used for the SPC immersion test tool by the same shipyard craftsman. The rack dimensions were kept the same as the SPC immersion test apparatus. However, instead of drilling the rack frame, this time, an iron chain was tangled into plastic self-locking strap ties that were linked to the panels. Moreover, panels in the rack were mounted side by side, and the distance between the adjacent was left 30 – 50 mm. Thus, panels were kept firmly in a vertical position against currents and the waves and so that the metallic contact with the rack was prevented. Panels and the exposure rack pictures can be seen in Figure 4-6.

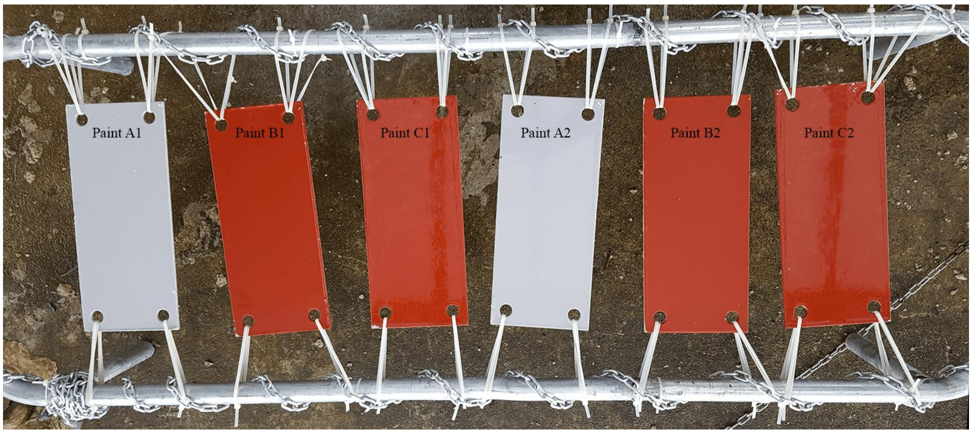


Figure 4-6: A General Look for the FR Immersion Test Tool

Following the completion, the FR immersion test apparatus was immersed at 130 cm depth from the surface on 12th February 2019 in a determined location with limited access to be observed weekly for the first month and then biweekly until 55th week in one year period. Fouling accumulation results are presented in Section 4.5.2 in this chapter.

4.3.2 Ship Tests

Ship tests are the most accurate method of testing an antifouling coating performance against biofouling, as aforementioned in Chapter 2. After negotiations with several fishing vessel stakeholders, one of the stakeholders agreed to cooperate. For that reason, the selected SPC coatings stated in Section 4.3 were applied on a purse seiner fishing vessel of 30 m LOA in the Black Sea. After applying several coatings on the selected ship hull, fouling accumulations are analysed and compared with the SPC immersion Test Panel results. Results of the ship tests are presented in Section 4.5.3 of this chapter. In order to apply coatings, the shipyard's painter, who was the same person who conducted the SPC immersion test coatings, painted the fishing vessel as a first step. During coating application, a specified area was left empty to apply the selected coatings by the painter. The coating application process can be seen in Figure 4-7, where the picture labelled by 1 represents the coating area separated for the coating application, and 6 shows the final condition of the coated area for the ship test.

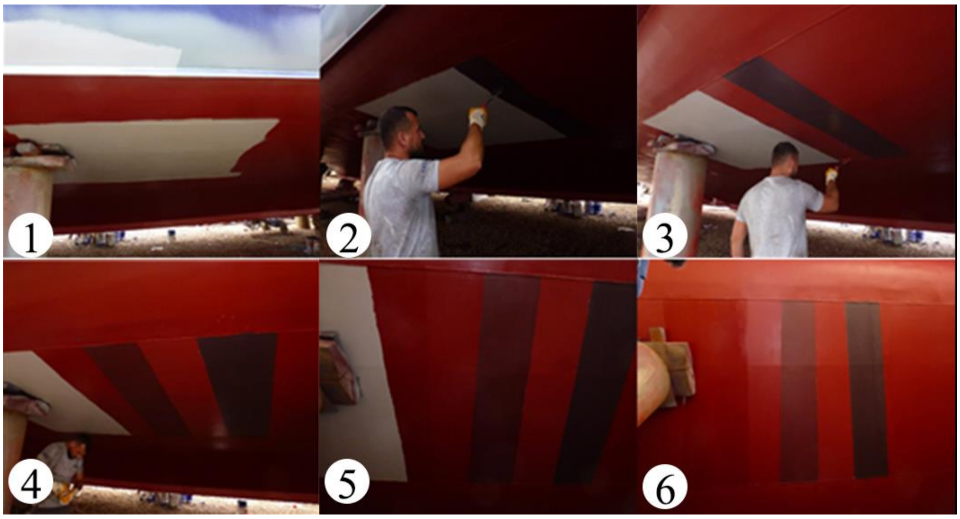


Figure 4-7: Ship test coating application process of selected antifouling coatings on selected fishing vessel

After applying coatings on the vessel, each coating was labelled. Labels were attached right above the paintings to identify each coating. Figure 4-8 illustrates the coating labels from left to right as Paint 1 (as Port – P1), Paint 2 (as Port – P2), Paint SH (as Port – P3), Paint 4 (as Port – P4), Paint 5 (as Port – P5), and Paint 6 (as Port – P6), respectively.

Figure 4-8: Labelling of the coatings applied on the Ship Test Fishing Vessel

As is illustrated on the labels, coatings are applied only on the port side of the vessel. The reason is linked to the vessel's operation profile. After having discussions with the relevant stakeholder, the vessel's operation behaviours helped the researcher to decide whether the coatings were applied on the starboard side or port side of the vessel. As the fishing nets are hauled from the starboard side of the vessel, and yet heavyweight of the net with the caught fish generate shear stress between the hull and the net, resulting in the wiping of the biofouling on the hull. This also causes deformation of the antifouling coating on the starboard side of the vessel. Therefore, the port side of the fishing vessel was chosen for antifouling coating applications.

During the coating application process, a couple of unexpected incidents occurred. The first and the most important one was the width of the area, which was supposed to be spared for ship test coating application. Although the arrangements were made with all of the stakeholders of the selected fishing vessel, the antifouling application was conducted by foreign labour. Due to lack of communication, the shipyard's painter invaded 40% of the area, which was supposed to be used for the ship test coating application with the antifouling coating that was used for coating the ship's underwater hull. In other words, the area in which the coatings were applied were smaller than the initially planned area. For that reason, the surface areas of each coatings applied are not the same as each other.

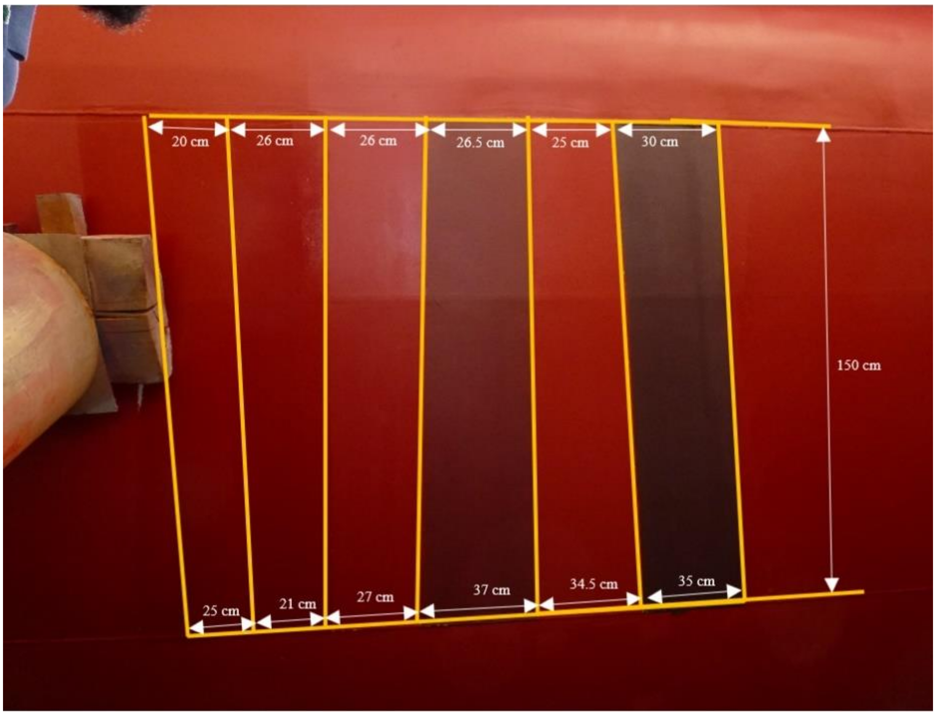


Figure 4-9: Dimensions of the Coatings Applied on the Fishing Vessel

Figure 4-9 illustrates the dimensions of the coatings applied on the underwater hull of the fishing vessel. Based on the dimensions in Figure 4-9, each surface area of the applied coatings was calculated in regard to the trapezoid surface area formula. Table 4-4 shows the surface areas of each applied coating on the vessel's underwater hull surface.

Table 4-4: Dimensions and Surface Areas of Each Applied Coating on the Ship Test Fishing Vessel

	Height in cm	Above line width in cm	Below line width in cm	Surface area in cm^2	Surface area in m^2
Paints					
Paint 1	150	20	25	3375	0.3375
Paint 2	150	26	21	3525	0.3525
Paint SH	150	26	27	3975	0.3975
Paint 4	150	26.5	37	4762.5	0.47625
Paint 5	150	25	34.5	4462.5	0.44625
Paint 6	150	30	35	4875	0.4875

After coating applications were conducted, mean roughness measurements were taken from two different parts of the coated areas for each coating applied on the ship hull. The first measurements were taken from the area that is closest to the sea surface of the coated area, which is stated as “Above”. The second measurements were taken from the area that is furthest to the sea surface, which is stated as “Below”. For this purpose, the same roughness measurement device, TQC Surface Roughness Gauge, was used, and the measurement results are presented in Table 4-5.

Table 4-5: Mean Roughness (R_a) Measurement Results for Each Applied Coating on the Ship Hull. (μm)

	Paint 1	Paint 2	Paint SH	Paint 4	Paint 5	Paint 6
R_a (Above)	200	131	95	159	115	145
R_a (Below)	128	123	94	132	142	216
R_a (Total)	164	127	94.5	145.5	128.5	180.5

On a final note, as stated previously in this section, the coatings applied on the SPC immersion test panels and the coatings applied on the selected vessel's hull were the same. Also, Paint SH was used for the ship test because the reference panel had no coating applied. Paint SH was the coating that the shipowner used, and this coating was not included in the SPC immersion Test panels due to an incident that occurred.

4.4 Rating System

Before presenting the results of the fouling accumulation or growth, it is essential to detail the method used to quantify the biofouling on the immersed panels and the ship coating tests. Naval Ship's Technical Manual (NSTM) standard's rating system was used to rate the fouling growth. NSTM rating is a fouling index that is used as guidance on hull cleaning by the US Navy. Hence, to determine the fouling condition of both the ship and field tests conducted in this study in situ, the NSTM rating system was used.

According to the NSMT rating system, there are three fouling categories described as soft, hard and composite, NSTM (2002). The soft fouling is assumed to be composed of slime and grass type fouling. For the slime accumulation, the hull surface is considered smooth and generally follows the hull contours. On the other hand, the grass accumulation for the soft fouling is described as the green formation, and as the submergence depth increases, the colour changes from green to brown. Furthermore, for hard fouling, there are two dominant forms; barnacles and tubeworms. Whilst barnacles have hard shells with jagged tops, tubeworms project out and lie on the hull. In addition to the advanced forms of fully grown barnacles and tubeworms, other calcareous organisms such as molluscs or bivalves like mussels, oysters or oyster hydroids, anemones and tunicates as shell-free organisms are considered as composite fouling.

Furthermore, the NSTM standards present a rating system starting from 0 to 100 with increasing severity. Whilst a rating of 0 symbolises a foul-free surface, ratings up to 30 represent soft fouling. Moreover, a rating of 40 indicates the early stages of calcareous fouling, and the fouling severity increases with increasing rating numbers. Finally, a rating of 100 denotes more than one type of larger calcareous fouling, which is considered composite fouling. Within this point, a clarification has to be made regarding the rating systems used. Due to the complex accumulation structure of the fouler organisms and transition phases from specific ratings to the following, fouling ratings denoted could not be matched with the descriptions given in NSTM standards on some occasions. For that reason, the author chose to use semi-ratings to describe these complex structures. Detailed NSTM rating system with the definitions of each rating grade can be seen in Table 4-6.

Table 4-6: Fouling Ratings (FR) with the increasing severity adapted from NSTM (2002)

Type	Fouling Rating (FR)	Description
Soft	0	A clean, foul-free; red and/or black AF paint or a bare metal surface.
Soft	10	Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.
Soft	20	Slime as dark green patches with yellow- or brown-coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling.
Soft	30	Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand.
Hard	40	Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height.
Hard	50	Calcareous fouling in the form of barnacles less than ¼ inch (6.4 mm) in diameter or height.
Hard	60	Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height.
Hard	70	Combination of tubeworms and barnacles, greater than ¼ inch (6.4 mm) in diameter or height.
Hard	80	Tubeworms are closely packed together and growing upright away from the surface. Barnacles are growing one on top of another, ¼ inch (6.4 mm) or less in height. Calcareous shells appear clean or white in colour.
Hard	90	Dense growth of tubeworms with barnacles, ¼ inch (6.4 mm) or greater in height; Calcareous shells brown in colour (oysters and mussels); or with slime or grass overlay.
Composite	100	All forms of fouling present, Soft and Hard, particularly soft sedentary animals without calcareous covering (tunicates) growing over various forms of hard growth.

As stated in Table 4-6, fouling ratings change depending on the height, length, diameter, species, formation, grouping, colour, and being able to rip off by hand. In addition to that, picture examples of the defined fouling conditions are illustrated in the NSTM standards, which can be seen in Figure 4-10.

Figure 4-10: Fouling Condition Examples for Each Fouling Rating (FR) adapted from NSTM (2002)

The roughness function of any hydraulic surface is an important hydrodynamic parameter representing the frictional drag characteristics of a rough surface. This includes a ship hull surface, including fouling growth on its coated surface. By using the roughness function, one can estimate the increase in the frictional resistance of the ship hull. In order to conduct such estimation practically, Schultz (2007) calculated the roughness function data for some specified hull surface roughness conditions, including certain fouling types, using the aforementioned NSTM rating system, as shown in Table 4-7. In this table, Schultz represented the roughness function for each surface condition represented by the corresponding NSTM rating by using the equivalent sand roughness height (k_s) and corresponding peak-to-trough coating roughness (Rt_{50})

Table 4-7: A range of representative coating and fouling conditions. The values of equivalent sand roughness heights (k_s) and average coating roughness (Rt_{50}) are based on the measurements of Schultz (2004) adapted from Schultz (2007)

Description of condition	NSTM Rating	$k_s(\mu m)$	$Rt_{50}(\mu m)$
Hydraulically smooth surface	0	0	0
Typical as applied AF coating	0	30	150
Deteriorated coating or light slime	10-20	100	300
Heavy slime	30	300	600
Small calcareous fouling or weed	40-60	1000	1000
Medium calcareous fouling	70-80	3000	3000
Heavy calcareous fouling	90-100	10000	10000

Therefore, after determining the relevant fouling rating for each coating type immersed and tested, the above data provided by Schultz (2007) was used to generate the roughness function data of both test panels in the field and test coatings on the ship hull over time.

4.5 Field and Ship Test Results for the Black Sea

4.5.1 SPC Immersion Test Panels

After the preparation of the SPC coatings field test setup, panels were checked regularly over a year. Each immersion test panel apparatus was taken out of the water as a first step. Following that, panels were skimmed through quickly. Next, photos of each panel were taken. After that, each panel was checked closely with both observation and probing by hand to specify relevant species. Following that, measurements were taken when necessary to take notes. Finally, panels were rated according to the NSTM standards.

4.5.1.1 Fouling Rating Assessment of SPC Coatings

For the SPC coating immersion test panels, each panel was observed over a year periodically. The first month was divided into four weeks. Following that, biweekly inspections were conducted until an entire year was up. After completing the whole year, the SPC Immersion field test panel was planned to be checked every three months; however, due to an unforeseen global pandemic- Covid-19, examinations were interrupted.

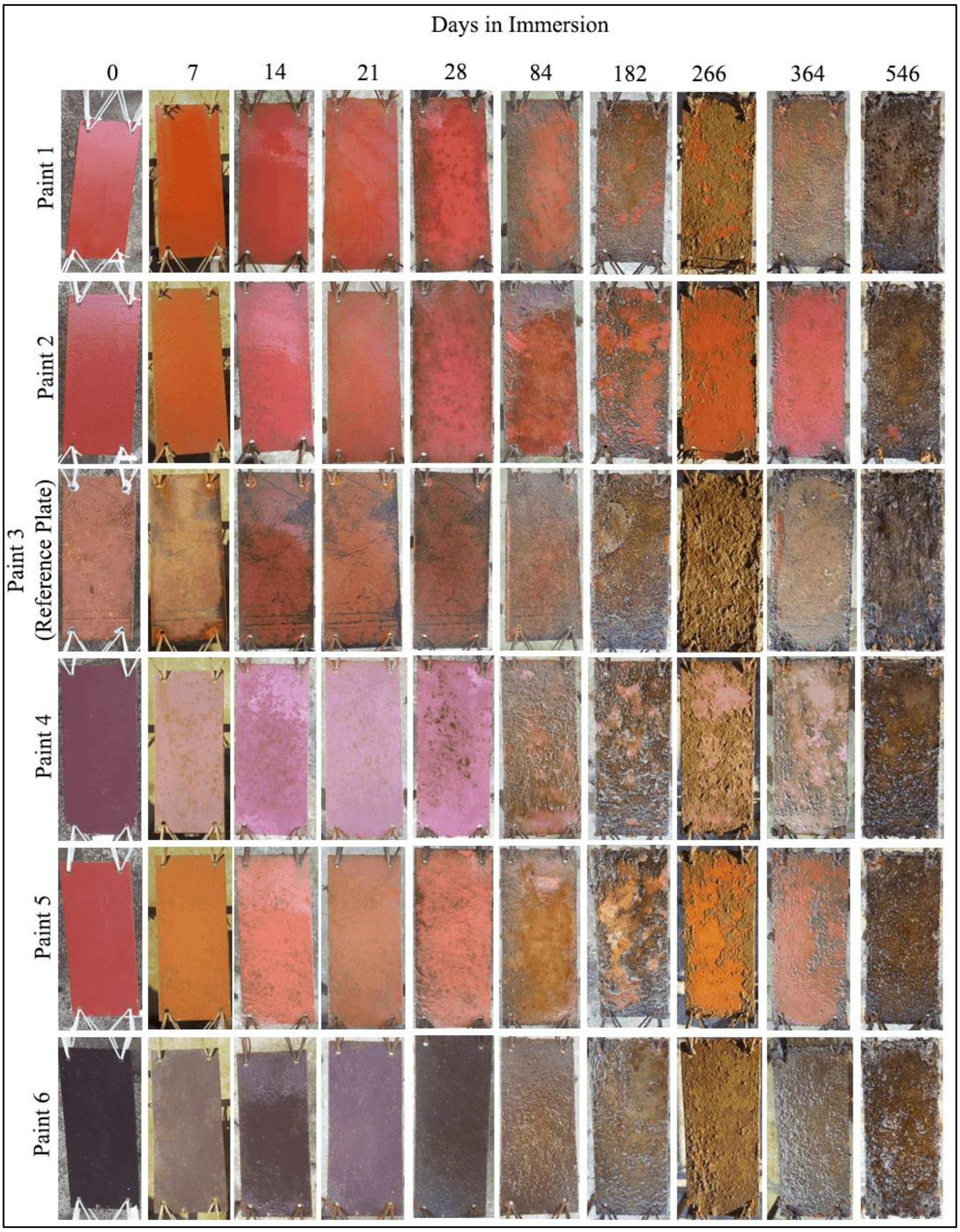


Figure 4-11: SPC Immersion test panels' accumulation results in first 4 weeks, and then 3 months, 6 months, 9 months, 12 months and 18 months, respectively.

For that reason, the SPC field test had to be ended after 2 more inspections with 18 months of immersion time in total. SPC Immersion test panels' accumulation results in the first 4 weeks, and then 3 months, 6 months, 9 months, 12 months and 18 months can be seen in Figure 4-11, respectively. It should be noted that, due to visual and practical convenience, only 10 fouling conditions of each coating are presented in this section. Pictures of each examination conducted for the SPC immersion test panels over 18 months are presented in Appendix B. In addition to that, fouling rating assessment of the SPC Immersion Test Panels illustrated in Figure 4-11 can be seen for each SPC coatings over time in Appendix D.

4.5.1.2 Logistic Growth Model Fitting for SPC Test Panels and Discussions

When it comes to modelling the accumulation or the growth characteristics of the fouler organisms, the population dynamics of the relevant organisms play a significant role. Furthermore, population dynamics take several factors into account as the rates of reproduction, death, and mitigation, whilst considering a group of organisms. Therefore, population modelling has to be carefully considered when the population size and the structure over time are of concern. Two mathematical growth models can be considered to model the biofouling accumulation over time; exponential and logistic growth models.

The exponential logistic growth model assumes that there is no resource limitation. Therefore exponential growth model is supposed to mimic a population's behaviour when there is no limitation. That is also important to state that individual growth rate is accepted to be the same, or in other words, it is assumed that growth rate is not affected by any factor for the exponential growth modelling. Thus, exponential growth plots a J-shaped curve. Although there might be times when the populations show exponential growth, the exponential model is unrealistic because environments impose certain limitations to the population and its growth rate.

Moreover, the logistic growth model modifies the exponential growth model by taking the carrying capacity into account. Due to having limited resources in the environment, the population growth rate is expected to become smaller until the population size reaches a maximum where the available sources are limited so that the growth rate becomes insignificant. This point at the maximum represents the carrying capacity for the population in nature. In other words, carrying capacity is an important parameter representing how environmental limitations affect population growth. Therefore, an S-shaped curve is produced with the logistic growth model (Sarkar, 2005). The logistic growth model, therefore, is assumed to model population change for fouling growth over time whilst focusing on the carrying capacity of the population, which results in S-curved growth (Babin et al., 2008; Breur, 2001).

After determining the fouling growth ratings of all the test panels and hull surface patches according to the NSTM rating system, a logistic growth model was used to fit the fouling ratings of the SPC immersion test panels in logistic curves. For this purpose, a logistic growth model over time used by Uzun et al. (2019) was modified to fit the fouling ratings using Equation 30.

$$\mathbf{FR} = \frac{\mathbf{P - p}}{\mathbf{1 + (exp^{b-ct})}} + \frac{\mathbf{d}}{\mathbf{1 + (exp^{f-gt})}} \qquad (30)$$

Where FR is the fouling ratings according to NSTM standards, P, p, b, c, d, f, and g are logistic growth model constants, and t is the sum of immersion time in days.

The NSTM ratings of each coating used in the SPC immersion test panel and logistic growth models fitted can be seen in Figure 4-12. Fouling ratings against immersion time were plotted and fitted in the logistic growth model by using Equation 30, and constant values for each coating is presented above the fitted curves. It should be noted that the logistic growth model constants used in Figure 4-12 represent approximately 18 months (546 days) lasting fouling conditions. Looking at Figure 4-12, although there are some deviations between the data points and the curve, the model matches with the trend from a general perspective. Further details of the fouling growth pattern for each test case are discussed in the following.

As it is observed in Figure 4-12 that the longer time the panels are immersed, the more the fouling ratings are, as expected. The reference panel (Paint 3) reaches the highest fouling rating, which is 70 and is described as a “Combination of tubeworms and barnacles, greater than ¼ inch (6.4 mm) in diameter or height”. Whilst Paint 4 reaches the maximum soft fouling rating in 43 days; Paint 2 presents a better performance in keeping the panel's surface less fouled than the other coatings. Paint 2 reaches the maximum NSTM fouling rating for the soft fouling condition in 112 days. Furthermore, although all of the panel's accumulation patterns reach the maximum level before the calcareous species appear in less than 100 days, the calcareous species start to appear on the panels approximately after 500 days of immersion.

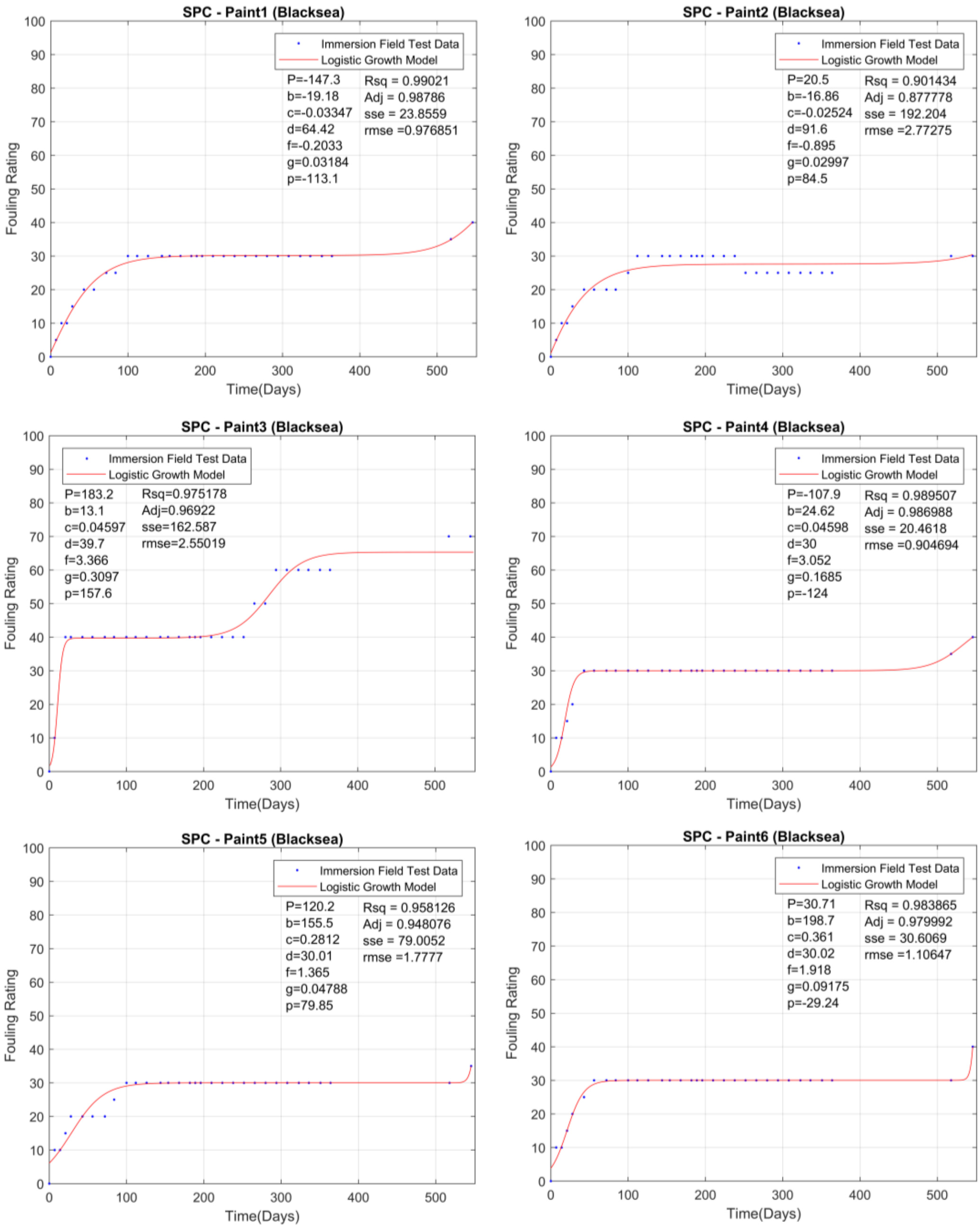


Figure 4-12: Fouling ratings fitted in logistic growth model for SPC coatings for 18 months

From Figure 4-12, it can be seen that after 546 days of immersion in the Black Sea, the maximum fouling rating that Paint 1's biofouling reaches is a fouling rating of 40. According to the NSTM fouling rating index, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height" represents a fouling rating of 40. Furthermore, it can be seen that the fouling rating for Paint 1 reaches the fouling rating of 30 after 150 days of immersion. Following that, fouling ratings seem to show no growth (in terms of fouling ratings) until the 400th day. After the 400th day, fouling growth seems to further develops and reaches the fouling rating of 40 after 546 days of immersion at the end. Due to the reason that fouling organisms' settlement requires a particular time for the ongoing fouling growth process, there might be several reasons behind this period with the fouling rating 30, such as the changes in environmental conditions (waves, light, nutrient, and pH and temperature).

For Paint 2, it can be seen from Figure 4-12 that the maximum fouling rating that the biofouling reaches is 30 after 546 days of immersion in the Black Sea. According to the NSTM fouling rating index, "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" represents the fouling rating of 30. Furthermore, it can be seen that fouling ratings for Paint 2 reach the fouling rating of 30 after 546 days of immersion. However, looking at Figure 4-12 in detail, the fouling rating over 546 days shows fluctuations for Paint 2. To be more specific, whilst the data points show that the fouling rating of 30 is reached only after approximately 125 days, there is a decrease in fouling rating from 250th day up until approximately 500th day. Although the reasons behind this fluctuation are uncertain, seasonal changes in environmental conditions such as waves, light, nutrients, pH, temperature, and predators might directly affect the biofouling conditions over time.

Figure 4-13: A pipefish (*Syngnathus typhle*) found tangled in the field test mechanism

Within this perspective, an example can be given in one of the fouling rating examinations from the field tests. Figure 4-13 shows that a pipefish (*Syngnathus typhle*) was found tangled in the field test mechanism during the field test inspections. Furthermore, Pipefish are commonly known to have a diet consists mainly of small crustaceans, and they are commonly associated with the grass beds (Oliveira et al., 2007). Combining all this information, one of the high possibilities of the fouling rating decrease for Paint 2 might be attributed to these animals among the others.

The maximum fouling rating that the biofouling reaches for Paint 3 (reference panel) is 70 after 546 days of immersion in the Black Sea. According to the NSTM fouling rating index, "Combination of tubeworms and barnacles, greater than ¼ inch (6.4 mm) in diameter or height." represents the fouling rating of 70. Looking at it in detail, in less than two weeks, a fouling rating of 40 is reached due to the unprotected surface panel (reference panel). After reaching the fouling rating of 40, fouling growth stays at the same fouling rating level until nearly the 7th month. Due to the reason that fouling organisms' settlement requires a particular time for the ongoing fouling growth process, there might be several reasons behind this period with the fouling rating of 40, such as the changes in environmental conditions (waves, light, nutrient, and pH and temperature). Fouling rating reaches the fouling rating of 50 for a month and then reaches the fouling rating of 60. At the end of a year of immersion test, the biofouling rating becomes 60. However, considering the 546 days of immersion time, biofouling growth continues, and the fouling rating reaches 70.

For Paint 4, it can be seen from Figure 4-12 that the maximum fouling rating that biofouling reaches is a fouling rating of 40 after 546 days of immersion in the Black Sea. According to the NSTM fouling rating index, “Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height.” represents fouling rating of 40. Furthermore, looking at the beginning of the immersion day, it can be seen that Paint 4 reaches to fouling rating of 30 after approximately a month of immersion. Following that, the fouling rating of 30 does not go up until the 500th day of immersion. Due to the reason that fouling organisms’ settlement requires a particular time for the ongoing fouling growth process, there might be several reasons behind this period with the fouling rating of 30, such as the changes in environmental conditions (waves, light, nutrient, and pH and temperature). After 500 days of immersion, paint 4’s fouling rating reaches the maximum fouling rating of 40 after 546 days of immersion.

For Paint 5, it can be seen from Figure 4-12 that the maximum fouling rating that biofouling reaches is fouling rating of 35 after 546 days of immersion in the Black Sea. According to the NSTM fouling rating index, “Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand.” represents the fouling rating of 30, and “Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height.” represents fouling rating of 40. Within this point, the author must remind that the semi-ratings were used on some occasions, as stated in Section 4.4. Furthermore, looking at the beginning of the immersion day, it can be seen that Paint 5 reaches to fouling rating of 30 after approximately three and a half months of immersion. Following that, the fouling rating of 30 does not go up until the 500th day of immersion. Due to the reason that fouling organisms’ settlement requires a particular time for the ongoing fouling growth process, there might be several reasons behind this period with the fouling rating of 30, such as the changes in environmental conditions (waves, light, nutrient, and pH and temperature). After 500 days of immersion, paint 5’s fouling rating reaches the maximum fouling rating of 35 after 546 days of immersion.

For Paint 6, it can be seen from Figure 4-12 that the maximum fouling rating that biofouling reaches is a fouling rating of 40 after 546 days of immersion in the Black Sea. According to the NSTM fouling rating index, “Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height.” represents a fouling rating of 40. Furthermore, it can be seen that fouling ratings for Paint 6 reach the fouling rating of 30 after approximately three months of immersion. Following that, fouling ratings seem to show no growth (in terms of fouling ratings) until the 500^{th} day. Due to the reason that fouling organisms’ settlement requires a particular time for the ongoing fouling growth process, there might be several reasons behind this period with the fouling rating 30, such as the changes in environmental conditions (waves, light, nutrient, and pH and temperature). After approximately 500 days of immersion, paint 5’s fouling rating reaches the maximum fouling rating of 40 after 546 days of immersion.

Overall, Paint 3 (reference panel) shows the worst performance as expected due to uncoated and defenceless surface area against fouler organisms. On the other hand, considering the first 200 days of immersion, it can be seen that all the test panels (except the reference panel) reach to fouling rating of 30. However, when the exact times that the fouling ratings reach 30 is checked, it can be seen that the antifouling performances of each coating differentiate. To elaborate this further, Paint 4 reaches a fouling rating of 30 in the shortest time (approximately one and a half months) among the antifouling coatings used in the SPC field tests. In other words, Paint 4 displayed the poorest performance amongst the test coatings as far as their antifouling performances are concerned. Following that, Paint 6 reaches to fouling rating of 30 in the second shortest time (approximately two and a half months) among the antifouling coatings used in the SPC field tests. It means that Paint 6’s antifouling performance results show the second-worst among the antifouling coatings used in the SPC field tests. After that, Paint 1 and Paint 5 display similar performance because the immersion times that are reached to fouling rating of 30 (approximately three and a half months) are close to each other. In other words, Paint 1 and Paint 5 take place in the second and the third-best antifouling coating performances among the others. Finally, among the SPC antifouling coatings used in the field tests, Paint 2’s antifouling ability is the best because the maximum fouling rating is reached longer than three and a half months. To summarise, based on the SPC field test results, a ranking can be made from the best to worst antifouling performance in the following descending order; Paint 2, Paint 1 and Paint 5, Paint 6, Paint 4, and Paint 3 (reference panel).

At this point, it should be borne in mind that the majority of the fishing vessels conduct hull cleaning at a frequency more often than every 18 months. Furthermore, the vessels are either obliged to anchor in the fishing port or dry-docked when the fishing season ends. For that reason, an additional logistic growth curve was fitted to the data points for 250 days to represent a fishing year. Thus, the NSTM ratings of each coating used in the SPC immersion test panel and logistic growth model curves fitted for a year can be seen in Figure 4-14.

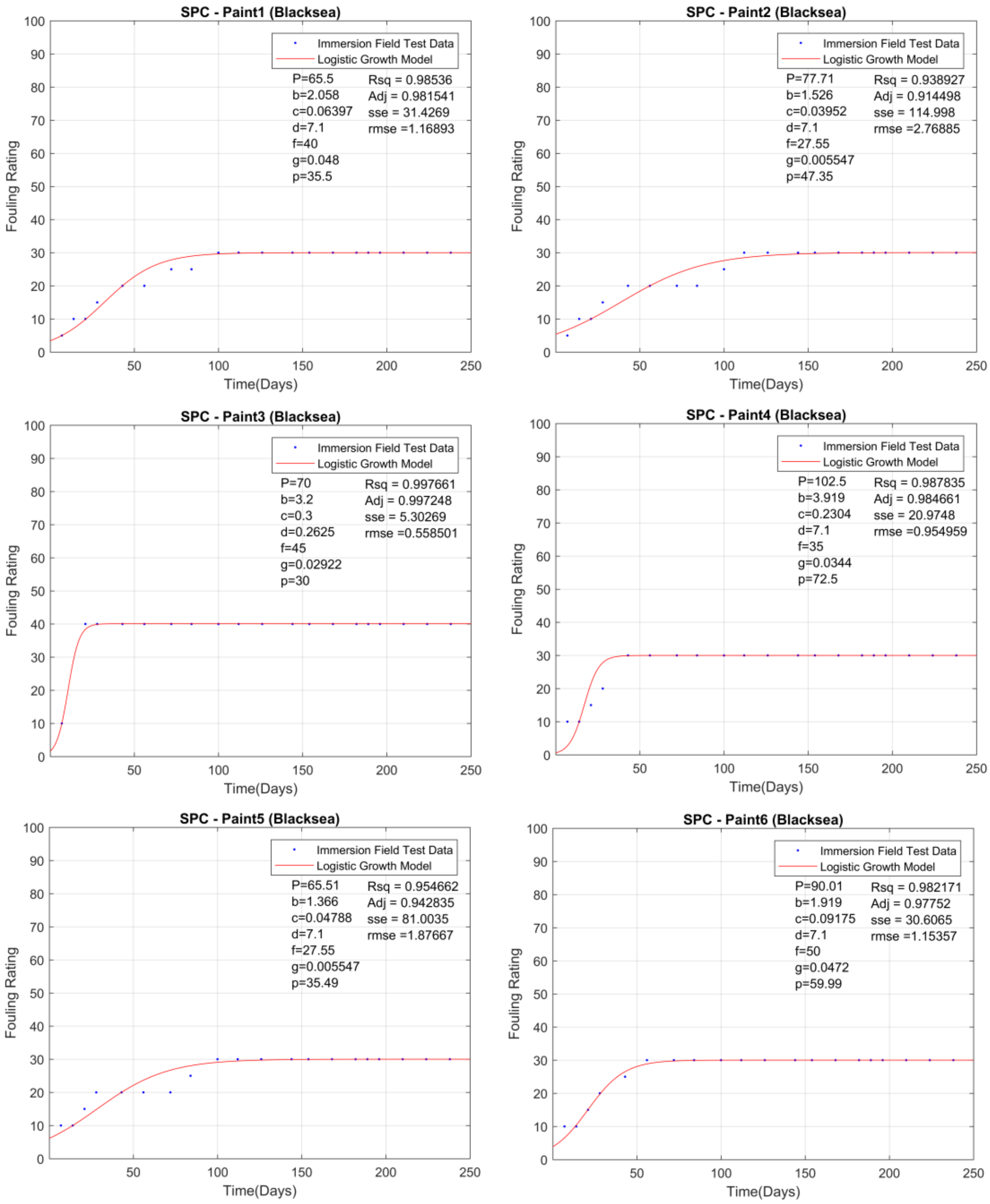


Figure 4-14: Fouling ratings fitted in logistic growth model for SPC coatings for a year

Having limited the fouling period to 250 days, as shown in Figure 4-14, the fouling growth pattern is still similar to the 18 months immersion time vs fouling rating pattern as shown in Figure 4-12, by following the same logistic growth fit. However, Paint 2 shows higher fouling ratings in comparison to 18 months due to the fluctuation and the decrease in fouling ratings as can be seen in Figure 4-12.

4.5.2 Foul Release (FR) Immersion Test Panels

After the preparation of the FR coatings field test setup, the test panels were checked regularly for over a year of the immersion period. Similar to the SPC Immersion test panels, the FR test panel apparatus was taken out of the water as a first step, the panels were skimmed through quickly, photos of each panel were taken, each panel was checked closely with both observation and probing by hand to specify relevant species, measurements were taken when necessary notes were taken, and finally, panels were rated according to the NSTM standards.

4.5.2.1 Fouling Rating Assessment of FR Coatings

For the FR coating immersion test panels, each panel was observed for a year periodically. The first month was divided into four weeks. Following that, biweekly inspections were conducted until the completion of a year of immersion. After completing the whole year, the FR Immersion field test panel was planned to be checked monthly; however, due to unforeseen global pandemic Covid-19, examinations were interrupted, and only one more inspection could be conducted and so that 13 months immersion time in total inspected.

The FR Immersion test panels' accumulation results in the first 4 weeks, and then 3 months, 6 months, 9 months, and 12 months can be seen in Figure 4-15, respectively. That should also be noted that, due to visual and practical convenience, only 10 fouling conditions of each coating are presented in this section and pictures of each examination conducted for the FR immersion test panels over 13 months are presented in Appendix C. In addition to that, fouling ratings of the FR Immersion Test Panels illustrated in Figure 4-15, can be seen in for the each FR coating over time in Appendix E.

Figure 4-15: FR Immersion test panels' accumulation results in the first 4 weeks, and then 3 months, 6 months, 9 months, and 12 months, respectively.

4.5.2.2 Logistic Growth Model Fitting for FR Test Panels and Discussions

The NSTM ratings of the foul release coatings were fitted in the logistic growth model using Equation 30, and the results are presented in Figure 4-16. It should be noted that the logistic growth model constants used in Equation 30 and reflected in Figure 4-16 represent 385 days of fouling conditions. Therefore, the sub-figures in Figure 4-16 are presented to generate a dataset for further studies.

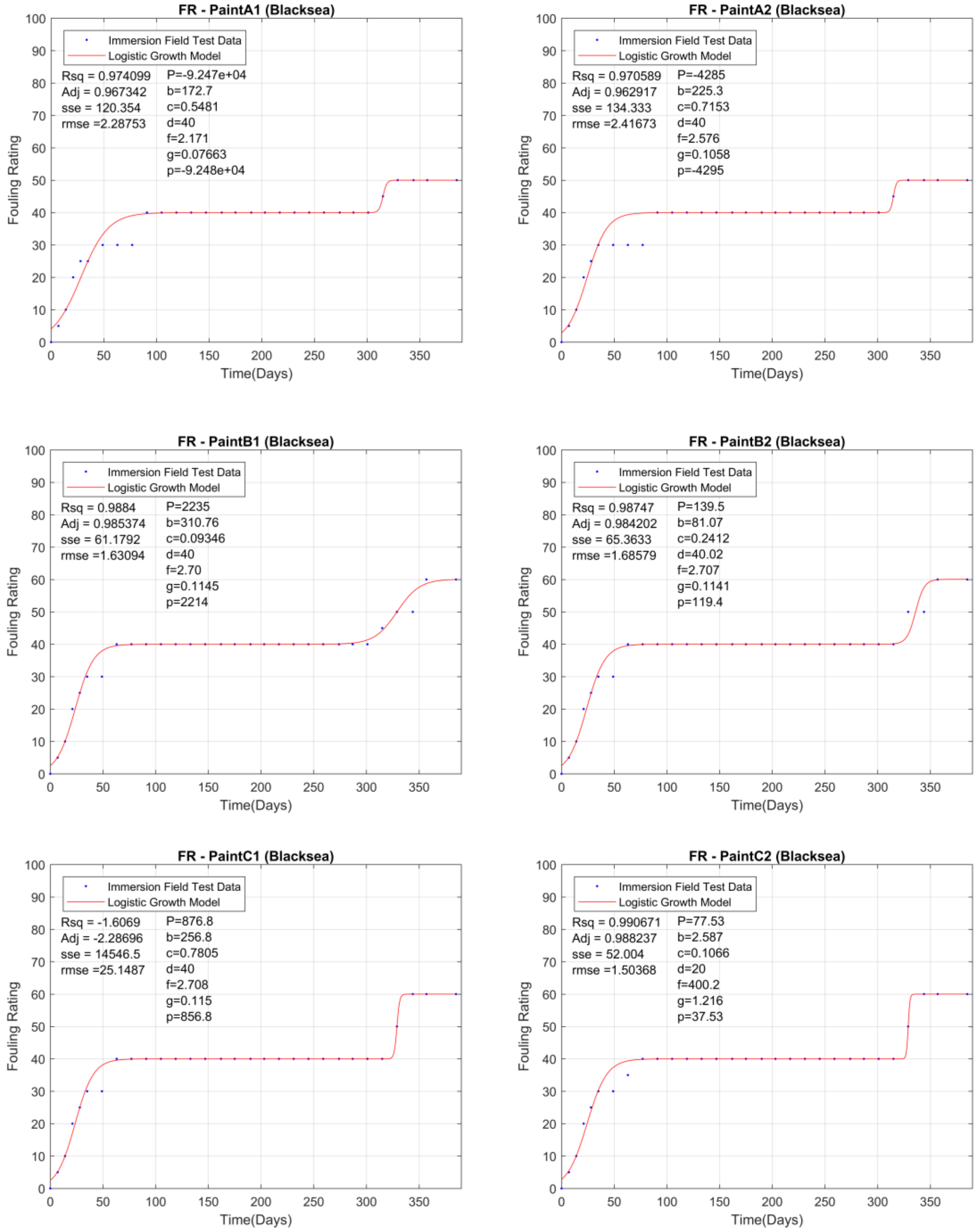


Figure 4-16: Fouling ratings fitted in logistic growth model for FR coatings

From Figure 4-16, it can be seen that after 385 days of immersion in the Black Sea, the maximum fouling rating that Paint A1 and Paint A2 reaches is a fouling rating of 50. The NSTM fouling rating index defines this rating as “Calcareous fouling in the form of barnacles less than ¼ inch (6.4 mm) in diameter or height”. Furthermore, it can be seen that fouling ratings for Paint A1 and Paint A2 reach the fouling rating of 40 approximately after 90 days of immersion. Following that, fouling ratings seem to show no growth (in terms of fouling ratings) until the 300th day. Due to the reason that fouling organisms’ settlement requires a particular time for the ongoing fouling growth process, there might be several reasons behind this period with the fouling rating 40, such as the changes in environmental conditions (waves, light, nutrient, and pH and temperature). After nearly the 300th day of immersion, fouling ratings for Paint A1 and Paint A2 reach to maximum fouling rating of 50.

For Paint B1 and Paint B2, it can be seen from Figure 4-16 that after 385 days of immersion in the Black Sea, the maximum fouling ratings reach to fouling rating of 60. The NSTM fouling rating index defines this rating as a “Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height.” Furthermore, it can be seen that fouling ratings for Paint B1 and Paint B2 reach the fouling rating of 40 approximately after 60 days of immersion. Following that, fouling ratings seem to show no growth (in terms of fouling ratings) until the 275th day. Due to the reason that fouling organisms’ settlement requires a particular time for the ongoing fouling growth process, there might be several reasons behind this period with the fouling rating 40, such as the changes in environmental conditions (waves, light, nutrient, and pH and temperature). After nearly the 300th day of immersion, fouling ratings for Paint B1 and Paint B2 reach to maximum fouling rating of 60.

For Paint C1 and Paint C2, Figure 4-16 reveals that after 385 days of immersion in the Black Sea, the maximum fouling rating reached is fouling rating of 60. The NSTM fouling rating index defines this rating as a “Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height”. Also, it can be noticed that fouling ratings for Paint C1 and Paint C2 reach the fouling rating of 40 approximately after 60 days of immersion. Following that, fouling ratings seem to show no growth (in terms of fouling ratings) until the 325th day. Due to the reason that fouling organisms’ settlement requires a particular time for the ongoing fouling growth process, there might be several reasons behind this period with the fouling rating 40, such as the changes in environmental conditions (waves, light, nutrient, and pH and temperature). After the 325th day of immersion, fouling ratings for Paint C1 and Paint C2 reach to maximum fouling rating of 60.

Overall, looking at the antifouling performances of the three FR type antifouling coatings (Paint A, Paint B, Paint C) over a year, it can be seen from Figure 4-16 that the replica and the original coatings show a good match with each other. A good example can be given for Paint A as such, whilst Paint A1 reaches the fouling rating of 40 after approximately three months of immersion, similar results can also be observed with Paint A2. Furthermore, it can be seen that at the end of approximately a year of immersion, Paint A performs the best antifouling results in terms of fouling ratings. Both Paint A1 and Paint A2 reach to maximum fouling rating of 50. On the other hand, Paint B and Paint C do not show a significant difference among each other, and so that after approximately a year of immersion, it can be seen that Paint B1, Paint B2, Paint C1, and Paint C2 reach the maximum fouling rating of 60 with poorer antifouling performances in comparison to Paint A.

Finally, when the foul release (FR) and self-polishing copolymer (SPC) coatings' antifouling performances are compared in static immersion field tests, in general, SPC coatings show better antifouling performance results in terms of fouling ratings. However, within more details, a better comparison can be made when making the comparison within a certain given immersion time. As the most important period for antifouling coatings are considered to be the first months after the immersion, comparing the first 100 days after immersion would be ideal. Nevertheless, under 100 days of immersion, all FR coatings were tested to reach the fouling rating of 40, which is considered the calcareous initiative fouling. However, looking at the fouling ratings of the SPC coatings after 100 days, it can be seen that none of the SPC coatings goes beyond the fouling rating of 40. This difference is attributed to the toxic biocide components of the SPC coatings that prevent fouler organisms' attachment to the coated surfaces. Within the framework of the performance comparison, it should be borne in mind that the low surface energy-based physical defence mechanism of the

FR coating is different to the chemically-based mechanism of the SPC coatings and hence requiring flow shear force to be caused mainly by the action of the relative water flow (e.g. due to forward speed of a ship, waves, current etc.). In other words, a rational comparison of the FR coating performance with the SPC or other coatings should be made using moving test surfaces, i.e. the coating patches on the hull surface or rotating drums in the test fields etc. that was beyond the scope of this research study due to the practical logistic reasons.

However, it should be noted that although FR coatings show poorer performance than the SPC coatings in the static immersion field, they still show better performance than an uncoated test panel (reference panel). Similarly, looking at the biofouling growth after a year of immersion time, the best FR coating still performs a poorer performance in comparison to the worst SPC coating performance. In other words, whilst the fouling ratings can reach over the fouling rating of 60, SPC coatings' maximum fouling ratings stay at the fouling rating of 30 after a year of immersion time. However, as stated above, this is expected based on the difference in the defence mechanisms of these coatings and the static immersion conditions and hardly present active current and waves action in the test field.

4.5.3 Ship Tests Coating Patches - Fouling Rating Assessment and Discussions

After applying the selected antifouling coatings on the selected fishing vessel as detailed in Section 4.3.2, fouling conditions of each coating was inspected after the fishing vessel completed her fishing activities. More specifically, the test vessel started her activities on 1st September 2018 and completed them on 10th April 2019. In other words, she spent 221 days in her fishing activities and returned to the home port for anchoring. Coated patches on the fishing vessel's hull and fouling growth on the coated patches after a fishing season of fishing activities can be seen in Figure 4-17.

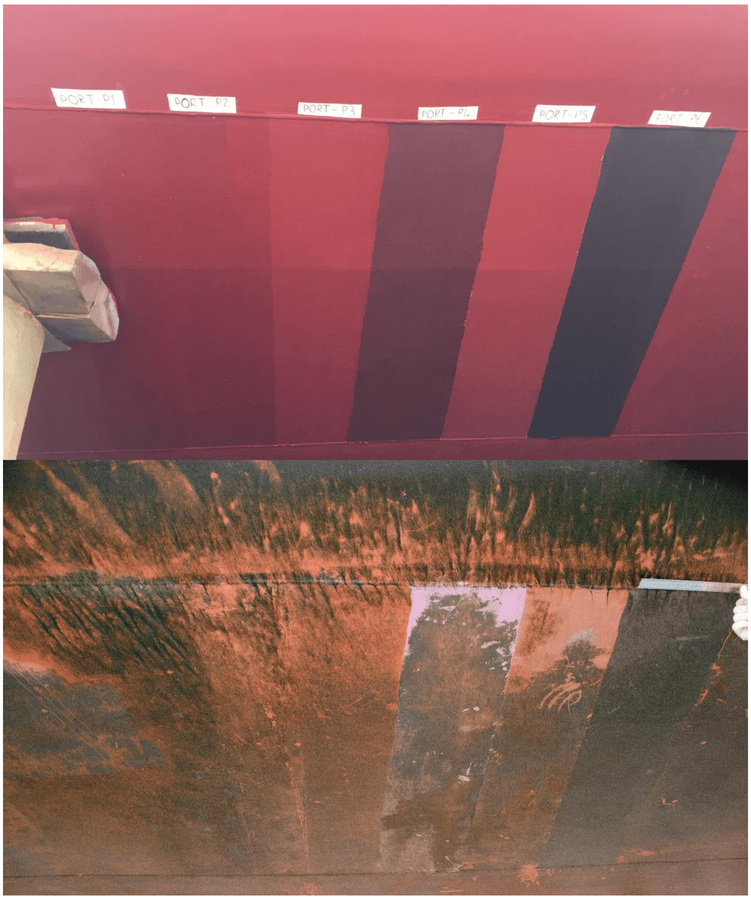


Figure 4-17: Fouling accumulation for the ship test after a fishing year of operation on the selected coatings

It can be seen from Figure 4-17 that fouling conditions on each coating varies among each other. However, examining biofouling growth on each coating on the ship hull in detail, it can be seen that the fouling conditions over antifouling coatings were similar to each other. Nevertheless, fouling accumulation results of the ship test showed that there was no hard fouling on any coated patches.

Furthermore, relevant operational data for the fishing vessel was obtained from the Automatic Identification System (AIS) via marinetraffic.com (MarineTraffic.com, 2020). AIS operational profile data was examined in detail, and results showed that 95 days were spent as idle time during the fishing activities for the test vessel. Within this point, that should be noted that the idle time that the selected fishing vessel spent during her 221 days lasting fishing activities in a fishing year is 95 days, and it is vital to remember. The reason behind this emphasis is to compare the fouling ratings of the ship-test-coating-patches results with the SPC immersion test panel results, which is presented further within this section.

Besides that, because the regional shipyards have long queues for the dry-docking process for the fishing vessels, it is uncertain for a fishing vessel to estimate how long she would be kept waiting for dry-docking in her fishing port. For that reason, the ship test vessel's underwater hull was inspected by two marine biologist divers as soon as the test vessel's fishing activities ended on 10th April 2019. Moreover, divers took photos and skimmed the hull surface with their hands by probing to detect any calcareous fouler organisms and took notes. Four days after the divers conducted underwater hull inspections, the fishing vessel was dry-docked. As soon as she was dry-docked, her underwater hull was further inspected in situ. Figure 4-18 shows the combination of the pictures taken by the divers, video captures of the underwater footage, dry-dock inspection pictures and related SPC immersion test results after 95 days of immersion for the selected antifouling coatings.

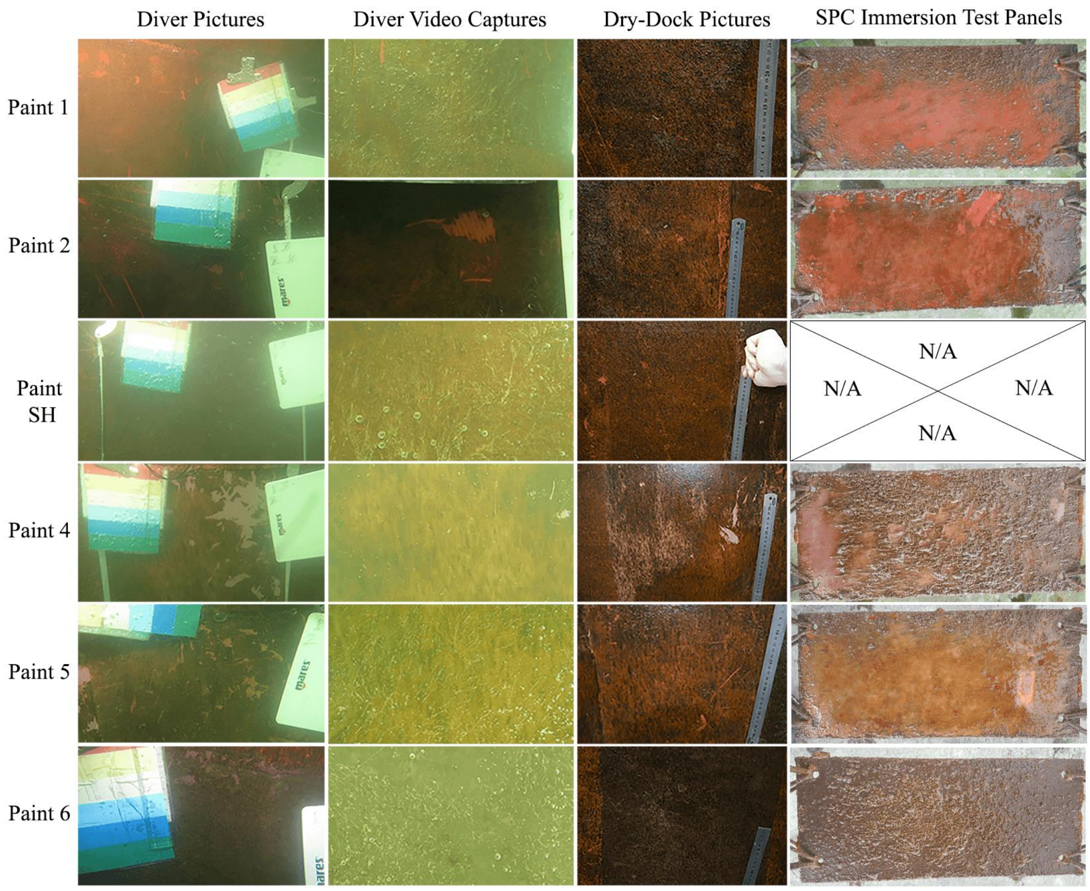


Figure 4-18: Fouling condition pictures taken by divers, video captures of the underwater footage, dry-dock inspection pictures and SPC immersion Test results after 72 days of immersion.

Fouling conditions of the ship-test-coating-patches results and the SPC immersion test panel results for 95 days representing the idle time (as emphasised before in this section) are compared and presented in Figure 4-18.

Following the diver and dry-dock inspections, the coating patches applied on the fishing vessel for the ship tests were rated according to the NSTM standards. Fouling rating comparisons of the ship-test-coating-patches results (after 221 days of fishing activities) and related SPC immersion test panel results for 95 days can be seen in Table 4-8.

Table 4-8: Idle Time accumulation results for Ship Test Fishing Vessel's NSTM fouling ratings in comparison with the Immersion Test accumulation results NSTM fouling ratings

	SPC Immersion Test NSTM Ratings	**Ship-Test-Coating-Patches NSTM Ratings**
Paint 1	25	20
Paint 2	20	15
Paint SH	N/A	10
Paint 4	30	20
Paint 5	25	15
Paint 6	30	20

From Table 4-8, it can be seen that there are insignificant differences between the immersion test and ship-test-coating-patches' fouling ratings. Furthermore, ship test results showed that the most effective antifouling coating is Paint SH with a fouling rating of 10. Following that, Paint 2 and Paint 5 performed the second most effective antifouling coatings with a fouling rating of 15. The worst antifouling coating performances were performed by Paint 6, Paint 4 and Paint 1 with a fouling rating of 20. In addition, the comparative results suggest that the coating patches applied on the hull surface of the test vessel have relatively lower fouling rates compared to the SPC immersion test Panel's assessment results as expected and discussed in the following.

As explained before in this chapter, immersion tests were conducted under stationary conditions in a natural marine environment. Therefore, an assumption was made as no other factor than environmental conditions (waves, salinity, light, nutrient, pH and temperature) influence biofouling growth on the panels coated with the selected antifouling coatings for the immersion tests. On the other hand, considering a fishing vessel's activities after a fishing year (221 days in this situation), many factors might affect the fouling growth, such as the total operation time, idle time spent in the total operation time, and most importantly the dynamic forward speed action and hence the flow shear action of the fishing vessel during her operations, and frequency of the change in ship speed.

Therefore, considering the environmental conditions are the same for both the SPC immersion panel and the ship tests conducted in this PhD research, the vessel's operational profile and operational activities play an important role in biofouling growth. Thus, it is predictable to assume why coating patches applied on the hull surface of the test vessel have lower fouling rates in comparison to SPC immersion test Panel's assessment results, as shown in Table 4-8. In other words, the reason behind fouling rating differences between the field and ship tests in this study is due to operational activities that the ship test had. This assumption can also be supported from the literature, e.g. by Radu et al. (2012), who also emphasised the increased fouling prevention effect of the vessel's operational speed and further removal of fouling accumulation.

Nonetheless, predicting the aforementioned fouling-rating differences for any ship based on examining immersion test panels is required to be calculated separately for each antifouling coating and each ship. Therefore it is impractical to generalise estimating the lower fouling ratings of the ship tests when comparing with the related immersion test panel assessment results. Furthermore, it is accepted that the ship test fouling rating results cross-validated the SPC immersion test panel assessment results due to having similar fouling ratings. Hence, SPC immersion test panel assessment results are employed in Uzun et al. (2019)'s time-dependent fouling growth model as the worst-case scenario. Thus, fouling ratings of determined antifouling coatings on selected fishing vessels are predicted over time. Further details of Uzun et al. (2019)'s time-dependent fouling growth model is briefly explained in Section 5.2.

4.6 Field Test Data Generation for the Mediterranean Sea

In order to implement the immersion test panels' data into Uzun et al. (2019)'s time-dependant biofouling growth model, two immersion test data from different locations of a particular SPC antifouling coating is required. Furthermore, for the reason that the only available data is in the Black Sea region (Section 4.5.1), another immersion test panels data generation is required for a different region. Therefore, once the relevant field test data is obtained from the Black Sea region, a similar data could be generated for the Mediterranean Sea using SST as an extrapolation parameter to present the fouling growth characteristics of the same coatings tested in the Black Sea. For this purpose, fouling rating curves of a particular SPC antifouling coating from the Mediterranean (~20^{o}C) and the Equatorial (~30^{o}C) regions are taken into consideration from Uzun et al. (2019). Later, the difference between the fouling rating curves due to SST are analysed and the percentage of the change per ^{o}C is calculated. It is assumed that this percentage of change per ^{o}C is accepted as the same for any SPC type antifouling coating. Based on this assumption, fouling rating curves of the determined coatings are generated for the Mediterranean Sea by taking the test data obtained in the Black Sea region as a reference point. Further details are given as in the following paragraphs.

According to Uzun et al. (2019), the time-dependent prediction of the calcareous fouling growth was made with the help of the logistic growth model function given by Equation 30. Therefore, after examining the two immersion field test panels' assessment results data of a particular SPC type antifouling coating from Uzun et al. (2019), logistic growth model constants of the immersion test panels are calculated for Equatorial and Mediterranean regions. It is important to underline that two immersion tests were conducted for the same SPC antifouling coating in Uzun et al. (2019)'s study, one conducted in the Mediterranean region and the other in the Equatorial region. Logistic growth model constants of the particular SPC type antifouling coating for the Mediterranean and the Equatorial regions from Uzun et al. (2019)'s study are displayed in Table 4-9.

Table 4-9: Logistic growth model constants of the SPC antifouling coating from Uzun et al. (2019)

Mediterranean	Equatorial
$P_{Mediterranean}$ =-3.8.25	$P_{Equatorial}$=95.59
$b_{Mediterranean}$ =6.145	$b_{Equatorial}$=23.27
$c_{Mediterranean}$ =0.02872	$c_{Equatorial}$=-0.2954
$d_{Mediterranean}$ =-3.105	$d_{Equatorial}$=70
$f_{Mediterranean}$ =3.012	$f_{Equatorial}$=2.817
$g_{Mediterranean}$ =-0.01065	$g_{Equatorial}$=0.03517
$p_{Mediterranean}$ =-73.83	$p_{Equatorial}$=4.411

After examining the logistic growth model constants in Table 4-9, it was figured out that when one of the constants (b or f) is changed, the S curve in the logistic growth model fit could be shifted. Therefore, one specific constant for each immersion test panel can be attributed to the responsibility for the biofouling growth constant. Furthermore, after examining the logistic growth model constants data from Table 4-9, constant "$f_{Equatorial}$" is determined as the biofouling growth constant for the Equatorial region, whilst constant "$b_{Mediterranean}$" is determined as the biofouling growth constant for the Mediterranean region. Within this point, that should be noted that the biofouling growth constant for any SPC immersion test panel's assessment results has to be determined separately. In other words, the biofouling growth constant might vary for every immersion test panel's assessment conducted.

Therefore, when the immersion tests for a determined SPC antifouling coating are conducted in more than one location, it is possible to correlate the biofouling growth constants of the relevant immersion test panels. Moreover, once the relevant logistic growth model constants and the biofouling growth constants are determined for any SPC immersion test panels, it is possible to estimate the biofouling growth of the same SPC antifouling coating for a randomly selected geographical location. These can be done with the help of sea surface temperature (SST) changes (and so latitude degree changes) of which the immersion test panels are immersed.

As a result, an extrapolation was made to generate a new data set for the Mediterranean Sea of the particular antifouling coatings immersed in the Black Sea region. This extrapolation is described in the following nine steps.

i. SPC immersion test panels' assessment results data is fitted in the logistic growth model curves for each SPC antifouling coating immersed in the Black Sea, as presented in Section 4.5.1. This is done by using the logistic growth model function given in Equation 30.
ii. The logistic growth model constants for the Black Sea immersion test panels are determined and presented in Figure 4-14.
iii. The biofouling growth constants for each SPC antifouling coating is obtained from the logistic growth model constants of the Black Sea immersion field test data. At this point, it should be noted that the biofouling growth constant for the SPC immersion test panels conducted in the Black Sea region is determined as constant "b" for the Black Sea.
iv. Logistic growth model constants of the particular SPC antifouling coating used in Uzun et al. (2019)'s study are taken into consideration in the following steps:
v. The difference between SSTs where the immersion tests were conducted is determined (for the Mediterranean and the Equatorial regions).
vi. The change among biofouling growth constants of different geographical locations is determined from Uzun et al. (2019)'s immersion test panels' geographical differences. That should be noted that the geographical changes are taken into consideration in terms of the latitude (degrees), and the longitude changes were neglected. The reason behind this is the assumption that the SST differences are relatively smaller compared to those in latitude, as stated in Bijl et al. (2009).
vii. Biofouling growth constants' change per ^{o}C in SST is calculated by using linear interpolation method. To elaborate on this, as aforementioned before, constant "$b_{Mediterranean}$" and constant "$f_{Equatorial}$" were determined as the biofouling growth constants for the SPC antifouling coating used in Uzun et al. (2019)'s study. The difference between these two constants ($b_{Mediterranean}$ and $f_{Equatorial}$) divided by SST difference (for where the SPC immersion tests are conducted) represents the biofouling growth constant change per ^{o}C in SST for the

particular SPC antifouling coating used in Uzun et al. (2019)'s study. The formulation of this step can be seen as in Equation 31.

$$\Delta bgc = \frac{|\, b_{Mediterranean} - f_{Equatorial} \,|}{|\, SST_{Mediterranean} - SST_{Equatorial} \,|} \tag{31}$$

where Δbgc is the biofouling growth constant change for a ^{o}C change in SST, $b_{Mediterranean}$ and $f_{Equatorial}$ are the biofouling growth constants of the places where the immersion test panels are conducted for the particular SPC antifouling coating, and $SST_{Mediterranean}$ and $SST_{Equatorial}$ are the sea surface temperatures of the test immersion location of Mediterranean and the Equatorial regions where the immersion tests are conducted, respectively.

viii. Next, Δbgc's % increase according to the desired reference immersion test location (in terms of biofouling growth constant) is calculated. For the reason that the new immersion test data generation is required for the Mediterranean Sea in this PhD thesis, $b_{Mediterranean}$ is taken as a reference. Therefore, when $b_{Mediterranean}$ is divided by $\Delta bgpc$, the % increase in the $b_{Mediterranean}$ per ^{o}C in SST is calculated. Therefore, when taking the immersion test panel conducted in the Mediterranean Sea from Uzun et al. (2019)'s study as a reference, formulation of this step can be seen as in Equation 32.

$$\%\Delta bgc = \frac{\Delta bgc \; x \; 100}{|b_{Mediterranean}|} \tag{32}$$

ix. The % increase in biofouling growth constant for a ^{o}C change in SST ($\%\Delta bgc$) is extrapolated for the immersion test panels' assessment results (as presented in Section 4.5.1) to generate the logistic growth model constants of the same antifouling coatings in the Mediterranean Sea with the help of immersion test panel conducted in the Black Sea.

Following the nine steps described above, immersion test panels' assessment results for the Black Sea were obtained, and $\%\Delta bgc$ was used to generate logistic growth model constants for the Mediterranean Sea of the antifouling coatings immersed in the Blacksea as detailed in Section 4.3.1.1. What is more, $\%\Delta bgc$ was taken as a reference with an assumption that any SPC type antifouling coating would show the same percentage change per ^{o}C in SST (in terms of biofouling growth constant). Therefore, logistic growth model constants were taken from Figure 4-14. Within this point, it is important to remember that the biofouling growth constant was determined as constant "b" for the Black Sea.

There is no performance data for each antifouling coating used in the field tests in different locations, and yet it is difficult to make an assumption for the antifouling performance of antifouling coatings in general. For that reason, following the determination of the biofouling growth constant changes against SST difference from Uzun et al. (2019), a further assumption has to be made for all SPC antifouling coatings in general. Therefore, calculated $\%\Delta bgc$ was taken as a reference with an assumption that any SPC type antifouling coating would show the same % change per ^{o}C change in SST (in terms of biofouling growth constant). In other words, the biofouling growth constant difference for a ^{o}C in SST of Uzun et al. (2019)'s SPC coating is accepted to be the same for the SPC coatings which are used in the SPC immersion tests conducted in the Black Sea in this PhD thesis. After that, latitude degree differences were found between the Black Sea and the Mediterranean immersion test locations. Next, $\%\Delta bgc$ extrapolated for the Black Sea immersion test panels. As a result, logistic growth model constants are taken from Figure 4-14, logistic growth model constants of Mediterranean is generated and presented in Table 4-10.

Table 4-10: Logistic growth model constants for the Black Sea and the Mediterranean (Generated)

	Black Sea						
	P	b	c	d	f	g	p
Paint 1	65.5	2.058	0.06397	7.1	40	0.048	35.5
Paint 2	77.71	1.526	0.03952	7.1	27.55	0.005547	47.35
Paint 3	70	3.2	0.3	0.2625	45	0.02922	30
Paint 4	102.5	3.919	0.2304	7.1	35	0.0344	72.5
Paint 5	65.51	1.366	0.04788	7.1	27.55	0.005547	35.49
Paint 6	90.01	1.919	0.09175	7.1	50	0.0472	59.99

	Mediterranean Sea (Generated)						
	P	b	c	d	f	g	p
Paint 1	65.5	1.612	0.06397	7.1	40	0.048	35.5
Paint 2	77.71	1.195	0.03952	7.1	27.55	0.005547	47.35
Paint 3	70	2.507	0.3	0.2625	45	0.02922	30
Paint 4	102.5	3.070	0.2304	7.1	35	0.0344	72.5
Paint 5	65.51	1.070	0.04788	7.1	27.55	0.005547	35.49
Paint 6	90.01	1.503	0.09175	7.1	50	0.0472	59.99

As it can be seen from Table 4-10, the only difference between the Black Sea and the generated Mediterranean Sea logistic growth model constants are in the constant "b" column for both regions. This difference is due to the fact that the biofouling growth constant is taken into consideration when generating the Mediterranean logistic growth constants. These logistic growth model constants for the Black Sea and the Mediterranean Sea were fitted in the logistic growth model curves. Nevertheless, the difference between the immersion field test data fitted in the logistic growth model by using Equation 30 for the Black Sea and the Mediterranean Sea can be seen in Figure 4-19.

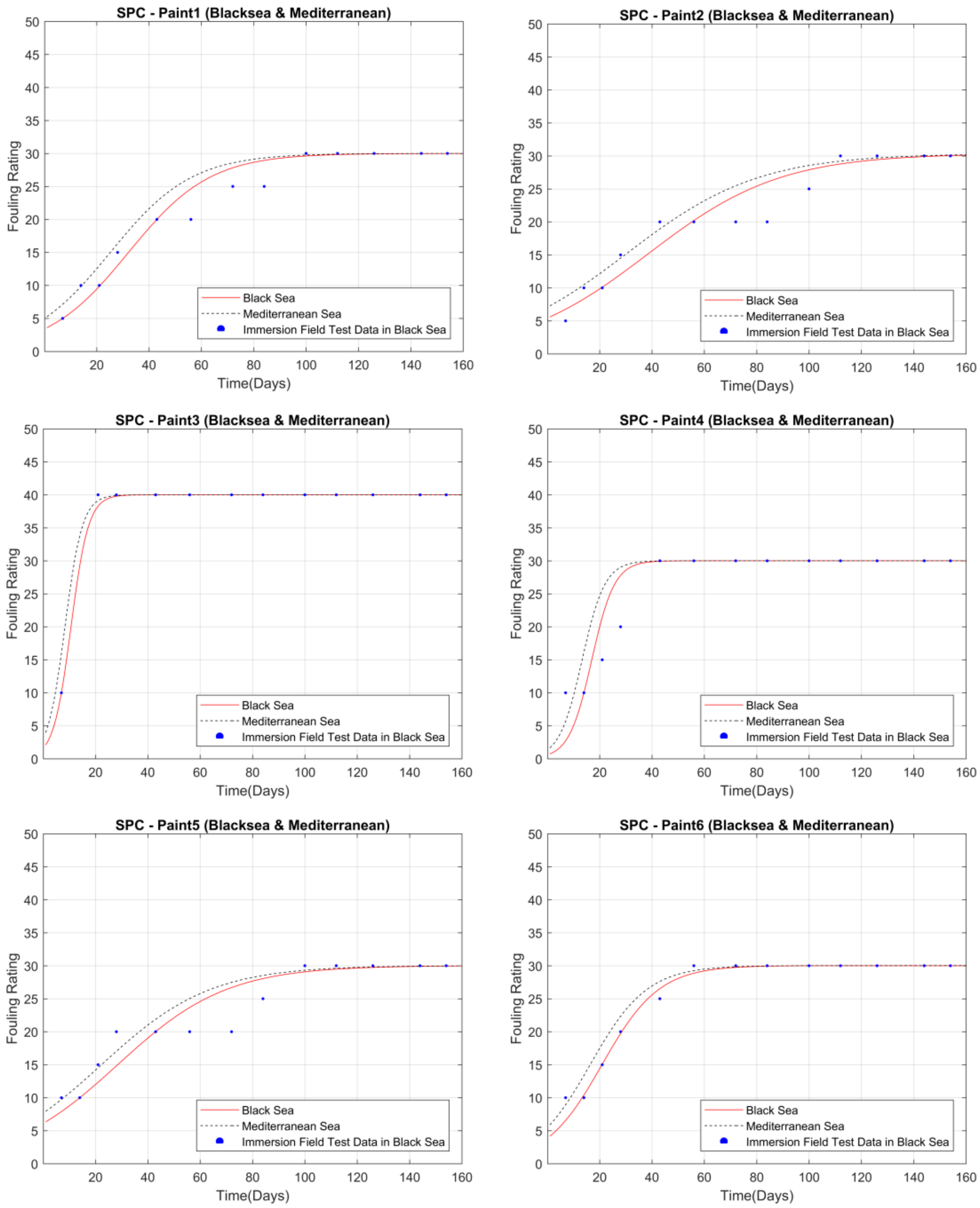


Figure 4-19: Logistic growth curves for the Mediterranean and the Black Sea for a year

As explained in the literature review chapter in this thesis, SST is the dominant factor influencing biofouling growth. Moreover, as can be seen from Figure 4-19, the difference between the Black Sea and the Mediterranean Sea is not vastly different from each other. Yet, it can be seen that the fouling growth in the Mediterranean Sea is faster in comparison with the Black Sea immersion field test data fitted in the logistic growth model. The reason behind this gap is due to the geographical location and so the SST differences. Because the SST change is only four ^{o}C between each location, the SST does not significantly change, and this change reflects the fouling ratings' change.

4.7 Chapter Summary and Conclusions

This chapter presented the design, data collection, and analysis of the field tests using the static immersion test panels and coated patches on a fishing vessel with different types of antifouling paints. First, a brief description of the immersion test tools is presented for the self-polishing copolymer (SPC) and foul release (FR) type coatings. In the next, ship tests patched are presented in detail. Following these, the rating system and the standards for the surface conditions of the test panels and hull surface test patches are discussed. The fouling accumulation results for the SPC and FR applications are presented and compared according to the US Navy's Naval Ship's Technical Manual (NSTM). The justification of the field tests and ship tests is discussed towards the end of the chapter, followed by the main conclusions obtained from this chapter as in the following.

The SPC immersion test panels' assessment results show that fouling ratings of the coated panels vary from fouling rating of 30 to 40 after 18 months of immersion. However, it was also noticed that the fouling rating of the reference panel could be as high as 70. Considering the SPC antifouling coating results and the reference panel results, these fouling rating differences show the efficacy of the SPC antifouling coatings. Furthermore, when a comparison is made among the SPC antifouling coatings, it can be seen that the maximum fouling rating that they reach is similar to each other. However, examining the time that the maximum fouling rating is reached, the differences become more visible. Among the antifouling coatings tested in the SPC immersion test panels, Paint 2's antifouling performance was the best, and Paint 4's antifouling performance was the worst in terms of fighting biofouling. Overall, based on the SPC field test results, a ranking can be made from the best to worst antifouling performance in the following descending order; Paint 2, Paint 1 and Paint 5, Paint 6, Paint 4, and Paint 3 (reference panel).

Another finding that should be noted is that SPC immersion test panels' assessment results show that locally available antifouling coatings show better performance than those internationally available. Furthermore, a comment might be that the larger antifouling coating companies still have a lot to learn from the local companies. Therefore, a further collaboration between locally and internationally available antifouling coating manufacturer companies might not only help with the fight against biofouling but would also improve the energy efficiency of the fleet in concern globally.

Also, the biocide contents of the coatings used in the SPC immersion test panels are examined. SPC immersion test panels' assessment results show that Di and CY biocides are more successful when fighting biofouling than ZP and CP biocides.

Foul release immersion test panels' assessment results show that fouling ratings of the panels coated with foul release coatings reach from fouling rating of 50 to fouling rating 60 after a year of immersion. Another critical point learnt from the FR immersion test panels' assessment results is that all foul release antifouling coatings reach a fouling rating of 40 (initial calcareous fouling) under 100 days. Nevertheless, Paint A performs the best antifouling performance among the foul release antifouling coatings with a fouling rating of 50. Furthermore, when a comparison is made between the SPC and the FR immersion test panels, it can be seen that SPC coatings perform better in terms of fouling ratings. To be more specific, the worst SPC antifouling coatings performance is better than the best performing foul release coatings considering the same immersion time. These performance comparison results are attributed to the antifouling coatings' working mechanisms between the SPC and FR coatings. However, one should be born in mind that the low surface energy-based physical defence mechanism of the FR coating is different to the chemically-based mechanism of the SPC coatings and hence requires flow shear force to be caused mainly by the action of the relative water flow (e.g. due to forward speed of a ship, waves, current etc.). In other words, a rational comparison of the FR coating performance with the SPC or other coatings should be made using moving test surfaces, i.e. the coating patches on the hull surface or rotating drums in the test fields etc. that was beyond the scope of this research study due to the practical logistic reasons, and should be considered as future work

Ship test results show no calcareous fouling growth after a fishing year of operation (221 days) on the selected SPC coatings applied on the fishing vessel. Furthermore, examining the ship test results fouling ratings, the maximum fouling rating is 20, and the minimum fouling rating is 10. Furthermore, when the ship test results are compared with SPC immersion test panels’ assessment results under the same equivalent idle time spent for the ship test vessel (95 days), the fouling ratings of the SPC immersion test panels’ rating results appeared to be insignificantly lower in comparison to SPC immersion test panels’ fouling ratings. Lower fouling ratings are attributed to the ship’s operational profile, velocity changes over the ship hull, currents, and waves.

After obtaining the relevant fouling ratings of the SPC and FR coatings, the immersion test panels’ assessment results are fitted into the logistic growth model. Logistic growth model constants were extrapolated and then interpolated to generate the Mediterranean Sea's relevant immersion field test data. For this purpose, relevant antifouling coatings’ immersion test panels data is used from the literature. That should be noted that because there is no data available for the foul release coatings’ immersion test panels data in a different region, FR immersion test panels’ assessment results could not be extrapolated and so generated for the Mediterranean Sea. After generating the logistic growth constants of the antifouling coatings used in the SPC immersion test, logistic growth model constants were presented. As expected, comparison results showed that biofouling accumulation is faster in the Mediterranean Sea than in the Black Sea.

5 Case Studies

5.1 Chapter Introduction

This chapter introduces case studies, and the results are presented and discussed. Firstly, Uzun (2019)'s time-based biofouling method is described in detail, and then, the details of added resistance data using the approach in Demirel et al. (2019) is provided. Next, selected fishing vessels for the case studies and their operational characteristics are presented, followed by the calculations of added resistance due to biofouling and an increase in effective power for the fishing vessels operating in different fishing zones.

Before detailing each step for the case studies, links between each step should be briefly described. Therefore, starting from the survey conducted with the fishermen, the most common antifouling coatings are determined among the industrial fishing vessels. Then, selected antifouling coatings were coated on panels and then deployed in a natural sea environment. Fouling growth over panels was periodically observed over a year. Next, biofouling accumulation on each antifouling coating was rated using the NSTM fouling rating index. After determining the NSTM fouling ratings over time, fishing vessels to be used in the case studies were selected, and the relevant operational profiles were obtained using AIS. Uzun (2019)'s time-dependent biofouling growth model is used to employ the fouling growths over time of each antifouling coating in the selected fishing vessels' operational profile. However, the time-dependent biofouling growth model inputs require antifouling coatings' field tests at least in two locations.

For that reason, with the antifouling coatings deployed in the Black Sea region, similar data was required to be generated using a similar field test data of an SPC antifouling coating from the literature. Therefore, a similar data was generated by extrapolating and interpolating relevant fouling growth datasets for the Mediterranean Sea. After that, biofouling growth over time for specific antifouling coatings was employed in Uzun (2019)'s time-dependent model and fouling ratings for the fishing vessels over time, considering the operational profiles, was obtained with the NSTM ratings. After that, a correlation was made using Schultz (2007)'s equivalent sand roughness height and NSTM rating conversion table, as shown in Table 4-7. Moreover, k_s values over time were obtained for each fishing vessel using this correlation shown in Equation 33.

Following that, ΔC_F values were obtained using Figure 2-15. Once the ΔC_F values are obtained, $\%\Delta P_E$ values over time was calculated using Equation 12. Furthermore, once the effective power and brake horsepower are calculated, fuel consumption is calculated using the engine's SFOC. An assumption is made as; the % increase in P_E is accepted the same with % increase in fuel consumption, and so that impact of biofouling on fuel consumption is calculated. Details of each step for the case studies are detailed in the following sections (Section 5.2, Section 5.3, and Section 5.4).

5.2 Time-Dependent Biofouling Model

Uzun (2019) conducted an extensive and systematic experimental study by using 3D printed barnacles to investigate the impacts of biofouling on ship resistance and powering. In his study, he attached the most common barnacle species to flat plates for towing tank experiments at Kelvin Hydrodynamics Laboratory in the University of Strathclyde. After determining the drag characteristics and roughness functions of the different fouling configurations with the help of towing tank tests, full-scale extrapolations were performed. More specifically, once the roughness functions were obtained from both the experiments and the literature, full-scale ship resistance calculations were calculated using Granville's similarity law scaling.

Moreover, in his research, Uzun (2019) developed a simplified time-dependent model to predict the biofouling growth on ship hulls as a decision support tool. Furthermore, among the factors affecting biofouling growth, Uzun (2019) took sea surface temperature into consideration as the primary factor and therefore built his model depending on the sea surface temperature differences between the antifouling field test locations. With the help of antifouling field tests data, he developed a model to predict biofouling growth in time (fouling ratings over time) as a first step. Following that, ship operation data, ship route and antifouling coating tests data (converted to equivalent sand roughness heights later) were deployed in the model. Within this point, that should be noted that he assigned idle times from the operation profile of the ship to the time parameter of the growth prediction model from antifouling field test data. After having fouling ratings over time, these fouling ratings were converted to the equivalent sand roughness heights with the help of roughness data from the literature and the experiments he conducted. After that, predicted equivalent sand roughness heights were used to predict the increase in the full-scale ship frictional resistance and powering with the help of Granville's similarity law scaling process. After predicting the increase in ship frictional resistance and powering, he validated his model using an operational and ship performance data supplied by a ship performance analysis company. Finally his predictions and the company's real-world operation data showed a good agreement with each other which makes the model confidential.

For that reason, the time-based biofouling model, developed by Uzun (2019), was modified to predict fouling accumulation for the selected fishing vessels for a fishing season. To do that, k_s values from the field tests from the Black Sea and generated k_s values for the Mediterranean Sea were used as inputs for the model. Following the determination of the cases, operation profiles of the relevant fishing vessels were obtained via AIS system from marinetraffic.com (MarineTraffic.com, 2020). From the operation profiles of the selected fishing vessels, ship speed, idle times, and cruising times were determined and used as inputs into the time-based biofouling model. As a result, the equivalent roughness heights of biofouling accumulated over time on the selected antifouling coatings for the fishing vessels in the case studies were determined. This procedure was followed by added frictional resistance calculations depending on the generated data in the following section.

5.3 Ship Speed, Ship Length, Roughness Height and ΔC_F Correlation

After determining the fouling conditions of each coating for the selected fishing vessels, relevant ks values were generated. Furthermore, the data provided by Schultz (2007), as shown in Table 4-7, was also used. To correlate the values between the fouling ratings and the equivalent sand roughness heights, the fouling rating results of the selected antifouling coatings were taken into consideration from the field test results for fishing vessel 1. Furthermore, it was observed that the maximum fouling ratings of the coatings tested in the field tests did not go beyond the fouling rating of 40, which corresponds to small calcareous fouling accumulation in the definition. If Table 4-7 is examined, it can be seen that the fouling rating of the 40 equals the value of 1000 as k_s values. For that reason, NSTM ratings from 0 to 40, and k_s values from 30 to 1000 were taken into consideration from Table 4-7 to correlate the NSTM ratings and k_s values.

If the values used in Table 4-7 are studied, it could be seen that whilst there is an increase in both NSTM ratings and equivalent sand roughness height values, Schultz (2007) stated that fouling rating 10 and fouling rating 20 have the same k_s value as 100 as shown in Table 4-7. For that reason, a regression curve was fitted to calculate the equivalent sand roughness heights for the NSTM fouling rating values. However, the fitted model behaves as if there is a decrease in equivalent sand roughness height after reaching 100 μm which is the k_s value of fouling rating 10 and fouling rating 20. For that reason, a correction was made to the NSTM rating and k_s regression. The decrease mentioned above in the k_s value was fixed to 100 μm when the fouling rating is between 7.98 and 20.3. After the correlation of the NSTM ratings and k_s values, the following Equation 33 was obtained and used to convert NSTM fouling ratings to equivalent sand roughness values based on the Table provided by Schultz (2007).

$$k_s = \begin{cases} 0.0487\,(FR)^3 - 1.9029\,(FR)^2 + 22.752\,(FR) + 14.892, & 0 \leq FR < 7.98 \\ 100, & 7.98 \leq FR < 20.3 \\ 0.0487\,(FR)^3 - 1.9029\,(FR)^2 + 22.752\,(FR) + 14.892, & 20.3 \leq FR \leq 40 \end{cases} \quad (33)$$

Once the ΔC_F values are obtained, $\%\Delta PE$ can be calculated. For that reason, an in-house code was developed to obtain the relevant ΔC_F values for the selected fishing vessels used in the case studies later in this chapter.

Demirel et al. (2019) developed an in-house code to predict the increase in frictional resistance coefficients (ΔC_F) based on Granville (1958)'s boundary layer similarity law analysis. As a result of this study, added resistance diagrams of ships of certain lengths against ship speeds at different fouling conditions were plotted and presented.

Furthermore, these diagrams from Demirel et al. (2019) were used to extract data points using MATLAB's GRABIT addon to generate a database to be used in the case studies in this thesis. In other words, data points for the ship speed (m/s), ship length (m), fouling conditions and ΔC_F values from the plots were determined by reverse engineering approach. Following that, fouling conditions obtained from the plots were converted into equivalent sand roughness height (k_s) values using Table 4-7. Thus, speed and ΔC_F correlations of fishing vessels of certain lengths at different k_s values were obtained by using diagrams. At this point, an example should be given to understand better the data generated. For example, the generated data provide a ΔC_F value of 4.25 x 10^{-4} under 30 μm equivalent roughness height condition for a 20 m length vessel cruising at 24 m/s speed.

However, considering the generated data points, there are significant gaps between roughness height (k_s) values. For example, there are not any data points between 300 and 1000 for the k_s values. For that reason, once the in-house code predicts k_s values between these ranges, an extrapolation or an interpolation should be conducted. In other words, since the aim is to evaluate biofouling accumulation in time, desired k_s values should be generated. As a result, ΔC_F values for in-between k_s values, which do not exist in Demirel et al. (2019)'s plots, were correlated using the data generated from the plots. In addition, a similar gap between the ship lengths can be seen from the data points. For instance, whilst there are ΔC_F values of ships cruising at certain speeds under certain k_s values for 20 m and 30 m ship lengths, there are no data points for ΔC_F of a 25 m ship under the same speed and k_s conditions. For that reason, ship lengths were interpolated to get ΔC_F values for the desired ship lengths cruising at a desired speed and k_s values.

5.4 Fuel Consumption, Fuel Costs and CO_2 Emissions

There are many factors affecting the fuel consumption of an industrial fishing vessel, such as weather conditions, operational profile, engine characteristics, fuel type etc. However, there is no such data available for the selected fishing vessels used in the case studies. For that reason, several steps were followed to calculate the fuel consumption for the fishing vessels in the case studies. Once the effective power of the relevant ship is calculated at the design speed for the calm water, propulsive efficiencies are taken into account to reach the brake horsepower as further detailed in Section 5.4. That should be noted that, propulsive efficiency (η_p) of the power plants of the fishing vessels used in the case studies are taken as 0.7 from the literature. Following that, estimated service allowance is taken into account. According to Kristensen and Lützen (2012), Harvald suggested the service allowance for Europe – Eastern Asia is roughly between 20 -25%, and these allowances can be used as guidance. Therefore, the service allowance for the fishing vessels operating in the Mediterranean and the Black Sea is accepted as 25%. Brake horsepower (kW) with the service allowance can be calculated using Equation 34.

$$P_{B_{service}} = \left({R_T V}/{\eta_p}\right)\ (1 + \frac{service\ allowance\ \%}{100}) \tag{34}$$

Where, $P_{B_{service}}$ is brake horsepower with service allowance, R_T is total resistance, V is ship speed, and η_p the propulsive efficiency. Following the brake horsepower calculation, the relevant fishing vessels' main engine fuel oil consumption (MEFC) values (l/h) at design speed was obtained as a next step. Main engine fuel oil consumption (l/h) values were obtained from the engine data sheets of the main engine used in the fishing vessels. The main engine used in the case studies was FPT IVECO Cursor 13 C13 825 E. Further details of the engine can be found on the engine's website (FPT IVECO, 2021). Furthermore, the AIS data was used to obtain the fishing vessel's operational profile. Next, brake horsepower with the service allowance, MEFC values (l/h) and cruising time of the fishing vessel were multiplied to calculate the fuel oil consumption at a given time.

Furthermore, to estimate the impacts of biofouling on the fuel consumption of the fishing vessels used in the case studies, an assumption was made as fuel consumption is directly linked to the % increase in effective power. In other words, the % increase in effective power due to biofouling is assumed to be the % increase in fuel consumption. Therefore once the fuel oil consumption is calculated, the increase in the fuel consumption due to biofouling is taken into consideration by increasing the fuel oil consumption with the % increase in effective power. Finally, CO_2 emissions in an operational year were calculated as detailed in Section 2.7 to illustrate the impacts of biofouling environmentally.

In addition, the survey results showed that the majority of the industrial fishing vessels are using diesel oil for combustion. For that reason, recent diesel oil prices were taken into account to make a financial analysis for the selected fishing vessels. To do that, the recent average price of diesel around the world, which is 0.77 GBP per litre, was used (GlobalPetrolPrices.com, Website). Hence, fuel consumption was converted into equivalent values in GBP. Therefore the differences between the fuel consumption costs under a variety of different fouling characteristics, fishing methods and the regions were calculated.

5.5 Characteristics of Fishing Vessels Performed in Case Studies

Three fishing vessels were selected for the case studies. Within this point, it is important to detail the selection process of the vessels used in the case studies. During the survey conducted with the fishermen, three shipyards were also visited with the aim of making an agreement. Two of the shipyard owners agreed to share their ships' characteristics verbally. Therefore when the shipyard owners were questioned about the most typical fishing vessels operating in the Black Sea and the Mediterranean Sea, they have stated that they use similar designs. Therefore, each fishing vessel selected reflects the most common fishing vessel characteristics for particular fishing zone. Furthermore, when it comes to total resistance coefficient values of the fishing vessels, both of the shipyard owners stated that C_T values for the fishing vessels were calculated through using the MAXSURF software. The selected hull form was firstly imported to software and then Holtrop&Mennen (1982) method, which is statistical regression method, was used to predict the resistance of the vessel at a specific ship speed. Characteristics of the fishing vessels can be seen in Table 5-1. Furthermore, details of the operational profiles for the fishing vessels selected are presented in the following subsections.

Table 5-1: Main Particulars of the Selected Fishing Vessels for the Case Studies

Parameter	*Symbols*	*Units*	*Fishing Vessel 1*	*Fishing Vessel 2*	*Fishing Vessel 3*
Design Length	L	m	31.5	28.1	31.5
Design Draught	T	m	4.2	3.5	4.2
Design Displacement	Δ	t	752.1	483.7	752.1
Displacement Volume	∇	m^3	733.8	471.9	733.8
Wetted Surface	S	m^2	425.7	322.7	425.7
Total Resistance Coefficient	C_T	N/A	0.0067617	0.0074534	0.0067617
Design Speed	V	knots	10	10	10

5.5.1 Fishing Vessel 1

The fishing vessel 1 selected for the case studies was the same fishing vessel that the coatings applied for the ship tests. As presented in Chapter 4, fishing vessel 1 is a purse seiner fishing in the Black Sea. As a result of the fact that one of the most common fisheries types in the Black Sea is European anchovy fisheries, this fishing vessel represents the most common fishing activity and the most common fishing vessel type in the region.

Figure 5-1: Operational Profile of Fishing Vessel 1

Following the operation profile data obtained via AIS, a heat map of the fishing vessel's operations was plotted through Microsoft Office's Excel 3D mapping tool. The operational profile and route of the fishing vessel 1 are illustrated in Figure 5-1. Figure 5-1 shows that most of the fishing activities are conducted in the same region where the red spots appear. The plot indicates that most of the fishing activities were conducted near coastal areas.

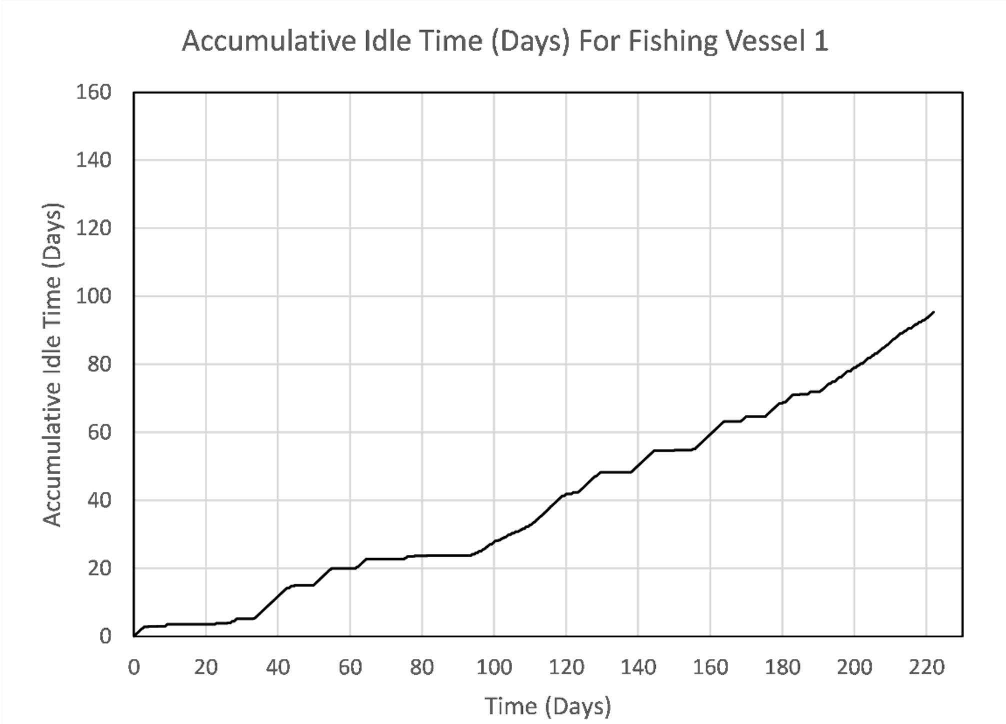


Figure 5-2: Accumulative Idle Time and Fishing Activities Spent In Total For The Fishing Vessel 1

After examining the AIS data for fishing vessel 1, it has been figured out that the fishing vessel's fishing season took 221 days. Moreover, fishing vessel 1 spent 95 days idle during her 221 days of the fishing season. What is more, fishing vessel 1 sailed 2622 nautical miles during her 221 days of fishing activities. Accumulative idle days spent in a fishing season for the fishing vessel 1 can be seen in Figure 5-2.

A key point should be noted that the idle time of the fishing vessels was calculated with the help of AIS data from marinetraffic.com (MarineTraffic.com, 2020). Furthermore, there are many reasons why fishing vessels stay idle during their fishing activities, such as hauling the net, releasing the net, scanning the fish stocks, transporting the caught fish to a tender vessel, bunkering, resting, maintenance, waiting for the target species to appear in sonars to save fuel. Therefore, descriptions of the idle time activities that the fishing vessels conducted may vary. Nevertheless, cruising operation reasons may similarly vary. For that reason, two modes of operation are taken into account from AIS data from marinetraffic.com, idle(stationary) and cruising conditions. Furthermore, fishing vessel 1 spent 95 days as idle time and 126 days in cruising condition on her 221 days of fishing activities, as shown in Figure 5-2.

5.5.2 Fishing Vessel 2

Fishing vessel 2 is a trawler operating in the Black Sea. The reason behind this selection is to represent the most second common fishing vessel operating in the region. The operation profile data obtained via AIS was plotted through Microsoft Office's Excel 3D mapping tool. The operational profile and route of the fishing vessel 2 are illustrated in Figure 5-3.

Figure 5-3: Operational Profile of Fishing Vessel 2

It can be seen from Figure 5-3 that, unlike fishing vessel 1, fishing vessel 2 tend to have fewer red spots. The reason behind this difference is due to the differences between the two fishing activities, as stated in Chapter 2 in this thesis.

Examination of the operation profile of fishing vessel 2 reveals that fishing vessel 2 spent 225 days in her fishing activities in a fishing season, including 145 days of idle time during her fishing activities. Furthermore, fishing vessel 2 sailed 2539 nautical miles during her 225 days of fishing activities. Accumulative idle time spent in a fishing season for the fishing vessel 2 can be seen in Figure 5-4.

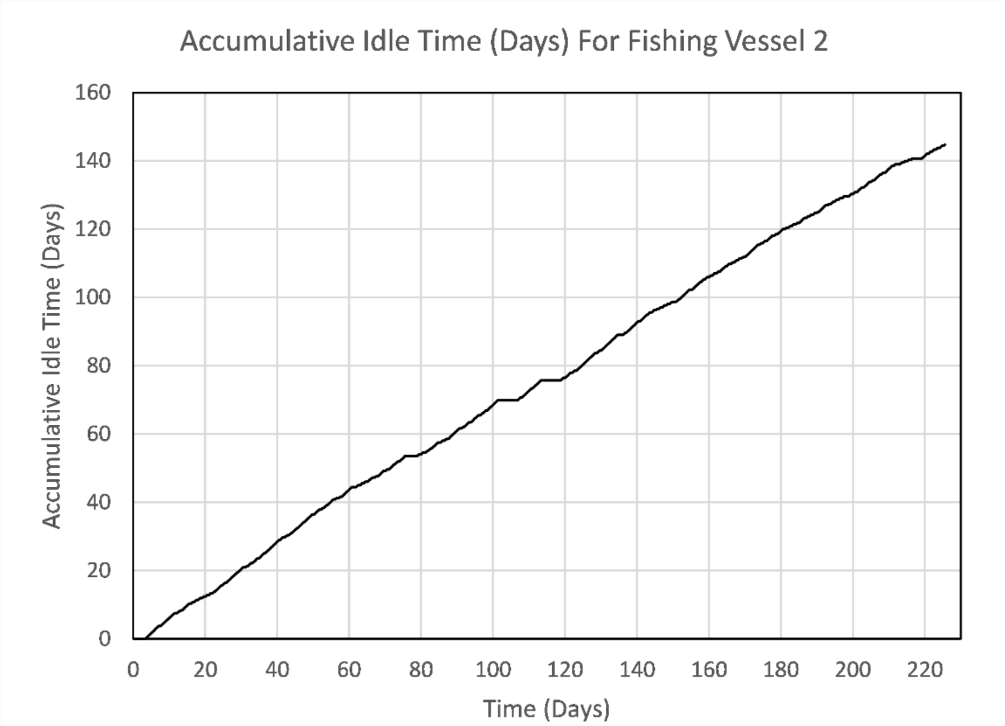


Figure 5-4: Accumulative Idle Time and Fishing Activities Spent in Total for The Fishing Vessel 2

A key point should be noted that the idle time of the fishing vessels was calculated with the help of AIS data from marinetraffic.com (MarineTraffic.com, 2020). Furthermore, there are many reasons why fishing vessels stay idle during their fishing activities, such as hauling the net, releasing the net, scanning the fish stocks, transporting the caught fish to a tender vessel, bunkering, resting, maintenance, waiting for the target species to appear in sonars to save fuel. Therefore, descriptions of the idle time activities that the fishing vessels conducted may vary. Nevertheless, cruising operation reasons may similarly vary. For that reason, two modes of operation are taken into account from AIS data from marinetraffic.com, idle(stationary) and cruising conditions. Furthermore, fishing vessel 2 spent 145 days as idle time and 80 days in cruising condition on her 225 days lasted fishing activities, as shown in Figure 5-4.

5.5.3 Fishing Vessel 3

Fishing vessel 3 is a purse seiner operating in the Mediterranean Sea. A purse seiner was selected is as it is the most common fishing technique used in the Mediterranean Sea. Once the operational profile data for the fishing vessel 3 was obtained via AIS, a heat map of the fishing vessel's operational profile was plotted through Microsoft Office's Excel 3D mapping tool. The operational profile and route of the fishing vessel 3 are illustrated in Figure 5-5.

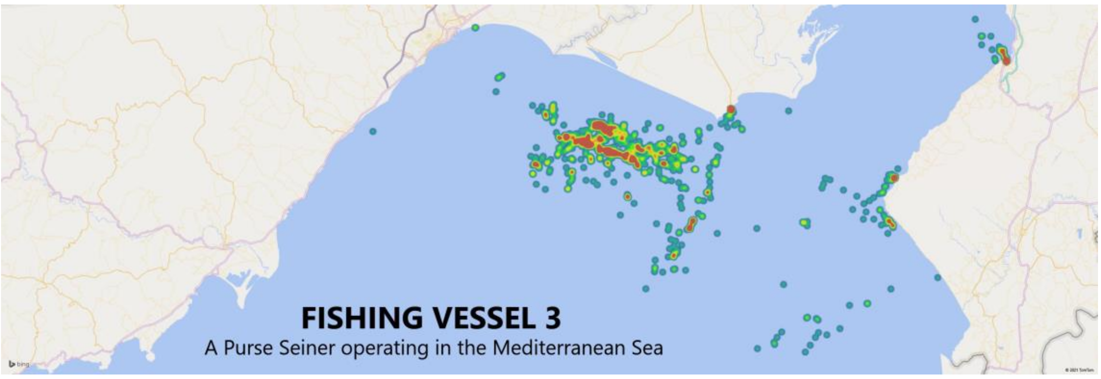


Figure 5-5: Operational Profile of Fishing Vessel 3

Looking at the heat map illustrated in Figure 5-5, it can be seen that the operation profile of fishing vessel 3 shows similarity with fishing vessel 1. Furthermore, it can be seen that the majority of the fishing activities are conducted in the same region where the red spots appear. In addition to that, the majority of the fishing activities are conducted near coastal areas. This similarity confirms the fishing habits of similar fishing vessels using the same fishing techniques.

Examining the operation profile of fishing vessel 3, it can be seen that fishing vessel 3 spent 225 days in her fishing activities in a fishing season, including 111 days of idle time during her fishing activities. Moreover, fishing vessel 3 sailed 2714 nautical miles during her 225 days of fishing activities. Accumulative idle time over days spent in a fishing season for the fishing vessel 3 can be seen in Figure 5-6.

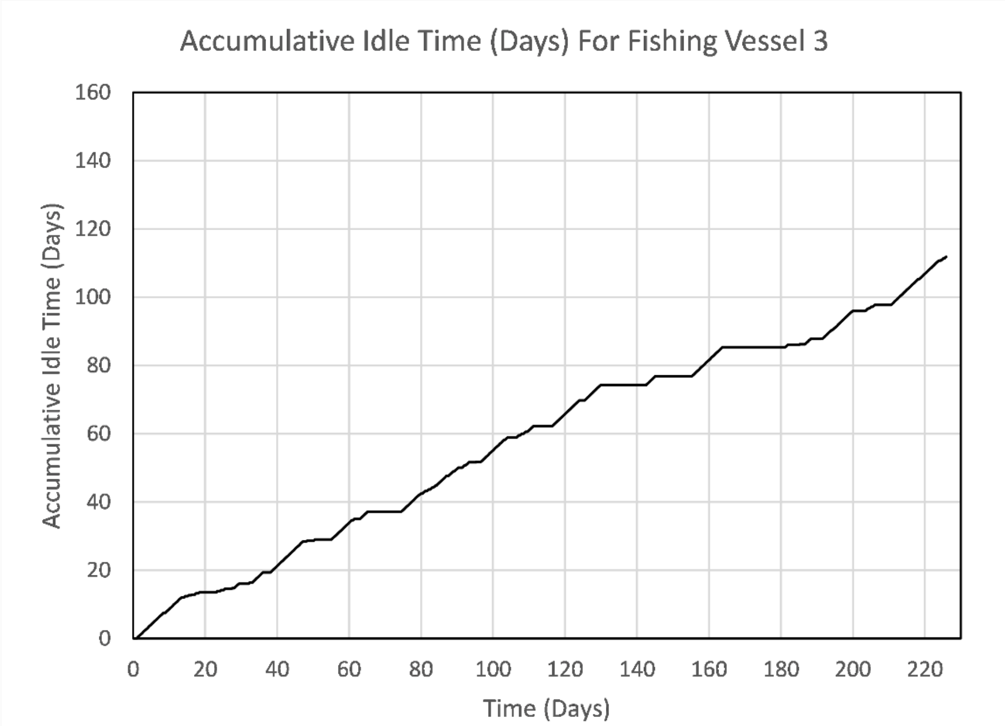


Figure 5-6: Accumulative Idle Time and Fishing Activities Spent in Total for The Fishing Vessel 3

A key point should be noted that the idle time of the fishing vessels was calculated with the help of AIS data from marinetraffic.com(MarineTraffic.com, 2020). Furthermore, there are many reasons why fishing vessels stay idle during their fishing activities, such as hauling the net, releasing the net, scanning the fish stocks, transporting the caught fish to a tender vessel, bunkering, resting, maintenance, waiting for the target species to appear in sonars to save fuel. Therefore, descriptions of the idle time activities that the fishing vessels conducted may vary. Nevertheless, cruising operation reasons may similarly vary. For that reason, two modes of operation are taken into account from AIS data from marinetraffic.com, idle(stationary) and cruising conditions. Furthermore, fishing vessel 3 spent 111 days as idle time and 114 days in cruising condition on her 225 days of fishing activities, as shown in Figure 5-6.

5.6 Results of Case Studies

5.6.1 Case Study 1: Antifouling Coatings Performances for an Industrial Purse Seiner Fishing in The Black Sea

To represent selected antifouling coatings' biofouling performances measured in the field tests on a fishing vessel, fishing vessel 1 was selected for case study 1. Following that, accumulative idle times of the fishing vessel 1, illustrated in Figure 5-2, were considered to be used as an input for Uzun (2019)'s time-based biofouling growth model. It should be noted that the selected antifouling coatings used in the field tests were also used as an input for Uzun (2019)'s time-based biofouling growth model. Next, Uzun (2019)'s time-based biofouling growth model was used to predict the biofouling growth on the fishing vessel 1's hull (coated with the selected SPC coatings) based on her operation profile over a fishing season. After that, biofouling growth over time for fishing vessel 1, coated with selected antifouling coatings, were plotted and illustrated in Figure 5-7. Additionally, the accumulative idle time of fishing vessel 1 against fishing activity time in total was also plotted over and illustrated in Figure 5-7.

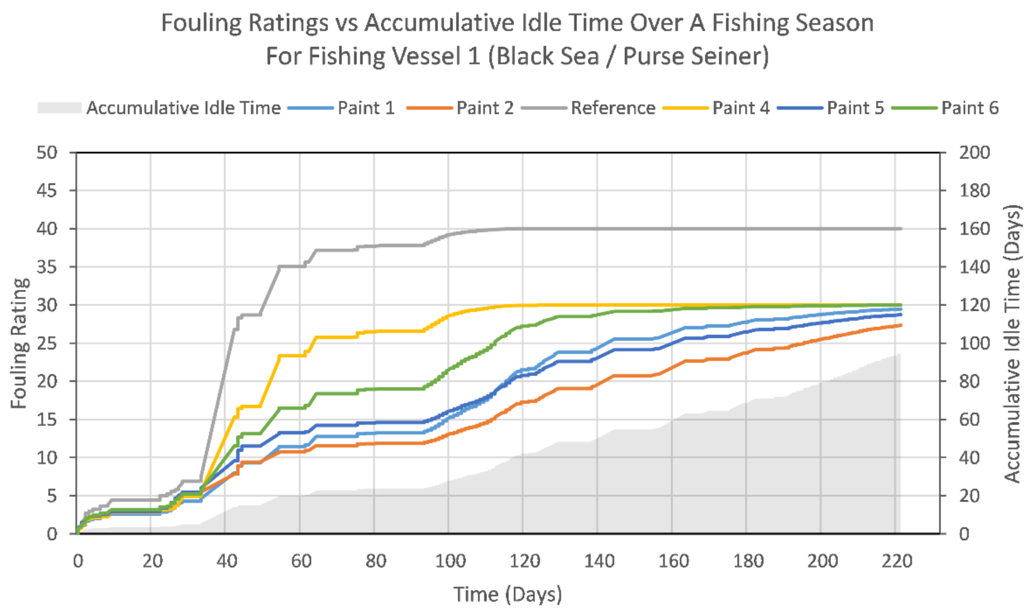


Figure 5-7: Fouling Ratings of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Idle Time.

It can be seen from Figure 5-7 that each coating requires a different fishing activity duration to reach its maximum fouling ratings. Moreover, the fouling rating increases of each antifouling coating and the accumulative idle time relation over time is visible. In addition, it can also be seen that the more the idle time increases, the more fouling growth over the antifouling coatings does.

Not surprisingly, whilst the Reference coating (uncoated coating) was the earliest to reach its maximum rating, Paint 4 followed it as the least successful coating against the fight with biofouling. It took nearly 120 days of fishing activity for the Paint 4 to reach its maximum fouling rating of heavy slime fouling accumulation. Furthermore, the Reference (uncoated) coating took almost 115 days to reach its maximum fouling rating: small calcareous fouling accumulation (fouling rating 40). In addition, it took nearly 190 days of fishing activity for the Paint 6 to reach its maximum fouling rating of heavy slime accumulation (fouling rating 30). On the other hand, Paint 2, Paint 5, and Paint 1 did not reach the maximum fouling ratings of heavy slime accumulation by the end of the fishing season for fishing vessel 1. These ratings are linked to the results of immersion test panel tests, as detailed in Section 4.5.1. For example, immersion test results of Paint 2 showed that the fouling rating of 30 is reached after nearly 150 days (which is the idle time immersed panel spent in seawater). Therefore, up until the approximately 150th idle time in a fishing vessel's operation time, Paint 2 is not expected to reach the fouling rating of 30. This situation can be seen in Figure 5-7 when the idle time and the fouling ratings of the relevant antifouling coatings are compared. Overall, Paint 2, Paint 5 and Paint 1 showed better antifouling performance than Paint 4 and Paint 6's antifouling performances, as shown in Figure 5-7.

Furthermore, considering the first 30 days of the fishing season for fishing vessel 1, it can be seen that the first month's fouling ratings show a similar increase compared to each other, with Reference paint (uncoated) showing slightly poorer performance in comparison to the antifouling coatings. This similar increase in the fouling condition can be attributed to idle time spent in the first month from the operational profile of the fishing vessel 1. As shown in Figure 5-7, in the first 30 days of her fishing activities in a fishing season, fishing vessel 1 spent nearly 5 idle (stationary) days. In other words, the majority of the first month's fishing activities included cruising condition.

Therefore, the fouling ratings were kept at lower values due to the logistic growth model fitting for the relevant antifouling coating's immersion test results, as shown in Figure 4-14.

Next, when the second month in the fishing season for fishing vessel 1 is considered, it can be seen that the growth rate in the fouling ratings is higher in comparison to the first month's accumulation results. In addition to the Reference coating's (uncoated) poor fouling performance, Paint 4's fouling ratings increase to a higher fouling rating, making it the poorest antifouling coating performance. Therefore, the second month of fishing for vessel 1 can be attributed to the duration when the antifouling coatings start losing their efficiency in the fight with the biofouling. That should also be noted that the idle time spent during the second month of the fishing season for fishing vessel 1 shows a similar increase with the fouling rating increases of the antifouling coatings, as shown in Figure 5-7. Moreover, the idle time in the second month of the fishing season for fishing vessel 1 is higher than the first month's idle time.

From the 60th to 100th days of the fishing season for the fishing vessel 1, fouling ratings show a relatively smaller increase than the second month's fouling rating increase. As shown in Figure 5-7, from the 60th to the 100th days of the fishing activities, none of the fouling ratings of the antifouling coatings and the Reference (uncoated) coating significantly increased. For example, the fouling rating of the Reference coating (uncoated) increases from 35 to 39, fouling ratings for the Paint 4 increase from 23 to 38, and the fouling rating of Paint 2 increases from 11 to 13. Within this point, it should be noted that the more an antifouling coating is successful, the less the fouling rating increase is. It can also be seen that whilst the fouling rating for the Paint 4 increase is only 4, a more successful antifouling coating such as Paint 2 shows an increase of 3 in fouling rating for the duration from the 60th to 100th days in a fishing season for the fishing vessel 1. In other words, Paint 2 shows a better antifouling performance than Paint 4 between the 60th and the 100th days of the fishing season.

Furthermore, when fouling rating after the first 100 days of the fishing season for the fishing vessel 1 is considered, it can be seen that the fouling rating for the reference panel (uncoated) is kept at the fouling rating of 40. Moreover, Paint 4 and Paint 6 reached a fouling rating of 30 by the end of the fishing season for fishing vessel 1. On the other hand, Paint 2, Paint 1 and Paint 5 showed a continuous increase in correlation with the accumulative idle time spent. The reason why the Reference coating (uncoated), Paint 4 and Paint 6 does not show any increase is due to not reaching the required idle time for the increase in fouling ratings. To be more specific, fishing vessel 1's fishing season takes 221 days, as stated before, and yet the accumulative idle time spent in the fishing season is 95 days for fishing vessel 1. Each antifouling coating requires different idle times to reach its maximum fouling ratings. For example, it can be seen from Figure 4-12 that the Reference panel's(uncoated) fouling rating does not go beyond the fouling rating of 40 up until the approximately 200th day. If there was a longer-lasting fishing season for fishing vessel 1 (for example, 500 days of fishing season) and if the fishing vessel 1 spent 200 days of idle time in that fishing season, the fouling rating for the Reference paint (uncoated) would then start increasing after that time. Similar comments can be made for Paint 4 and Paint 6.

When the performance of each coating is examined in terms of the fouling rating that they reach by the completion of the fishing season, the reference (uncoated) coating reaches a fouling rating of 40 as the highest fouling rating. Next, Paint 4 and Paint 6 reach a fouling rating of 30 by the end of the fishing season. Within this point, it should be noted that Paint 4 reaches the fouling rating of 30 earlier than Paint 6, which makes Paint 4 a less successful antifouling coating compared to Paint 6. Paint 1 reaches a fouling rating of 29.4, Paint 5 reaches a fouling rating of 28.7, and Paint 2 reaches a fouling rating of 27.3 by the end of the fishing season. To summarise, based on the SPC antifouling coatings' fouling results and their fouling ratings on a purse seiner operating in the Black Sea by the end of a fishing season, a ranking can be made from the best to worst antifouling performance in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (uncoated) paint as shown in Figure 5-7.

The next step was to convert the fouling ratings of the selected coatings into k_s values for the fishing vessel 1. Equation 33 is used for this conversion. Equivalent sand roughness heights of the fouling conditions over time are presented in Figure 5-8.

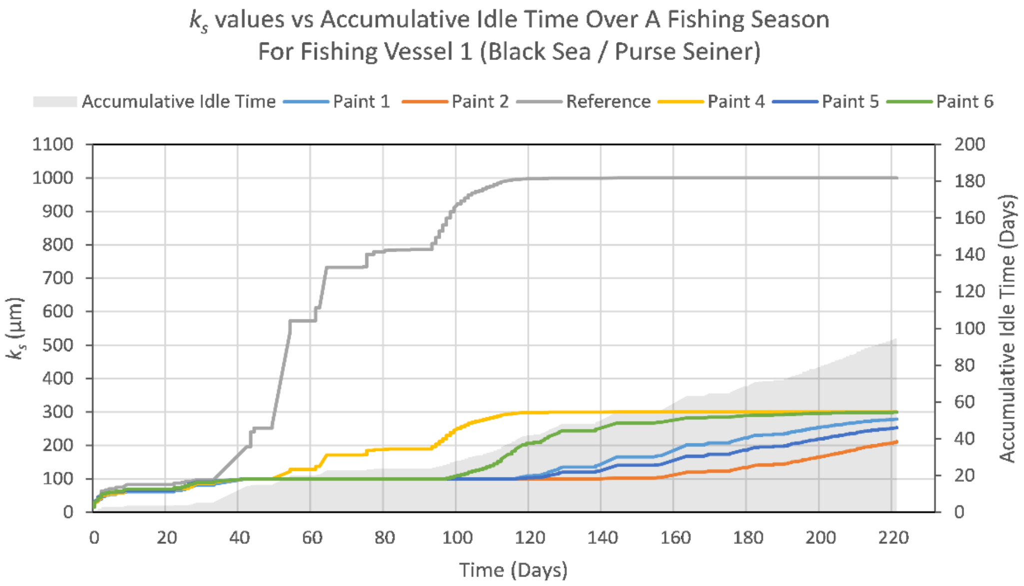


Figure 5-8: Equivalent Sand Roughness Heights (k_s) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Idle Time.

As shown in Figure 5-8, each coating requires a different fishing activity duration to reach its maximum k_s values. Moreover, k_s values of the antifouling coatings for the fishing vessel 1 reach a maximum value of 300 μm whilst the Reference coating (uncoated) reaches the value of 1000 μm. To be more specific, the Reference coating (uncoated) reached to k_s value of 1000 μm as the highest k_s value. Next, Paint 4 and Paint 6 reached k_s value of 300 μm by the end of the fishing season. Within this point, that should be noted that Paint 4 reached the k_s value of 300 μm earlier than Paint 6. Following that, Paint 1 reached the k_s value of 279 μm, Paint 5 reached the k_s value of 253 μm, and Paint 2 reached the k_s value of 211 μm by the end of the fishing season. When a comparison is made between the best and the worst antifouling coating performances, the difference between biofouling accumulation of each antifouling coating's equivalent k_s values can reach up to 91 μm by the end of a fishing season for the fishing vessel 1. Based on the SPC antifouling coatings' fouling results and their k_s value conversions on a purse seiner operating in the Black Sea by the end of a fishing season, a ranking can be made from the best to worst antifouling performance in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference coating (uncoated) as shown in Figure 5-8.

Furthermore, as a result of the conversion conducted between fouling ratings and k_s values using Equation 33, ranking results in k_s values of the antifouling coatings show a good agreement with the fouling rating rankings shown in Figure 5-7. Within this point, a note should be taken into consideration. In Figure 5-8, it can be seen that once the k_s values reach 100 μm, it takes a particular time for each antifouling coating to go beyond and show an increase after reaching 100 μm in k_s values. This condition occurs due to the correction made when converting NSTM fouling ratings to k_s values, using Equation 33. As explained in Section 5.3 in detail, a regression curve was fitted to calculate the k_s values for the NSTM fouling rating values. However, because the fitted model behaves as if there is a decrease in k_s values after reaching 100 μm which is the ks value of NSTM fouling rating of 10 and 20, a correction was made to the NSTM rating and k_s regression. Therefore, once the fouling ratings of the antifouling coatings reach the fouling rating of 7.98, k_s values were set to 100 μm until the fouling rating reached 20.3. In addition, the vast difference in k_s values between the antifouling coatings and the Reference coating (uncoated) is due to the difference between the equivalent k_s values of the fouling ratings of 30 and 40 according to Table 4-7. As shown in Table 4-7, whilst the fouling rating of 40 equals to k_s value of 1000 μm, fouling rating of 30 equals to k_s value of 300 μm. Therefore, once the Reference coating (uncoated) goes beyond the fouling rating of 30, k_s value of the Reference coating (uncoated) shows a significant increase in comparison to the antifouling coatings' k_s values as the maximum fouling rating for the antifouling coatings is 30 by the end of the fishing season for the fishing vessel 1.

Similar to the fouling rating increases in Figure 5-7, k_s values show similar increases in the first 30 days of the fishing activities for fishing vessel 1. Due to a lower increase in accumulative idle time, k_s values of the antifouling coatings and the Reference coating (uncoated) do not show a significant increase in the first 30 days. Furthermore, when the time from the 30th to the 100th day of the fishing season is considered, it can be seen from Figure 5-8 that all of the antifouling coatings' k_s values reach 100 μm. Nevertheless, only Paint 4 and Reference coating continue showing an increase shortly after reaching to k_s value of 100 μm from the 30th to 100th day of the fishing season. Moreover, the rest of the antifouling coatings do not show any increase by the 100th day of the fishing season for the fishing vessel 1. Due to their poorer performance compared to the other antifouling coatings, Reference (uncoated) and Paint 4 continue to increase in k_s values after reaching approximately the k_s value of 300 μm and 1000 μm as having the poorest performance in the fight with the biofouling. After the 100th day of the fishing season for fishing vessel 1, it can be seen that Paint2, Paint 5, Paint 1 and Paint 6 started showing an increase respectively due to their efficiency in the fight with the biofouling.

Once the relevant k_s values of the surfaces coated with the selected antifouling coatings over time were obtained, ΔC_F values for fishing vessel 1 were calculated using the approach presented in Section 5.3. Added resistance diagrams of the fishing vessel 1, cruising at design speed and coated with the selected antifouling coatings over time, is plotted and presented in Figure 5-9.

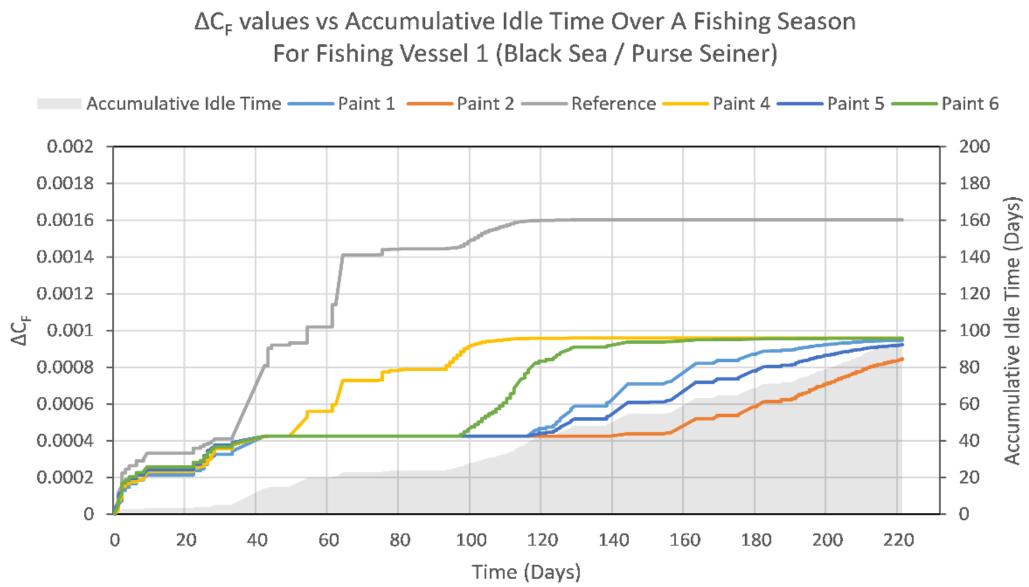


Figure 5-9: Frictional Resistance Differences (ΔC_F) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Idle Time.

As explained in Section 5.3, ΔC_F values were obtained using the practical diagrams from Demirel et al. (2019)'s study and k_s values from the field tests presented in Chapter 4. In addition, ship speed and LOA of the ship were used as input to calculate ΔC_F values. Therefore, as the LOA and the ship speed were taken constants in this case study, the only changing parameter was considered as the k_s values of the fouling conditions over time for each antifouling coating when calculating the ΔC_F values.

Nevertheless, looking at Figure 5-9, the increase in ΔC_F values for each coating show similarities with the increase in k_s values of each antifouling coating between certain periods of the fishing season for the fishing vessel 1 (such as the first, second and third months). The similarities between the increases in the k_s and ΔC_F values can be seen by comparing Figure 5-8 and Figure 5-9.

As shown in Figure 5-9, each coating requires a different fishing activity duration to reach its maximum ΔC_F values. ΔC_F values of the antifouling coatings for the fishing vessel 1 reach a maximum value of 0.95 x 10^{-3} whilst the Reference (uncoated) reaches 1.6 x 10^{-3}. To be more specific, the Reference (uncoated) coating reached to ΔC_F value of 1.6 x 10^{-3} as the highest ΔC_F value. Next, Paint 4 and Paint 6 reached ΔC_F value of 0.95 x 10^{-3} by the end of the fishing season. Within this point, that should be noted that Paint 4 reaches the ΔC_F value of 0.95 x 10^{-3} earlier than Paint 6. Following that, Paint 1 reached the ΔC_F value of 0.94 x10^{-3}, Paint 5 reached the ΔC_F value of 0.92 x10^{-3}, and Paint 2 reached the ΔC_F value of 0.84 x 10^{-3} by the end of the fishing season. In addition, it can be seen that accumulative idle time and the increases in the ΔC_F values show relevance with each other. In other words, the faster the accumulative idle time increases, the quicker ΔC_F values increase. Therefore, based on the SPC antifouling coatings' fouling results and their ΔC_F value conversions on a purse seiner operating in the Black Sea by the end of a fishing season, a ranking can be made from the best to worst antifouling performance in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference coating (uncoated) as shown in Figure 5-9. The obtained ΔC_F values for the fishing vessel 1 cruising at her design speed under certain fouling conditions show similar results compared to the values shown in Figure 2-15 (practical added resistance diagrams).

After obtaining the differences between smooth and rough frictional resistance coefficients (ΔC_F) of the surfaces coated with the selected antifouling coatings, Equation 12 was used to calculate the percentage increase in effective power ($\%\Delta P_E$) for the fishing vessel 1. The increase of P_E values over time for the fishing vessel 1 coated with the selected antifouling coatings were plotted and illustrated in Figure 5-10.

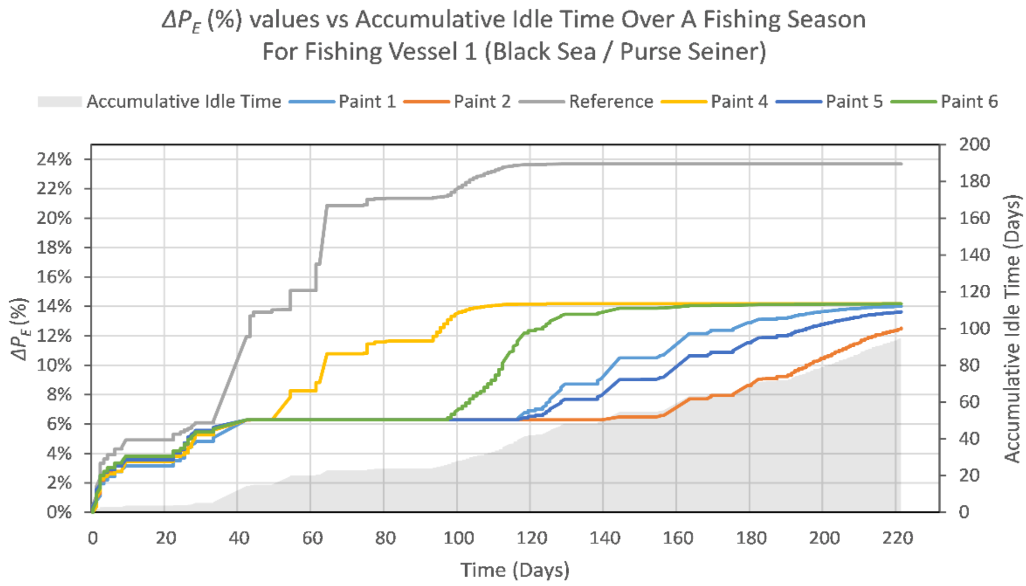


Figure 5-10: % Increase in the Effective Powers of Fouled Surfaces ($\%\Delta P_E$) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Idle Time.

Examining the results in Figure 5-10 shows that the biofouling can cause an increase in effective power varying between 12.52% and 23.69% at the design speed for a purse seiner fishing in the Black Sea by the end of a fishing season. More specifically, if fishing vessel 1 is not coated with an antifouling coating (Reference coating), biofouling can cause a 23.69% increase in effective power by the end of the fishing season. Within this point, that should be noted that it is not realistic to estimate an uncoated fishing vessel's % increase in effective power as no fishing vessel operates with an uncoated hull. However, considering the fact that one of the aims of this research is "to train the fishermen on selecting the most suitable antifouling coating", showing the worst-case scenario (as the uncoated vessel) would be necessary in order to emphasise antifouling coatings' abilities in preventing the penalties caused by biofouling. In other words, in order to emphasise the importance and efficiency of the antifouling coatings in the fight with the biofouling, an uncoated fishing vessel scenario (with reference coating) was also included in the case studies.

Furthermore, If the fishing vessel 1 is coated with Paint 4, Paint 6, Paint 1, Paint 5, and Paint 2 separately, biofouling causes, respectively, 14.17%, 14.17%, 14.01%, 13.64%, and 12.52% increase in effective power by the end of the fishing season for fishing vessel 1. It can also be seen that Paint 4 and Paint 6 show the same % increase in the effective power due to biofouling at the end of the fishing season. However, when these two antifouling coatings' performances with regards to the increase in effective power are examined, it can be seen that Paint 4 shows an increase of 14.17% after nearly 120 days and yet Paint 6 shows the same % increase after approximately 180 days. Therefore, when a comparison is made between Paint 4 and Paint 6, it can be seen that, due to time to reach the maximum % increase in effective power, fishing vessel 1 coated with Paint 4 consumes more power and hence fuel in comparison to the fishing vessel 1 coated with the Paint 6 when a complete fishing season is considered.

Nevertheless, based on the SPC antifouling coatings' fouling results by the end of a fishing season, from higher to lower, power requirements of the fishing vessel 1 coated with the selected antifouling coatings would be in the following order: Reference (uncoated), Paint 4, Paint 6, Paint 1, Paint 5, and Paint 2. Therefore, whilst Paint 2 shows the best antifouling performance, Paint 4 shows the poorest antifouling performance in the fight with the biofouling, considering the fishing vessel 1 in a fishing season.

Looking at Figure 5-10, coating fishing vessel 1 with the best antifouling coating (Paint 2) can save approximately 1.65% in effective power compared to fishing vessel 1 coated with the worst antifouling coating (Paint 4) by the end of the fishing season. Within this point, it should be noted that the amount of the savings between the best and the worst performing antifouling coatings can change depending on the operational profile, ship characteristics such as LOA, the idle time that the fishing vessel spent during her fishing activities, the length of the fishing season, and fouling ratings. For example, if fishing vessel 1 lasted her fishing activities after 140 days of fishing, coating fishing vessel 1 with the best antifouling coating (Paint 2) would save approximately 7.88% in effective power compared to fishing vessel 1 coated with the worst antifouling coating (Paint 4). Therefore, with the fouling accumulation on the coatings, coating fishing vessel 1 with the best antifouling coating can save up to 7.88% in effective power compared to any of the selected antifouling coatings (Paint 1, Paint 4, Paint 5, and Paint 6).

Finally, to comment on the periods of the fishing season, % increases in the effective power, and the idle time spent for the fishing vessel 1 over a fishing season, Figure 5-10 and Figure 5-9 can be compared. Due to the reason that the ΔC_F values are directly used to calculate the $\%\Delta P_E$ using Equation 12, the same comments for the ΔC_F values increase over time, and the accumulative idle time spent for the fishing vessel 1 can be applied on the % increase in ΔP_E over the fishing season for the fishing vessel 1. For example, in Figure 5-9 it can be seen that in the first month of the fishing season, the increase in the ΔC_F values is lower than in the second month. Moreover, in Figure 5-10, the % trend in ΔP_E over time shows significant similarities with the ΔC_F trends illustrated in Figure 5-9.

Following that, the fuel consumption of fishing vessel 1 was considered. Moreover, the procedure detailed in Section 5.4 was followed to estimate accumulative fuel consumption over time. Main engine output power (kW) was determined with the service allowance, and then the MEFC was obtained using the main engine's manual. Furthermore, installed main engine power is 551 kW and MEFC was calculated as 88.13 litres per hour from the main engine's manual. Figure 5-11 shows the accumulative fuel consumption (L) increase due to the biofouling of fishing vessel 1 with the selected SPC antifouling coatings applied over time in a fishing operation year. It should be noted that the idle time from the operation profile was deducted. The fuel consumption over time was estimated only when the ship was in a cruising state (active time).

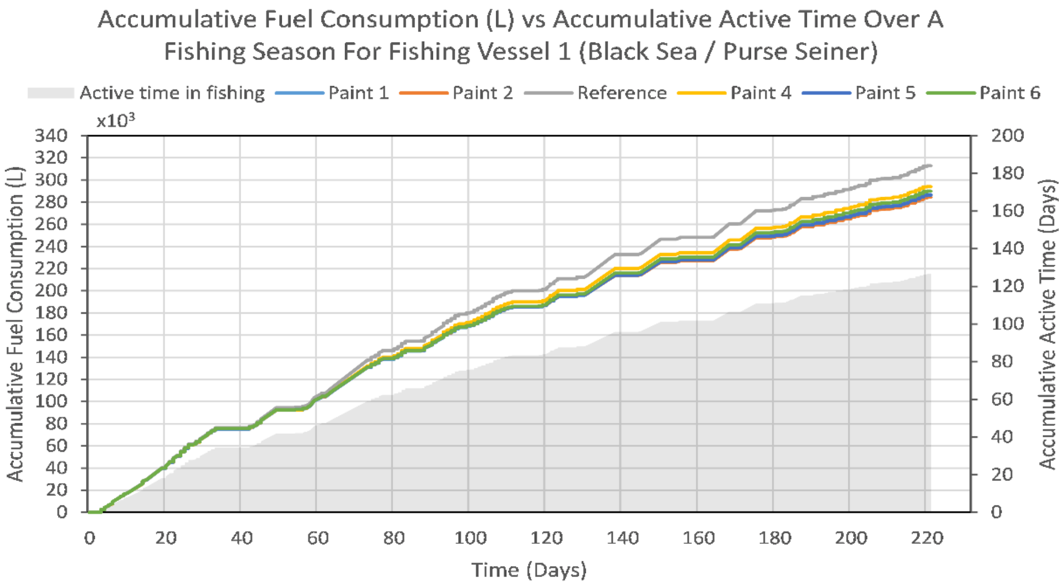


Figure 5-11: Accumulative Fuel Consumption (Litres) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Active (Cruising) Time.

From Figure 5-11, it can be seen that a purse seiner fishing vessel coated with the selected antifouling coatings (and the uncoated reference coating) operating in the Black Sea region can consume from 284 to 313 thousand litres of fuel when a fishing season is considered. In addition, from Figure 5-11, the increase in the accumulative active time and the accumulative fuel consumption show similar trends. However, looking at it in detail, it can be seen that the increase in the accumulative fuel consumption becomes faster in comparison to the accumulative active time by the end of the fishing year. Whilst the trends between accumulative active time and the accumulative fuel consumption are closer to each other at the beginning of the fishing season, the trends become further apart by the end of the fishing season. For that reason, a comment may be suitable as this gap increase over time can be directly linked to the biofouling growth over time.

In addition, a further bar chart was plotted to detail total fuel consumption (L) over a fishing season for fishing vessel 1 coated with the selected antifouling coatings. Figure 5-12 shows the total fuel consumption (litres) of the selected SPC coatings and Reference (uncoated) applied on the fishing vessel 1 (purse seiner fishing in the black sea region) over a fishing season.

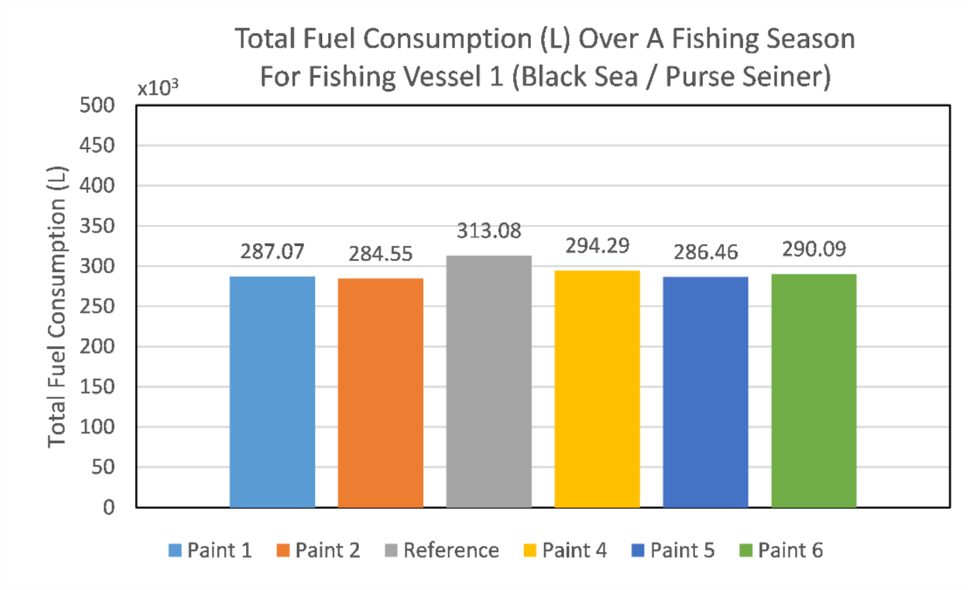


Figure 5-12: Total Fuel Consumption (Litres) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season.

Looking at Figure 5-12, it can be seen that coating a purse seiner with the selected SPC coatings or Reference (uncoated) can consume up to 313.08 thousand litres of fuel in a fishing season. More specifically, fishing vessel 1 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (Uncoated) respectively consume 284.55, 286.46, 287.07, 290.09, 294.29, and 313.08 thousand of fuel in litres in a fishing season. In addition to that, it can be seen from Figure 5-12, a simple antifouling coating selection decision for a purse seiner fishing in the Black Sea can save up to 9740 litres of fuel (when Paint 2 and Paint 4 are compared) for the fishing vessel 1 by the end of a fishing season. Moreover, by only coating fishing vessel 1 with any of the selected antifouling coatings, up to 28530 litres of fuel (when Paint 2 and Reference are compared) can be saved in a fishing season.

Within this point, that should be noted that after calculating the fuel consumption of a Black Sea purse seiner coated with the selected antifouling coatings in case study 1, the shipowner validated fuel consumption results from the noon report. More specifically, fishing vessel 1's owner stated that fishing vessel 1 spent around 280 thousand litres of fuel in a fishing year. This result shows a good agreement with the calculated fuel consumption results presented in case study 1. What is more, this validation can be interpolated and extrapolated for case studies 2 and 3.

Furthermore, that should be noted that these numbers represent fuel consumption with the biofouling accumulation on the selected antifouling coatings by the end of the fishing season, which were applied on the fishing vessel 1. Therefore, in order to illustrate how coating fishing vessel 1 with any of the selected antifouling coatings would save in comparison to each other in fuel consumption by the end of the fishing season, a further figure was plotted and presented in Figure 5-13. Figure 5-13 shows total fuel consumption savings (%) for the selected SPC coatings in comparison to Reference (uncoated) applied on the fishing vessel 1 (purse seiner fishing in the black sea region) over a fishing season.

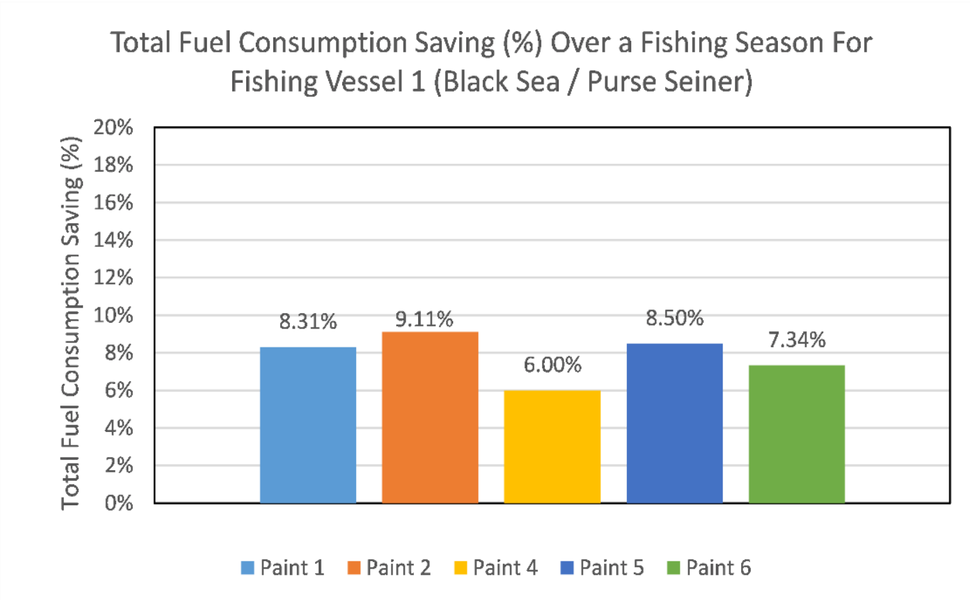


Figure 5-13: Total Fuel Consumption Savings (%) for the Selected SPC Coatings in Comparison to Reference (Uncoated) Applied on the Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season.

As shown in Figure 5-13, coating fishing vessel 1 with any of the selected antifouling coatings in comparison to Reference (uncoated) can save from 6% to 9.11% in total fuel consumption. To be more specific, if fishing vessel 1 is coated with Paint 2, Paint 5, Paint 1, Paint 6, and Paint 4, respectively, 9.11%, 8.5%, 8.31%, 7.34%, and 6% in fuel consumption can be saved in comparison to Reference (uncoated) by the end of a fishing season. Demonstrating these percentages is essential to underline the vital role of antifouling coatings in preventing the penalties caused by biofouling. More importantly, when the selected antifouling coatings are compared with each other, it can be seen that making a simple antifouling coating selection decision for a purse seiner fishing in the Black Sea can save up to 3.11% (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) of the fuel consumed by the end of a fishing season. Further saving derivations can be made by comparing other selected antifouling coatings illustrated in Figure 5-13. Within this point, it should be noted that due to having a direct link between the fuel consumption, fuel cost, and CO_2 emissions released into the atmosphere, the saving numbers (%) presented in Figure 5-13 is valid for the total fuel cost and total CO_2 emission savings by the end of fishing season for the fishing vessel 1.

In addition to the total fuel consumption of the fishing vessel 1 coated with the selected SPC coatings and Reference (uncoated) shown in Figure 5-12, a bar chart showing the total fuel cost for the fishing vessel 1 by the end of the fishing year is plotted and presented in Figure 5-14. Figure 5-14 shows the total fuel cost (£) of the selected SPC coatings and Reference (uncoated) applied on the fishing vessel 1 (purse seiner fishing in the black sea region) over a fishing season.

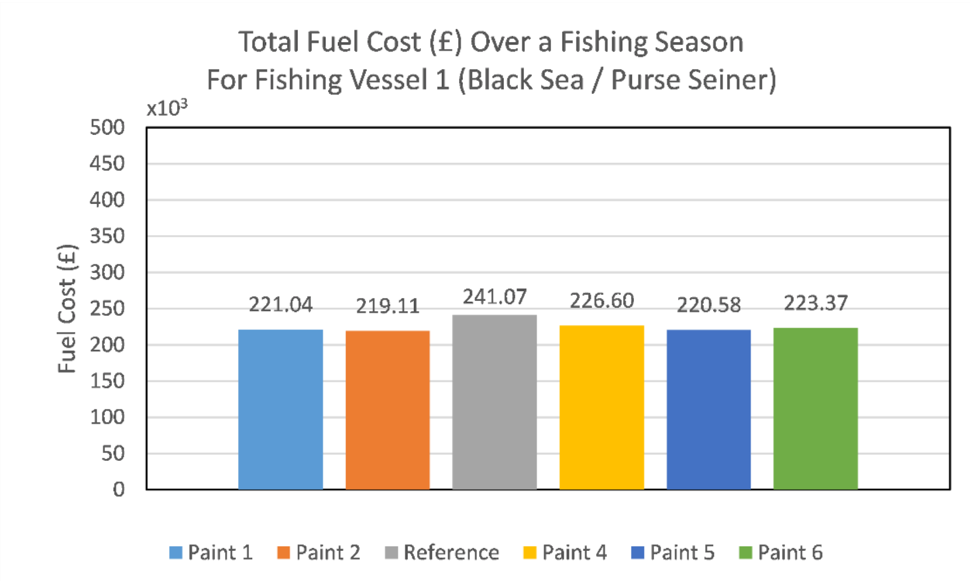


Figure 5-14: Total Fuel Cost (£) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season.

In Figure 5-14, it can be seen that coating a purse seiner with the selected SPC coatings and Reference (uncoated) can cause up to 241.07 thousand of GBP fuel cost in a fishing season. To be more specific, the total fuel cost for the fishing vessel 1 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference paint(uncoated), respectively, can be 219.04, 220.58, 221.04, 223.37, 226.6 and 241.07 thousands of GBP. It should be noted that the fuel costs presented in Figure 5-14 are the most recent fuel price as detailed in Section 5.4. Moreover, these costs may be too much when considering the countries surrounding the Black Sea fishing region for a yearly based fuel cost. However, considering that the fishing vessels benefit from fuel subsidies in varying amounts in different countries, the amount that the fishermen spent for the fuel cost may be lower than estimated and presented in Figure 5-14. Because the fuel subsidies that a fishing vessel receives depend on many factors, such as LOA, country, and type of fisheries, these numbers are estimated without considering the fuel subsidies as a simpler approach (Schuhbauer et al., 2020). It should also be noted that it would be easier to calculate the fuel costs if the carbon tax, which has been discussed among the authorities, is introduced as subsidies will disappear. It can be seen from Figure 5-14, by only coating fishing vessel 1 with any of the selected antifouling coatings, up to 21.96 thousand of GBP for fuel cost (when Paint 2 and Reference are compared) can be saved in a fishing season. More importantly, a simple antifouling coating selection decision for a purse seiner fishing in the Black Sea can save up to 7.49 thousand GBP for fuel cost (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) by the end of a fishing season.

In addition, a further bar chart was plotted to detail total CO_2 emission (tonnes) over a fishing season for fishing vessel 1 coated with the selected SPC coatings and Reference paint (uncoated). Figure 5-15 shows the total CO_2 emission (tonnes) of the selected SPC coatings and Reference (uncoated) applied on the fishing vessel 1 (purse seiner fishing in the black sea region) over a fishing season.

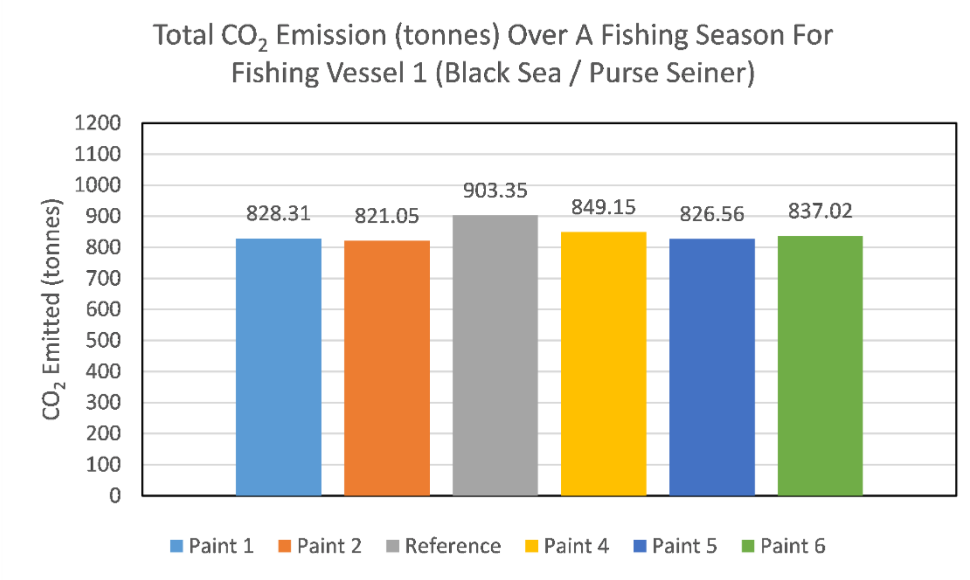


Figure 5-15: Total CO_2 emission (tonnes) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 1 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season.

From Figure 5-15, it can be seen that coating a purse seiner with the selected SPC coatings or Reference (uncoated) can emit up to 903.35 tonnes of CO_2 into the atmosphere. More specifically, fishing vessel 1 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (Uncoated) respectively emit 821.05, 826.56, 828.31, 837.02, 849.15 and 903.35 tonnes of CO_2 into the atmosphere by the end of a fishing season. More importantly, it can be seen from Figure 5-15, a simple antifouling coating selection decision for a purse seiner fishing in the Black Sea can stop up to 28.01 tonnes of CO_2 emitted into the atmosphere (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) for the fishing vessel 1 by the end of a fishing season. Moreover, by only coating fishing vessel 1 with any of the selected antifouling coatings, up to 82.3 tonnes of CO_2 emission into the atmosphere (when Paint 2 and Reference are compared) can be prevented by the end of a fishing season in comparison to uncoated (Reference) fishing vessel 1.

5.6.2 Case Study 2: Antifouling Coatings Performances for an Industrial Trawler Fishing in The Black Sea

To determine the biofouling performances of the selected antifouling coatings used in the field tests on a fishing vessel, fishing vessel 2 was selected for case study 2. Following that, accumulative idle times of the fishing vessel 2, illustrated in Figure 5-4, were considered to be used as an input into Uzun (2019)'s time-based biofouling growth model. It should be noted that the selected antifouling coatings used in the field tests were also taken as an input for Uzun (2019)'s time-based biofouling growth model. Next, Uzun (2019)'s time-based biofouling growth model was used to predict the biofouling growth on the fishing vessel 2's hull (coated with the selected SPC coatings) based on her operation profile in a fishing season. After that, biofouling growth over time for fishing vessel 2, coated with selected antifouling coatings, were plotted. Additionally, the accumulative idle time of fishing vessel 2 against fishing activity time in total was also plotted over and illustrated in Figure 5-16.

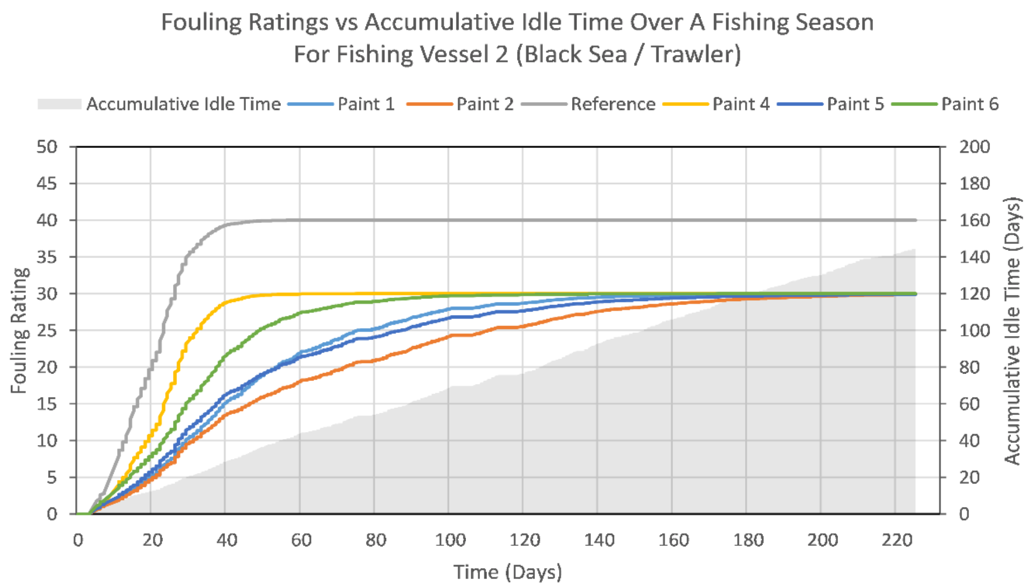


Figure 5-16: Fouling Ratings of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Idle Time.

It can be seen from Figure 5-16 that each coating requires a different fishing activity duration to reach its maximum fouling ratings. Moreover, the fouling growth of each antifouling coating and the accumulative idle time relation to total time is visible in Figure 5-16. What is more, it can be seen that the more the idle time increases, the more fouling growth over the antifouling coatings occurs.

Predictably, whilst the Reference coating (uncoated coating) reached its maximum rating as the earliest, Paint 4 followed it as the least successful coating against the fight with biofouling. It took approximately 60 days of fishing activity for the Paint 4 to reach its maximum fouling rating of heavy slime fouling accumulation (fouling rating 30). Furthermore, the Reference (uncoated) coating took almost 55 days to reach its maximum fouling rating: small calcareous fouling accumulation (fouling rating 40). In addition, it took nearly 120 days of fishing activity for the Paint 6 to reach its maximum fouling rating of heavy slime accumulation (fouling rating 30). Following that, it took nearly 180 days of fishing activity for Paint 1 to reach its maximum fouling rating of heavy slime accumulation (fouling rating 30). Next, it took nearly 190 days of fishing activity for the Paint 5 to reach its maximum fouling rating of heavy slime accumulation (fouling rating 30).

Moreover, it took approximately 210 days of fishing activity for the Paint 2 to reach its maximum fouling rating of heavy slime accumulation (fouling rating 30). It should be noted that when a fouling rating of an antifouling coating reaches its maximum fouling rating earlier than the other antifouling coatings, the impact of the biofouling will last longer and bigger for the selected fishing vessel. Therefore, reaching higher fouling ratings earlier means insufficient fight with the biofouling for antifouling coatings applied on a fishing vessel. Therefore, based on the Case 2 results, a ranking can be made from the best to worst antifouling performance in the descending order: Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (uncoated). In other words, if fishing vessel 2 is coated with Paint 4, for example, the impacts of the biofouling on fishing vessel 2 will be higher in comparison to the fishing vessel 2 coated with other antifouling coatings.

Furthermore, considering the first 60 days of the fishing season for fishing vessel 2, it can be seen that the second month's fouling ratings show a similar increase compared to each other, with Reference (uncoated) showing the poorest performance in comparison to the antifouling coatings. In addition, it can be seen from the figure that in the first 60 days of her operational activities, there is a sudden increase in the fouling rating. This similar and sudden increase in the fouling condition can be attributed to idle time spent in the first 60 days of the operational profile of the fishing vessel 2. More specifically, as shown in Figure 5-16, in the first 60 days of her fishing activities in a fishing season, fishing vessel 2 spent approximately 40 idle (stationary) days. In other words, the majority of the first 60 days' fishing activities included idle time. As more idle time spent in the sea means more biofouling accumulation, therefore, the fouling ratings were kept at higher fouling ratings as a result of the logistic growth model fitting for the relevant antifouling coating's immersion test results, as shown in Figure 4-14. In addition to that, it can be seen from Figure 5-16 that although Paint 1 shows a better performance in the early days of the first 60 days of the fishing season, Paint 1 starts showing a poorer antifouling performance by the end of the first 60 days of the fishing season. This poor performance results in Paint 5 and Paint 1 performing the same antifouling performance by the end of the first 60 days of the fishing season.

From the 60^{th} to the end of the fishing season for fishing vessel 2, fouling ratings show a relatively smaller increase than the first 2 month's fouling rating increase. As shown in Figure 5-16, from the 60^{th} to the end of the fishing activities, none of the fouling ratings of the antifouling coatings and the Reference (uncoated) coating significantly increased. Specifically, the Reference (uncoated) and Paint 4 do not show any increase in the fouling ratings. Moreover, for the rest of the antifouling coatings, it can be seen that once they reach their maximum fouling ratings, which is 30, they show no further increase in the fouling ratings. The reason behind this (no further increase in the fouling rating situation) is due to not reaching the required idle time required for the increase in fouling ratings. To be more specific, fishing vessel 2's fishing season takes 225 days, as stated before, and yet the accumulative idle time spent in the fishing season is 145 days for fishing vessel 2. Each antifouling coating requires different idle times to reach its maximum fouling ratings. For example, it can be seen from Figure 4-12 that the Reference coating's (uncoated) fouling rating does not go beyond the fouling rating of 40 up until the approximately 200th day. Therefore, if there was a longer-lasting fishing season for the fishing vessel 2 (for example, 500 days of fishing season) and if the fishing vessel 2 spent 200 days idle in that fishing season, the fouling rating for the Reference coating (uncoated) would then start increasing after that moment. Similar comments can be made for Paint 4, Paint 1, Paint 2, Paint 4, Paint 5, and Paint 6.

To comment on the comparative performance of each coating in terms of fouling rating that they reach by the completion of the fishing season, Reference (uncoated) coating reached a fouling rating of 40 as the highest fouling rating. Furthermore, it can be seen from Figure 3-16 that all of SPC antifouling coatings reach a fouling rating of 30 by the end of the fishing season. Therefore, any antifouling coating applied on fishing vessel 2 would have similar fouling ratings when considering the fishing season. However, as explained before in this section, each antifouling coating reaches the fouling rating of 30 at different times. Therefore, the impacts of each antifouling coating applied on the fishing vessel 2 would show different impacts.

To summarise, based on the SPC antifouling coatings' fouling results and their fouling ratings on a trawler operating in the Black Sea by the end of a fishing season, a ranking can be made from the best to the worst antifouling performance by different coatings in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (uncoated) as shown in Figure 5-16.

The next step was to convert the fouling ratings of the selected coatings into k_s values for the fishing vessel 2. Equation 33 was used for this conversion. Equivalent sand roughness heights of the fouling conditions over time are presented in Figure 5-17.

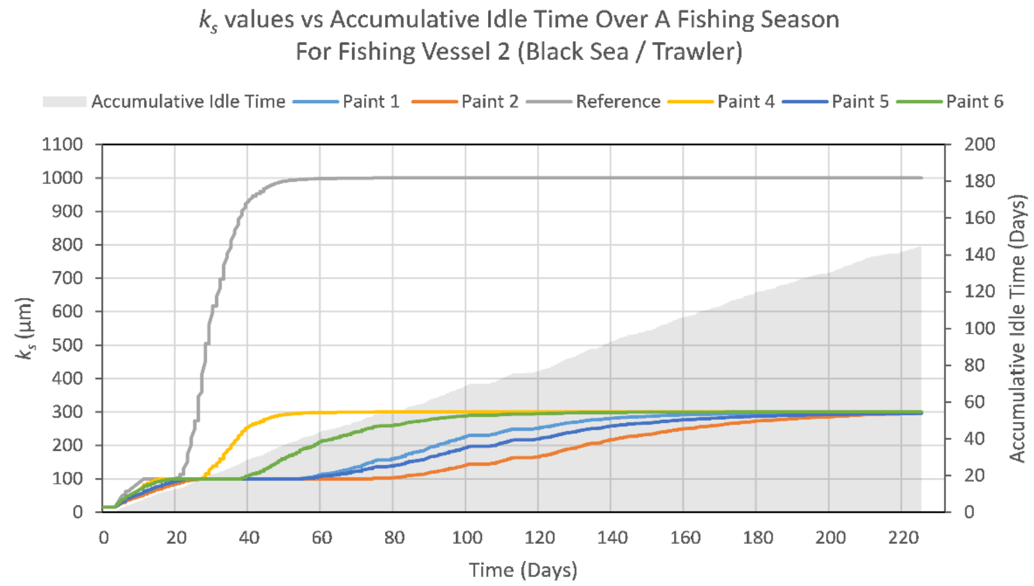


Figure 5-17: Equivalent Sand Roughness Heights (ks) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Idle Time.

As shown in Figure 5-17, each coating requires a different fishing activity duration to reach its maximum k_s values. Moreover, k_s values of the antifouling coatings for the fishing vessel 2 reach a maximum value of 300 whilst the Reference coating (uncoated) reaches the k_s value of 1000 μm. To be more specific, the Reference coating (uncoated) reached to k_s value of 1000 μm as the highest k_s value. Next, Paint 4, Paint 6, Paint 1, Paint 5 and Paint 6 reached k_s value of 300 μm by the end of the fishing season. Within this point, it should be noted that each antifouling coating reaches its maximum k_s values at different times, as illustrated in Figure 5-17. Although all of the antifouling coatings reach the ks value of 300 by the end of the fishing season, a ranking can be made depending on the time that each coating reaches its maximum k_s values. Nevertheless, based on the SPC antifouling coatings' fouling results and their k_s value conversions on a trawler operating in the Black Sea by the end of a fishing season, a ranking can be made from the best to the worst antifouling performance in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference coating (uncoated) as shown in Figure 5-17.

Furthermore, as a result of the conversion conducted between fouling ratings and k_s values using Equation 33, ranking results in k_s values of the antifouling coatings show a good agreement with the fouling rating rankings as shown in Figure 5-16. In Figure 5-17, it can be seen that once the k_s values reach k_s values of 100 μm, it takes a particular time for each antifouling coating to go beyond and show an increase in k_s values. As explained before in Section 5.1.1, this condition occurs due to the correction made when converting NSTM fouling ratings to k_s values, using Equation 33. As explained in Section 5.3 in detail, a regression curve was fitted to calculate the k_s values for the NSTM fouling rating values. However, because the fitted model behaves as if there is a decrease in k_s values after reaching 100 μm which is the ks value of NSTM fouling rating of 10 and 20, a correction was made to the NSTM rating and k_s regression. Therefore, once the fouling ratings of the antifouling coatings reach the fouling rating of 7.98, k_s values were set to 100 μm until the fouling rating reached 20.3. In addition, the vast difference in k_s values between the antifouling coatings and the Reference coating (uncoated) is due to the difference between the equivalent k_s values of the fouling ratings of 30 and 40 according to Table 4-7. As shown in Table 4-7, whilst the fouling rating of 40 equals to k_s value of 1000 μm, fouling rating of 30 equals to k_s value of 300 μm. Therefore, once the Reference coating (uncoated) goes beyond the fouling rating of 30, k_s value of the Reference (uncoated) shows a significant increase in comparison to the antifouling coatings' k_s values as the maximum fouling rating for the antifouling coatings is 30 by the end of the fishing season for the fishing vessel 2.

Similar to the fouling rating increases in Figure 5-16, k_s values show similar increases in the first 30 days of the fishing activities for the fishing vessel 2. Due to a faster increase in accumulative idle time, k_s values of the antifouling coatings and the Reference (uncoated) show a sudden increase in the first 30 days. Furthermore, it can be seen from Figure 5-17 that all of the SPC antifouling coatings reach to k_s value of 100 μm after approximately 30 days of fishing operation for the fishing vessel 2. Furthermore, when the time period from the 30th day to the end of the fishing season is considered, it can be seen from Figure 5-17 that all of the antifouling coatings' k_s values reach 300 μm and Reference coating's (uncoated) k_s value reach 1000 μm.

Once the relevant k_s values of the surfaces coated with the selected antifouling coatings over time were obtained, ΔC_F values for fishing vessel 2 were calculated using the approach presented in Section 5.3. Added resistance diagrams of the fishing vessel 2, cruising at design speed and coated with the selected antifouling coatings over time, is plotted and presented in Figure 5-18.

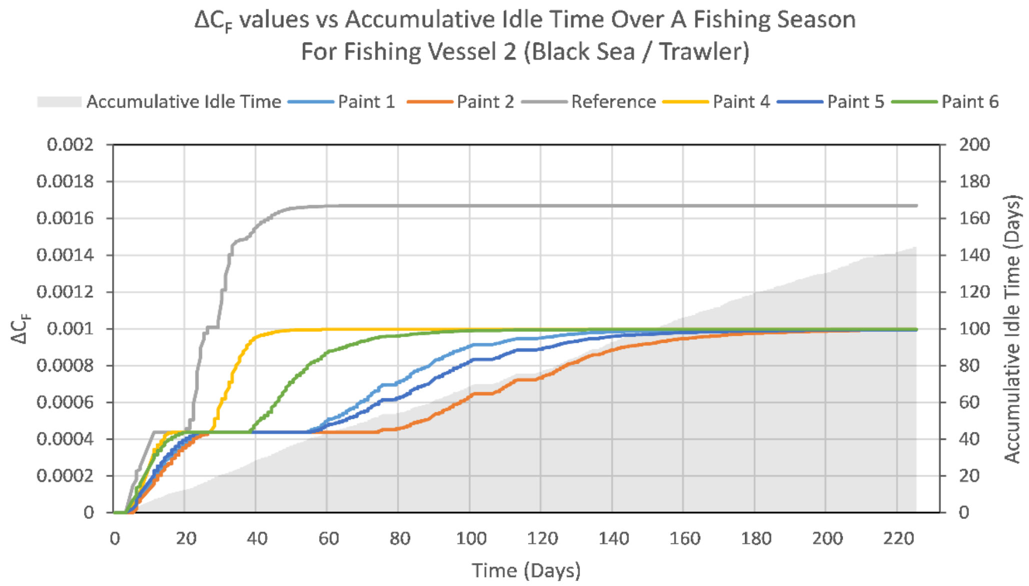


Figure 5-18: Frictional Resistance Differences (ΔC_F) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Idle Time.

As explained in detail in Section 5.3, ΔC_F values were obtained using the practical diagrams from Demirel et al. (2019)'s study and k_s values from the field tests presented in Chapter 4. In addition, ship speed and LOA of the ship were used as input to calculate ΔC_F values. Therefore, as the LOA and the ship speed were taken constants in this case study, the only changing parameter was considered as the k_s values of the fouling conditions over time for each antifouling coating when calculating the ΔC_F values. Nevertheless, looking at Figure 5-18, the increase in ΔC_F values for each coating show similarities with the increase in k_s values of each antifouling coating between certain periods of the fishing season for the fishing vessel 2 (such as the first month and the rest of the fishing season). The similarities between the k_s and ΔC_F values increases can be seen by comparing Figure 5-17 and Figure 5-18.

As it can be seen from Figure 5-18, that each coating requires a different fishing activity duration to reach its maximum ΔC_F values. ΔC_F values of the antifouling coatings for the fishing vessel 2 reach a maximum value of 0.99 x 10^{-3} whilst the Reference (uncoated) reaches the value of 1.66 x 10^{-3} in a fishing season. In addition, it can be seen that accumulative idle time and the increases in the ΔC_F values show relevance with each other. In other words, the faster the accumulative idle time increases, the quicker ΔC_F values increase. Therefore, based on the SPC antifouling coatings' fouling results and their ΔC_F value conversions on a trawler operating in the Black Sea by the end of a fishing season, a ranking can be made from the best to the worst antifouling performance in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (uncoated) as shown in Figure 5-18. Furthermore, it should be noted that obtained ΔC_F values for the fishing vessel 2 cruising at her design speed under certain fouling conditions show similar results compared to the values shown in Figure 2-15 (practical added resistance diagrams).

After obtaining the differences between smooth and rough frictional resistance coefficients (ΔC_F) of the surfaces coated with the selected antifouling coatings, Equation 12 was used to calculate the percentage increase in effective power ($\%\Delta P_E$) for the fishing vessel 2. The increase of P_E values over time for the fishing vessel 2 coated with the selected antifouling coatings were plotted and illustrated in Figure 5-19.

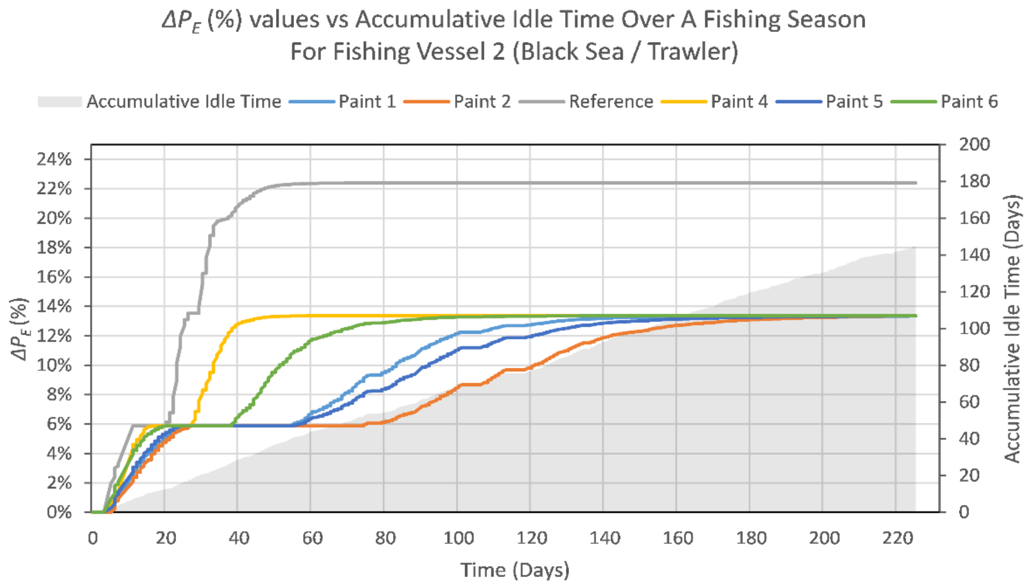


Figure 5-19: % Increase in the Effective Powers of Fouled Surfaces ($\%\Delta P_E$) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Idle Time.

Examining the results in Figure 5-19 shows that the biofouling causes from 13.34% to 22.39% increase in effective power at the design speed for a trawler fishing in the Black Sea by the end of a fishing year. In other words, if fishing vessel 2 is not coated with an antifouling coating (Reference coating), biofouling can cause 22.39% increase in effective power by the end of the fishing season. Within this point, that should be noted that it is not realistic to estimate an uncoated fishing vessel 2's % increase in effective power as no fishing vessel operates with an uncoated hull. However, considering the fact that one of the aims of this research is "to train the fishermen on selecting the most suitable antifouling coating", showing the worst-case scenario (as the uncoated vessel) would be necessary in order to emphasise antifouling coatings' abilities in preventing the penalties caused by biofouling. In other words, in order to emphasise the importance and efficiency of the antifouling coatings in the fight with the biofouling, an uncoated fishing vessel 2 scenario (with reference coating) was also included in the case studies.

Moreover, if fishing vessel 2 is coated with any of the selected antifouling coatings, biofouling causes 13.34% increase in effective power by the end of the fishing season. Furthermore, it can also be seen that, due to biofouling, all of the antifouling coatings applied on the fishing vessel 2 show the same % increase in the effective power by the end of the fishing season. However, when antifouling coatings reach their maximum % increases in effective power are examined, it can be seen that antifouling coatings reach their maximum % increase in effective power at different times. To put it another way, once an antifouling coating reaches its maximum % increase in effective power, the poorer performance is observed, and the impacts of the biofouling on the fishing vessel 2 are higher in comparison to the rest of the selected SPC coatings. Nevertheless, based on the SPC antifouling coatings' fouling results by the end of a fishing season, from higher to lower, power requirements of the fishing vessel 2 coated with the selected antifouling coatings would be in the following order: Reference coating (uncoated), Paint 4, Paint 6, Paint 1, Paint 5 and Paint 2. Therefore, whilst Paint 2 shows the best antifouling performance, Paint 4 shows the poorest antifouling performance in the fight with the biofouling, considering the fishing vessel 2 in a fishing season.

Moreover, looking at Figure 5-19, coating fishing vessel 2 with any of the selected antifouling coatings do not show any difference by the end of the fishing season. However, a key point has to be stated at this point. It should be noted that the amount of the savings between the antifouling coatings can change depending on the operational profile, ship characteristics such as LOA, the idle time that the fishing vessel spent during her fishing activities, the length of the fishing season, and fouling ratings of the relevant coatings. For example, if fishing vessel 2 lasted her fishing activities after 60 days of fishing, coating fishing vessel 2 with the best antifouling coating (Paint 2) would save approximately 7.49% in effective power compared to fishing vessel 2 coated with the worst antifouling coating (Paint 4). Therefore, with the fouling accumulation on the coatings, coating fishing vessel 2 with the best antifouling coating can save up to 7.49% in effective power compared to any of the selected antifouling coatings (Paint 1, Paint 4, Paint 5, and Paint 6).

Finally, to comment on the periods of the fishing season, % increases in the effective power, and the idle time spent for the fishing vessel 2 over a fishing season, Figure 5-19 and Figure 5-18 can be compared. Due to the reason that the ΔC_F values are directly used to calculate the %ΔP_E using Equation 12, the same comments for the ΔC_F values increase over time, and the accumulative idle time spent for the fishing vessel 2 can be applied on the % increase in ΔP_E over the fishing season for the fishing vessel 2. For example, in Figure 5-18, it can be seen that in the first 2 months of the fishing season, the increase in the ΔC_F values is faster than the rest of the fishing season for Paint 2. Moreover, in Figure 5-19, the % trend in ΔP_E over time shows significant similarities with the ΔC_F trends illustrated in Figure 5-18.

Accumulative fuel consumption over time is estimated using the procedure detailed in Section 5.4. Main engine output power (kW) was determined with the service allowance, and then the MEFC was obtained using the main engine's manual. Furthermore, installed main engine power is 551 kW and MEFC was calculated as 76 litres per hour from the main engine's manual. Figure 5-20 shows the accumulative fuel consumption (L) increase due to the biofouling of fishing vessel 2 with the selected SPC antifouling coatings applied over time in a fishing operation year. It should be noted that the idle time from the operation profile was deducted. The fuel consumption over time was estimated only when the ship is in cruising state (active time).

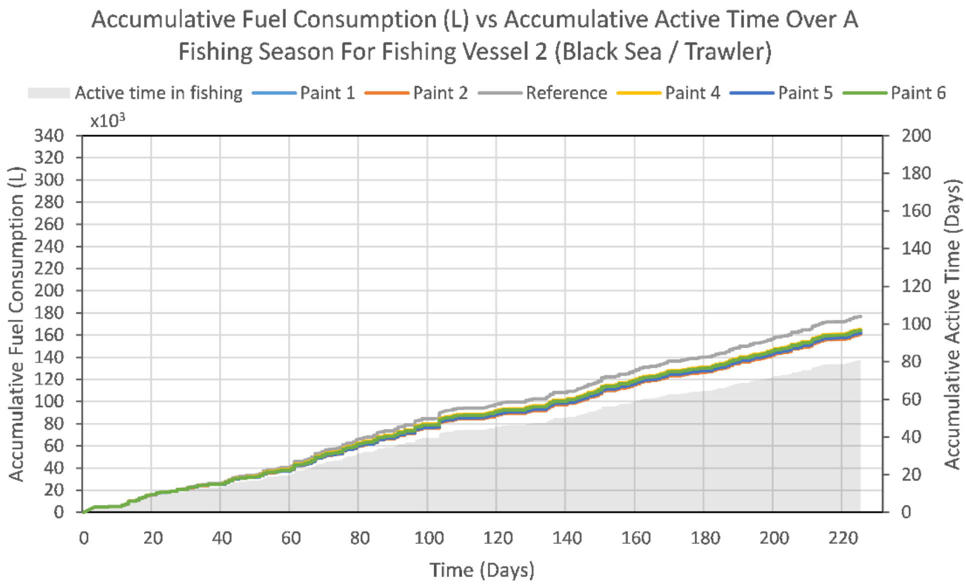


Figure 5-20: Accumulative Fuel Consumption (Litres) of the Selected SPC coatings and Reference coating (Uncoated) Applied to Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season with the Accumulative Active (Cruising) Time.

From Figure 5-20, it can be seen that a trawler coated with the selected antifouling coatings (and the uncoated reference coating) operating in the Black Sea region can consume from 160 to 177 thousand litres of fuel when a fishing season is considered. Moreover, as shown from Figure 5-20, the accumulative active time and the accumulative fuel consumption increase shows similar trends. However, the increase in the accumulative fuel consumption becomes faster than the accumulative active time by the end of the fishing year. Therefore, it can be seen that whilst the trends between accumulative active time and the accumulative fuel consumption are closer to each other at the beginning of the fishing season, the trends become further apart by the end of the fishing season. For that reason, a comment may be suitable as this gap increase over time can be directly linked to the biofouling growth over time.

In addition to Figure 5-20, a further bar chart was plotted to detail total fuel consumption (L) over a fishing season for fishing vessel 2 coated with the selected antifouling coatings and Reference coating (uncoated). Figure 5-21 shows the total fuel consumption (litres) of the selected SPC coatings and Reference (uncoated) applied on the fishing vessel 2 (trawler fishing in the Black Sea region) over a fishing season.

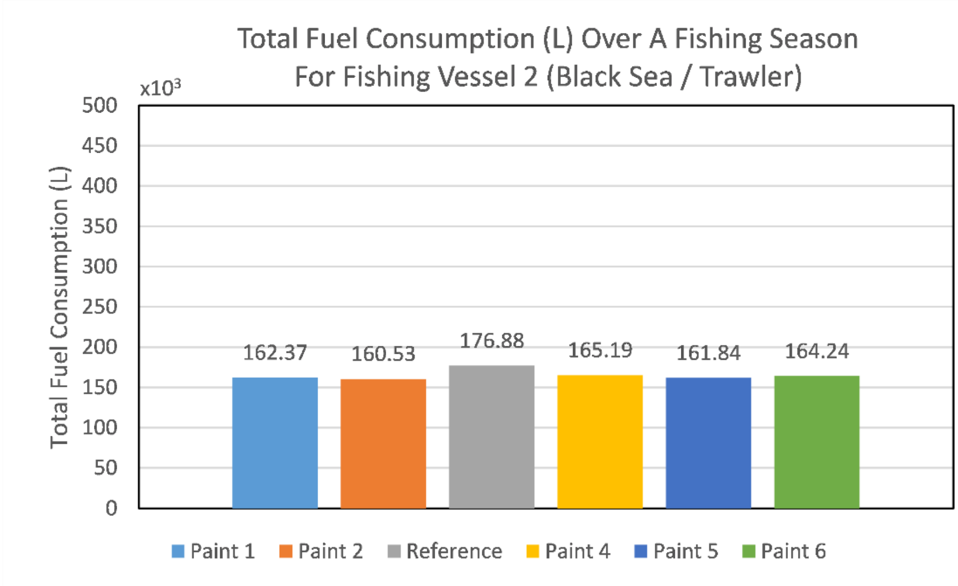


Figure 5-21: Total Fuel Consumption (Litres) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season.

Looking at Figure 5-21, it can be seen that coating a trawler with the selected SPC coatings or Reference coating (uncoated) can consume up to 168.88 thousand litres of fuel in a fishing season. More specifically, fishing vessel 2 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4 and Reference (Uncoated) respectively consume 160.53, 161.84, 162.37, 164.24, 165.19, and 176.88 thousand litres of fuel in a fishing season. In addition to that, it can be seen from Figure 5-21, a simple antifouling coating selection decision for a trawler fishing in the Black Sea can save up to 4660 litres of fuel (when Paint 2 and Paint 4 are compared) for the fishing vessel 2 by the end of a fishing season. Moreover, by only coating fishing vessel 2 with any of the selected antifouling coatings, up to 16350 litres of fuel (when Paint 2 and Reference coating are compared) can be saved in a fishing season. It should be noted that these numbers represent fuel consumption with the biofouling accumulation on the selected antifouling coatings by the end of the fishing season, which were applied on the fishing vessel 2. Therefore, in order to illustrate how coating fishing vessel 2 with any of the selected antifouling coatings would save in comparison to each other in fuel consumption by the end of the fishing season, a further figure was plotted and presented in Figure 5-22. Figure 5-22 shows total fuel consumption savings (%) for the selected SPC coatings in comparison to Reference (uncoated) applied on the fishing vessel 2 (trawler fishing in the Black Sea region) over a fishing season.

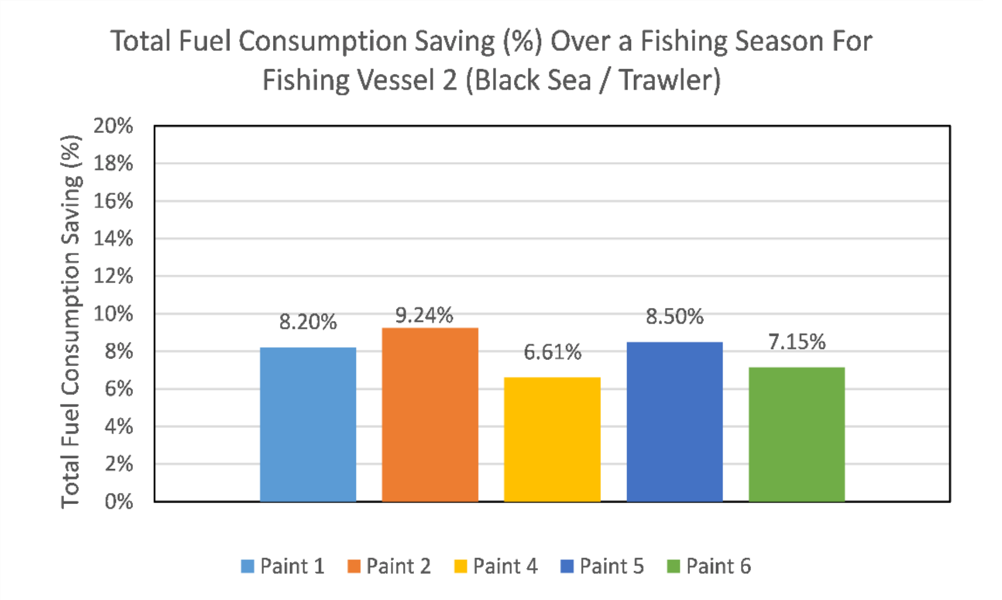


Figure 5-22: Total Fuel Consumption Savings (%) for the Selected SPC Coatings in Comparison to Reference (Uncoated) Applied on the Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season.

As shown in Figure 5-22, coating fishing vessel 2 with any of the selected antifouling coatings in comparison to Reference (uncoated) can save between 6.61% and 9.24% in total fuel consumption. To be more specific, if fishing vessel 2 is coated with Paint 2, Paint 5, Paint 1, Paint 6, and Paint 4, respectively, 9.24%, 8.5%, 8.2%, 7.15%, and 6.61% in fuel consumption can be saved in comparison to Reference coating (uncoated) by the end of a fishing season. Demonstrating these percentages is essential to underline the vital role of antifouling coatings in preventing the penalties caused by biofouling. More importantly, when the selected antifouling coatings are compared with each other, it can be seen that making a simple antifouling coating selection decision for a trawler fishing in the Black Sea can save up to 2.63% (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) of the fuel consumed by the end of a fishing season. Further saving derivations can be made by comparing other selected antifouling coatings illustrated in Figure 5-22. It should be noted that due to having a direct link between the fuel consumption, fuel cost, and CO_2 emissions released into the atmosphere, the saving numbers (%) presented in Figure 5-22 is valid for the total fuel cost and total CO_2 emission savings by the end of fishing season for the fishing vessel 2.

In addition, a bar chart showing the total fuel cost for the fishing vessel 2 by the end of the fishing year is plotted and presented in Figure 5-23. Figure 5-23 shows the total fuel cost (£) of the selected SPC coatings and Reference (uncoated) applied on the fishing vessel 2 (trawler fishing in the Black Sea region) over a fishing season.

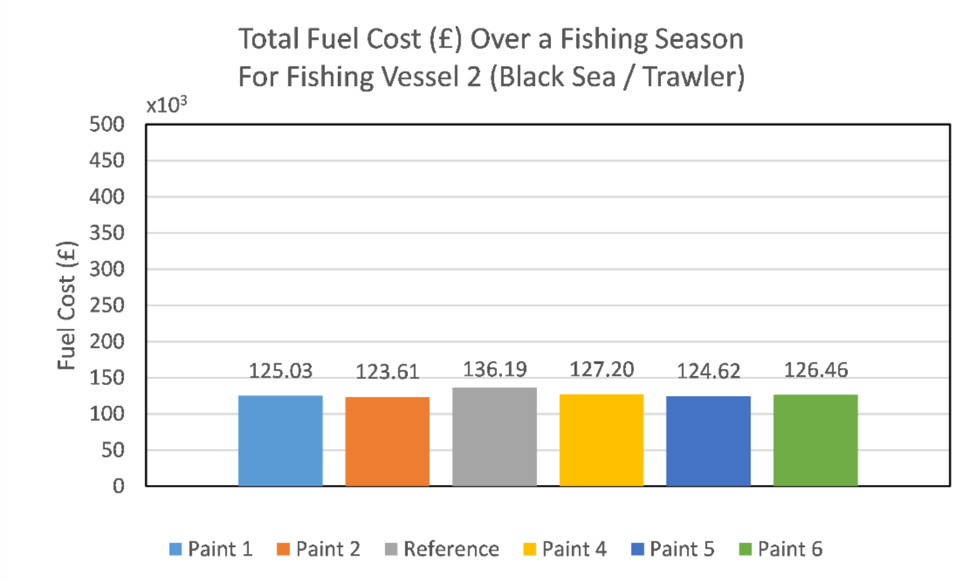


Figure 5-23: Total Fuel Cost (£) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season.

Looking at Figure 5-23, it can be seen that coating a trawler with the selected SPC coatings and Reference (uncoated) can cause up to 136.19 thousands GBP fuel cost in a fishing season. To be more specific, the total fuel cost for the fishing vessel 2 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4 and Reference (uncoated), respectively, can be 123.61, 124.62, 125.03, 126.46, 127.20 and 136.19 thousands of GBP. It should be noted that the fuel costs presented in Figure 5-23 are the most recent fuel prices, as detailed in Section 5.4. Moreover, these costs may be too much when considering the countries surrounding the Black Sea fishing region for a yearly based fuel cost. However, considering that the fishing vessels benefit from fuel subsidies in varying amounts in different countries, the amount that the fishermen spent for the fuel cost may be lower than estimated and presented in Figure 5-23. Because the fuel subsidies that a fishing vessel receives depend on many factors, such as LOA, country, and type of fisheries, these numbers are estimated without considering the fuel subsidies as a simpler approach (Schuhbauer et al., 2020). It should also be noted that it would be easier to calculate the fuel costs if the carbon tax, which has been discussed among the authorities, is introduced as subsidies will disappear. It can be seen in Figure 5-23, by only coating fishing vessel 2 with any of the selected antifouling coatings, up to 12580 GBP for fuel cost (when Paint 2 and Reference are compared) can be saved in a fishing season. More importantly, a simple antifouling coating selection decision for a trawler fishing in the Black Sea can save up to 3590 GBP for fuel cost (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) by the end of a fishing season.

In addition, a further bar chart was plotted to detail total CO_2 emission (tonnes) over a fishing season for fishing vessel 2 coated with the selected SPC coatings and Reference coating (uncoated). Figure 5-24 shows the total CO_2 emission (tonnes) of the selected SPC coatings and Reference (uncoated) applied on the fishing vessel 2 (trawler fishing in the Black Sea region) over a fishing season.

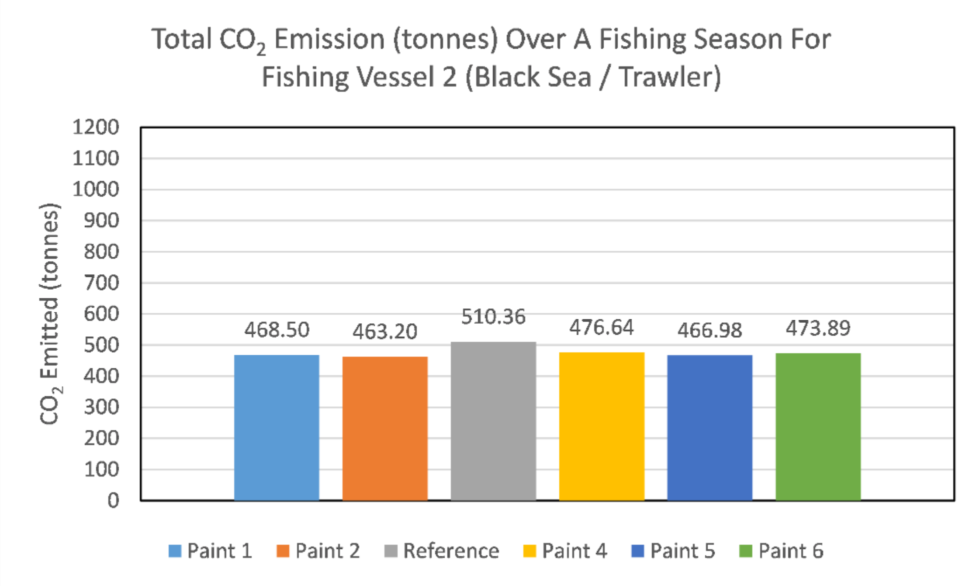


Figure 5-24: Total CO_2 emission (tonnes) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 2 (Trawler Fishing in the Black Sea Region) Over a Fishing Season.

Looking at Figure 5-24, it can be seen that coating a trawler with the selected SPC coatings or Reference (uncoated) can emit up to 510.36 tonnes of CO_2 into the atmosphere. More specifically, fishing vessel 2 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4 and Reference (Uncoated) respectively emit 463.2, 466.98, 468.5, 473.89, 476.64 and 510.36 tonnes of CO_2 into the atmosphere by the end of a fishing season. More importantly, it can be seen in Figure 5-24 that a simple antifouling coating selection decision for a trawler fishing in the Black Sea can stop up to 13.44 tonnes of CO_2 emitted into the atmosphere (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) for the fishing vessel 2 by the end of a fishing season. Moreover, by only coating fishing vessel 2 with any of the selected antifouling coatings, up to 47.16 tonnes of CO_2 emission into the atmosphere (when Paint 2 and Reference coating are compared) can be prevented by the end of a fishing season in comparison to uncoated (Reference) fishing vessel 2.

5.6.3 Case Study 3: Antifouling Coatings Performances for an Industrial Purse Seiner Fishing in the Mediterranean Sea

To represent the biofouling performances of the selected antifouling coatings used in the field tests on a fishing vessel, fishing vessel 3 was selected as case study 3. Following that, accumulative idle times of the fishing vessel 3, illustrated in Figure 5-6, were considered to be used as an input into Uzun (2019)'s time-based biofouling growth model. It should be noted that the selected antifouling coatings that were used in the field tests were also taken as an input into Uzun (2019)'s time-based biofouling growth model. Next, Uzun (2019)'s time-based biofouling growth model was used to predict the biofouling growth on the fishing vessel 3's hull (coated with the selected SPC coatings) based on her operation profile in a fishing season. After that, biofouling growth over time for fishing vessel 3, coated with selected antifouling coatings, were plotted and illustrated in Figure 5-25. In addition to that, the accumulative idle time of fishing vessel 3 against fishing activity time in total was also plotted over and illustrated in Figure 5-25.

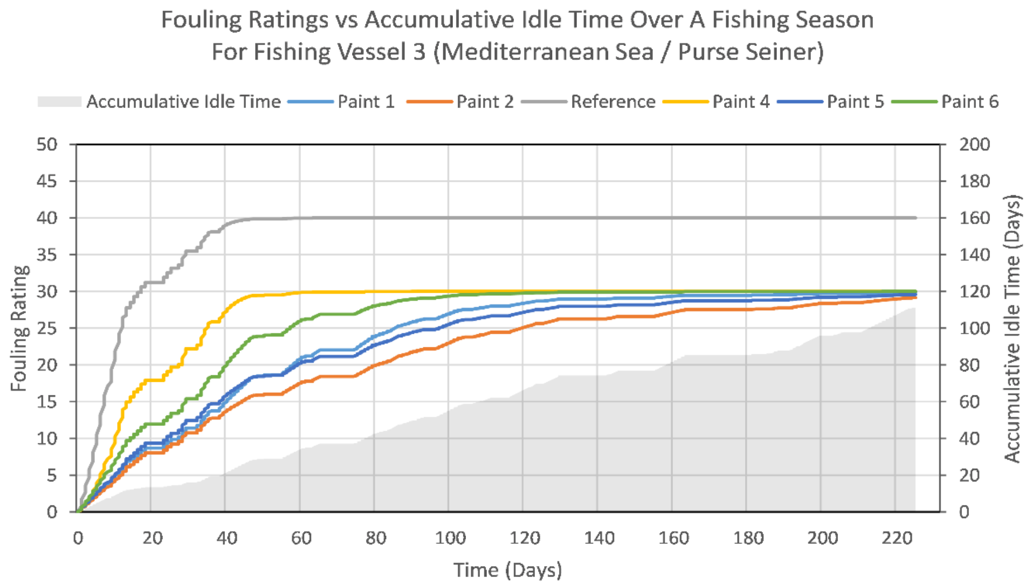


Figure 5-25: Fouling Ratings of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 3 (Purse Seiner Fishing in the Mediterranean Sea Region) Over a Fishing Season with the Accumulative Idle Time.

It can be seen from Figure 5-25 that each coating requires different fishing activity times to reach its maximum fouling ratings. Moreover, the fouling growth of each antifouling coating and the accumulative idle time relation over time is visible. In other words, it can be seen that the more idle time increases, the more fouling growth over the antifouling coatings occurs.

Not surprisingly, whilst the Reference (uncoated) coating reached its maximum rating as the earliest, Paint 4 followed it as the least successful coating against the fight with biofouling. It took nearly 65 days of fishing activity for the Paint 4 to reach its maximum fouling rating of heavy slime fouling accumulation (fouling rating 30). Furthermore, the Reference (uncoated) coating took almost 60 days to reach its maximum fouling rating: small calcareous fouling accumulation (fouling rating 40). It took nearly 135 days of fishing activity for the Paint 6 to reach its maximum fouling rating of heavy slime accumulation (fouling rating 30). On the other hand, although it is difficult to identify in Figure 5-25, Paint 2, Paint 5, and Paint 1 did not reach their maximum fouling ratings of heavy slime accumulation (fouling rating 30) by the end of the fishing season for fishing vessel 3. That should be noted that these fouling ratings are based on the relevant coatings' immersion test results, as detailed in Section 4.5.1. To give an example, immersion test panels' accumulation results from Figure 4-14 for Paint 2 showed that the fouling rating of 30 is reached after nearly 150 idle days (which is the idle time spent in marine water). Therefore, up until the approximately 150th idle day in a fishing vessel's operation time, Paint 2 is not expected to reach the fouling rating of 30. This situation can be seen in Figure 5-25 when the idle time and the fouling ratings of the relevant antifouling coatings are compared. Overall, Paint 2, Paint 5 and Paint 1 showed better antifouling performance in comparison to Paint 4 and Paint 6's antifouling performances, as shown in Figure 5-25.

Furthermore, considering the first 30 days of the fishing season for fishing vessel 3, it can be seen that the first month's fouling ratings show sudden and a similar increase compared to each other, with Reference coating (uncoated) showing the poorest performance in comparison to the antifouling coatings. This similar increase in the fouling condition can be attributed to idle time spent in the first month in the operational profile of the fishing vessel 3. As shown in Figure 5-25, in the first 30 days of her fishing activities in a fishing season, fishing vessel 3 spent nearly 15 idle (stationary) days. In other words, almost half of the first month's fishing activities were conducted whilst the fishing vessel was in a stationary condition. Therefore, the fouling ratings showed a sudden increase in a short time due to the logistic growth model fitting for the relevant antifouling coating's immersion test results, as shown in Figure 4-14.

Next, when the second month in the fishing season for fishing vessel 3 is considered, it can be seen that the growth rate in the fouling ratings is lower in comparison to the first month's accumulation results. In addition to the Reference coating's (uncoated) poorest antifouling performance, Paint 4's fouling ratings increase to the highest fouling rating point (fouling rating 30) earliest, making it the poorest antifouling coating performance. Therefore, the second month of fishing for vessel 1 can be attributed to the duration when the antifouling coatings start losing their efficiency in the fight with the biofouling. It should also be noted that the idle time spent during the second month of the fishing season for fishing vessel 3 shows a similar increase with the fouling rating increases of the antifouling coatings, as shown in Figure 5-25.

Moreover, the idle time increase in the second month of the fishing season for fishing vessel 3 is higher than the first month's increase in accumulative idle time.

For fishing vessel 3, from the 60th day to the end of the fishing season, fouling ratings show a relatively smaller increase than the first 2 months' fouling rating increases. As shown in Figure 5-25, from the 60th to the end of the fishing season, whilst Paint 4 and Reference (uncoated) show no increase in fouling ratings. Nevertheless, Paint 2, Paint 5, Paint 1, and Paint 6 show relatively small increases compared to the first 60 days of the fishing season. Moreover, once Paint 6 reaches its maximum fouling rating of heavy slime accumulation (fouling rating 30), same as the Reference coating (uncoated) and Paint 4, no fouling rating increase is observed. This condition is due to not reaching the required idle time for the increase in fouling ratings. To be more specific, fishing vessel 3's fishing season takes 225 days, as stated before, and yet the accumulative idle time spent in the fishing season is 111 days for fishing vessel 3. Therefore, as each antifouling coating requires different idle times to reach its maximum fouling ratings, a particular time in idle time is required. For example, it can be seen from Figure 4-12 that the Reference coating's (uncoated) fouling rating does not go beyond the fouling rating of 40 up until the approximately 200th day. Therefore, if there was a longer-lasting fishing season for the fishing vessel 3 (for example, 500 days of fishing season) and if the fishing vessel 3 spent 200 days idle in that fishing season, the fouling rating for the Reference (uncoated) would then start increasing after that moment. Similar comments can be made for Paint 4 and Paint 6.

A comparative performance assessment indicates that reference (uncoated) coating reached to fouling rating of 40 as the highest fouling rating. Next, Paint 4 and Paint 6 reached a fouling rating of 30 by the end of the fishing season. Within this point, that should be noted that Paint 4 reaches the fouling rating of 30 earlier than Paint 6, which makes Paint 4 a less successful antifouling coating compared to Paint 6. Following that, Paint 1 reached a fouling rating of 29.8, Paint 5 reached a fouling rating of 29.6, and Paint 2 reached a fouling rating of 29.1 by the end of the fishing season. To summarise, based on the SPC antifouling coatings' fouling results and their fouling ratings on a purse seiner operating in the Mediterranean Sea by the end of a fishing season, a ranking can be made from the best to the worst antifouling performance in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference coating (uncoated) as shown in Figure 5-25.

The next step was to convert the fouling ratings of the selected coatings into k_s values for the fishing vessel 3. Equation 33 is used for this conversion. Equivalent sand roughness heights of the fouling conditions over time are presented in Figure 5-26. Additionally, the accumulative idle time of fishing vessel 3 against total fishing activity time was also plotted over and illustrated in Figure 5-26.

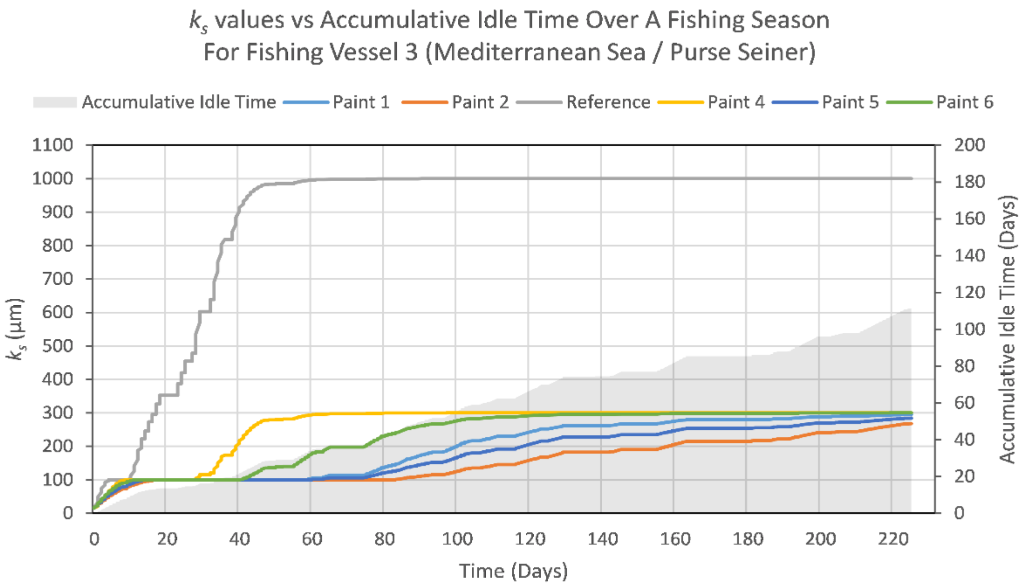


Figure 5-26: Equivalent Sand Roughness Heights (k_s) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 3 (Purse Seiner Fishing in the Mediterranean Sea Region) Over a Fishing Season with the Accumulative Idle Time.

As it can be seen in Figure 5-26, that each coating requires a different fishing activity duration to reach its maximum k_s values. Moreover, k_s values of the antifouling coatings for the fishing vessel 3 reach a maximum value of 300 whilst the Reference coating (uncoated) reaches the value of 1000 μm. To be more specific, the Reference coating (uncoated) reached a k_s value of 1000 μm as the highest k_s value. Next, Paint 4 and Paint 6 reached k_s value of 300 μm by the end of the fishing season. It should be noted that Paint 4 reaches the k_s value of 300 μm earlier than Paint 6 (90 days and 130 days, respectively). Following that, Paint 1 reached the k_s value of 294 μm, Paint 5 reached the k_s value of 284 μm, and Paint 2 reached the k_s value of 268 μm by the end of the fishing season. When a comparison is made between the best and the worst antifouling coating performances, the difference between biofouling accumulation of each antifouling coating's equivalent k_s values can reach up to 32 μm by the end of a fishing season for the fishing vessel 1. Nevertheless, based on the SPC antifouling coatings' fouling results and their k_s value conversions on a purse seiner operating in the Mediterranean Sea by the end of a fishing season, a ranking can be made from the best to worst antifouling performance in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (uncoated) as shown in Figure 5-26.

Furthermore, as a result of the conversion conducted between fouling ratings and k_s values using Equation 33, ranking results in k_s values of the antifouling coatings show a good agreement with the fouling rating rankings as shown in Figure 5-26. In Figure 5-26, it can be seen that once the k_s values reach k_s values of 100 μm, it takes a particular time for each antifouling coating to go beyond and show an increase in k_s values. This condition occurs due to the correction made when converting NSTM fouling ratings to k_s values, using Equation 33. As explained in Section 5.3 in detail, a regression curve was fitted to calculate the k_s values for the NSTM fouling rating values. However, because the fitted model behaves as if there is a decrease in k_s values after reaching 100 μm which is the ks value of NSTM fouling rating of 10 and 20, a correction was made to the NSTM rating and k_s regression. Therefore, once the fouling ratings of the antifouling coatings reach the fouling rating of 7.98, k_s values were set to 100 μm until the fouling rating reached 20.3. In addition, the vast difference in k_s values between the antifouling coatings and the Reference coating (uncoated) is due to the difference between the equivalent k_s values of the fouling ratings of 30 and 40 according to Table 4-7. As shown in Table 4-7, whilst the fouling rating of 40 equals to k_s value of 1000 μm, fouling rating of 30 equals to k_s value of 300 μm. Therefore, once the Reference coating (uncoated) goes beyond the fouling rating of 30, k_s value of the Reference coating (uncoated) shows a significant increase in comparison to the antifouling coatings' k_s values as the maximum fouling rating for the antifouling coatings is 30 by the end of the fishing season for the fishing vessel 3.

Similar to the fouling rating increases shown in Figure 5-25, k_s values show similar increases in the first 30 days of the fishing activities for the fishing vessel 3. Due to 15 idle days spent in the first month's fishing operation, k_s values of the antifouling coatings and the Reference coating (uncoated) show a sudden increase in the first 30 days. Reference (uncoated) coating's k_s value continues increasing after reaching 100 μm while all the SPC antifouling coatings reach the maximum k_s value of 100 μm. Furthermore, when the second month of the fishing season is considered, it can be seen from the Figure 5-26 that Reference (uncoated) coating reaches the maximum ks value of 1000 μm, Paint 4 reach the maximum ks value of 300 μm and Paint 6 begins to show a relatively smaller increase in comparison to the Paint 4 and Reference coating (uncoated). When the period after the second month is considered, it can be seen that, whilst Paint 4 and Reference coating show no increase, Paint 2, Paint 5, Paint 1, and Paint 6 continue to increase in ks values similar to their increase in fouling ratings as illustrated in Figure 5-25.

Once the relevant k_s values of the surfaces coated with the selected antifouling coatings over time were obtained, ΔC_F values for fishing vessel 3 were calculated using the approach presented in Section 5.3. Added resistance diagrams of the fishing vessel 3, cruising at design speed and coated with the selected antifouling coatings over time, is plotted and presented in Figure 5-27. Additionally, the accumulative idle time of fishing vessel 3 against fishing activity time in total was also plotted over and illustrated in Figure 5-27.

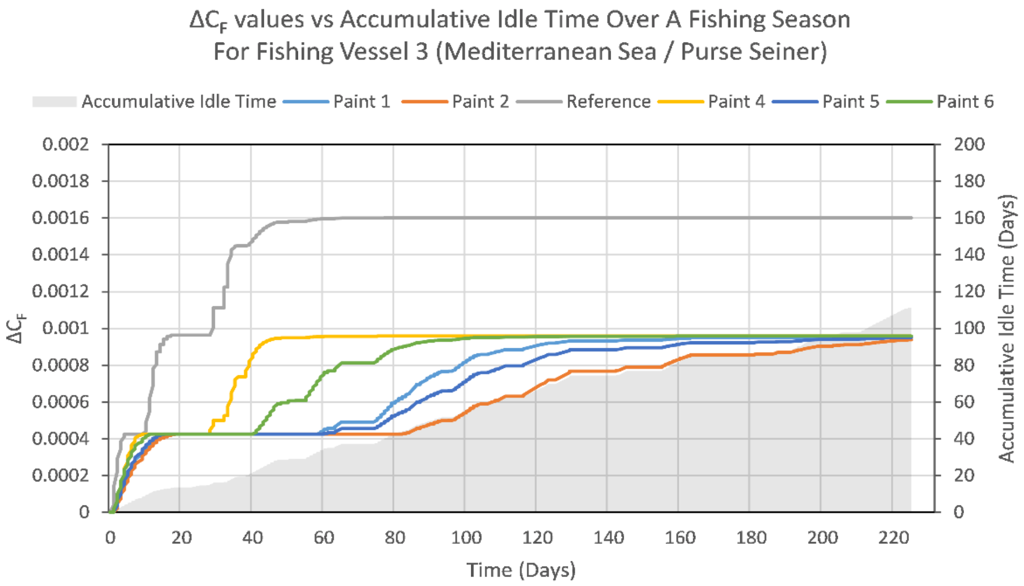


Figure 5-27: Frictional Resistance Differences (*ΔC*$_F$) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 3 (Purse Seiner Fishing in the Mediterranean Sea Region) Over a Fishing Season with the Accumulative Idle Time.

As explained in detail in Section 5.3, ΔC_F values were obtained using the practical diagrams from Demirel et al. (2019)'s study and k_s values from the field tests presented in Chapter 4. In addition, ship speed and LOA of the ship were used as input to calculate ΔC_F values. As the LOA and the ship speed were taken constants in this case study, the only changing parameter was considered as the k_s values of the fouling conditions over time for each antifouling coating when calculating the ΔC_F values. Nevertheless, looking at Figure 5-27, increase in ΔC_F values for each coating show similarities with the increase in k_s values of each antifouling coating between certain periods of the fishing season for the fishing vessel 2 (such as the first month, second month, and the rest of the fishing season). The similarities between the k_s and ΔC_F values increases can be seen by comparing Figure 5-26 and Figure 5-27.

Nevertheless, as shown from Figure 5-27, each coating requires a different fishing activity duration to reach its maximum ΔC_F values. ΔC_F values of the antifouling coatings for the fishing vessel 3 reach a maximum value of 0.95 x 10^{-3} whilst the Reference coating (uncoated) reaches the value of 1.6 x 10^{-3} in a fishing season. In addition, it can be seen that accumulative idle time and the increases in the ΔC_F values show relevance with each other. In other words, the faster the accumulative idle time increases, the quicker ΔC_F values increase. Therefore, based on the SPC antifouling coatings' fouling results and their ΔC_F value conversions on a purse seiner operating in the Mediterranean Sea by the end of a fishing season, a ranking can be made from the best to the worst antifouling performance in the following descending order; Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference coating (uncoated) as shown in Figure 5-27. It should be noted that ΔC_F values obtained for the fishing vessel 3 cruising at her design speed under certain fouling conditions show similar results to those shown in Figure 2-15 (practical added resistance diagrams).

After obtaining the differences between smooth and fouled frictional resistance coefficients (ΔC_F) of the surfaces coated with the selected antifouling coatings, Equation 12 was used to calculate the percentage increase in effective power ($\%\Delta P_E$) for the fishing vessel 3. The increase of P_E values over time for the fishing vessel 3 coated with the selected antifouling coatings were plotted and illustrated in Figure 5-28. Additionally, the accumulative idle time of fishing vessel 3 against fishing activity time in total was also plotted over and illustrated in Figure 5-28.

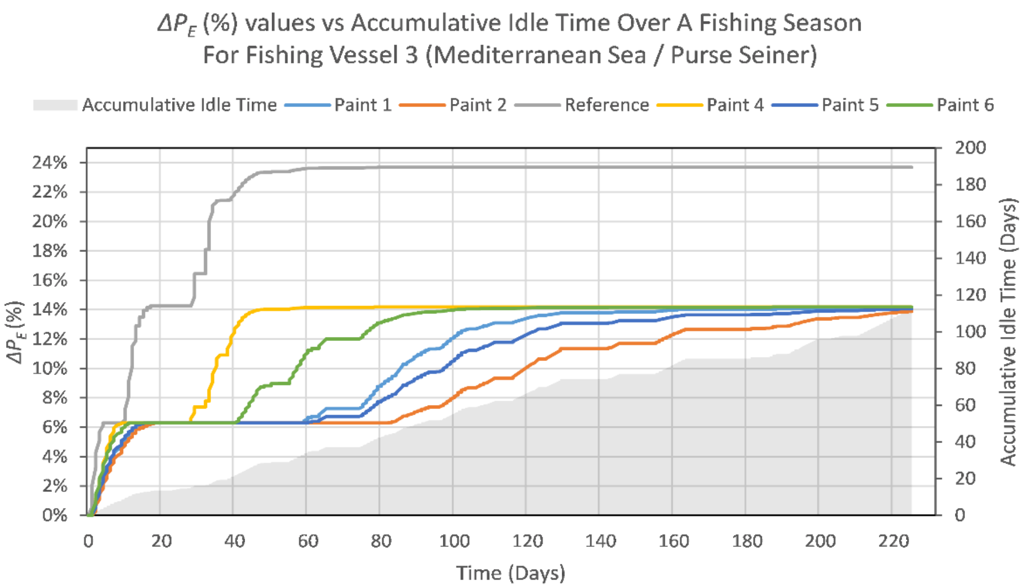


Figure 5-28: % Increase in the Effective Powers of Fouled Surfaces ($\%\Delta P_E$) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 3 (Purse Seiner Fishing in the Mediterranean Sea Region) Over a Fishing Season with the Accumulative Idle Time.

Examining the results from Figure 5-28 shows that the biofouling causes between 13.88% and 23.69% increase in effective power at the design speed for a purse seiner fishing in the Mediterranean Sea at the end of a fishing year. More specifically, if fishing vessel 1 is not coated with an antifouling coating (Reference coating), biofouling can cause a 23.69% increase in effective power by the end of the fishing season. Within this point, that should be noted that it is not realistic to estimate an uncoated fishing vessel's % increase in effective power as no fishing vessel operates with an uncoated hull. However, considering the fact that one of the aims of this research is "to train the fishermen on selecting the most suitable antifouling coating", showing the worst-case scenario (as the uncoated vessel) would be necessary in order to emphasise antifouling coatings' abilities in preventing the penalties caused by biofouling. In other words, in order to emphasise the importance and efficiency of the antifouling coatings in the fight with the biofouling, an uncoated fishing vessel scenario (with reference coating) was also included in the case studies.

Moreover, if the fishing vessel 3 is coated with Paint 4, Paint 6, Paint 1, Paint 5, and Paint 2 separately, biofouling causes, respectively, 14.17%, 14.17%, 14.14%, 14.06%, and 13.88% increase in effective power by the end of the fishing season. Furthermore, it can also be seen that Paint 4 and Paint 6 show the same % increase in the effective power due to biofouling at the end of the fishing season. However, when these two antifouling coatings reach their maximum % increase in effective power, it can be seen that Paint 4 shows an increase of 14.17% after nearly 90 days and yet Paint 6 shows the same % increase after approximately 130 days. Therefore, when a comparison is made between Paint 4 and Paint 6, it can be seen that, due to fouling the maximum % increase in effective power earlier, fishing vessel 3 coated with Paint 4 spends more power in comparison to the fishing vessel 3 coated with the Paint 6 when a complete fishing season is considered.

To put it another way, Paint 4 shows a poorer performance than Paint 6's antifouling performances. Nevertheless, based on the SPC antifouling coatings' fouling results by the end of a fishing season, from higher to lower, power requirements of the fishing vessel 1 coated with the selected antifouling coatings would be in the following order: Reference (uncoated), Paint 4, Paint 6, Paint 1, Paint 5 and Paint 2. Therefore, whilst

Paint 2 shows the best antifouling performance, Paint 4 shows the poorest antifouling performance in the fight with the biofouling, considering the fishing vessel 3 in a fishing season.

Looking at Figure 5-28, coating fishing vessel 3 with the best antifouling coating (Paint 2) can save approximately 0.29% in effective power compared to fishing vessel 3 coated with the worst antifouling coating (Paint 4) by the end of the fishing season. Within this point, it should be noted that the amount of the savings between the best and the worst performing antifouling coatings can change depending on the operational profile, ship characteristics such as LOA, the idle time that the fishing vessel spent during her fishing activities, the length of the fishing season, and fouling ratings. For example, if fishing vessel 3 lasted her fishing activities after 80 days of fishing, coating fishing vessel 3 with the best antifouling coating (Paint 2) would save approximately 7.88% in effective power compared to fishing vessel 3 coated with the worst antifouling coating (Paint 4). Therefore, with the fouling accumulation on coatings, coating fishing vessel 3 with the best antifouling coating can save up to 7.88% in effective power compared to any of the selected antifouling coatings (Paint 1, Paint 4, Paint 5, and Paint 6).

Finally, to comment on the periods of the fishing season, % increase in the effective power, and the idle time spent for the fishing vessel 3 over a fishing season, Figure 5-28 and Figure 5-27 can be compared. Due to the reason that the ΔC_F values are directly used to calculate the $\%\Delta P_E$ using Equation 12, the same comments for the ΔC_F values increase over time, and the accumulative idle time spent for the fishing vessel 3 can be applied on the % increase in ΔP_E over the fishing season for the fishing vessel 3. For example, in Figure 5-27, it can be seen that in the first month of the fishing season, the increase in the ΔCF values is lower than the second month's ΔC_F values. Moreover, in Figure 5-28, the % trend in ΔPE over time shows significant similarities with the ΔC_F trends illustrated in Figure 5-27.

Accumulative fuel consumption over time was calculated by following the procedure detailed in Section 5.4. Main engine output power (kW) was determined with the service allowance, and then the MEFC was obtained using the main engine's manual. Furthermore, installed main engine power is 551 kW and MEFC was calculated as

88.13 litres per hour from the main engine's manual. Figure 5-29 shows the accumulative fuel consumption (L) increase due to the biofouling of fishing vessel 3 with the selected SPC antifouling coatings applied over time in a fishing operation year. It should be noted that the idle time from the operation profile was deducted and so that the fuel consumption over time was estimated only when the ship is in cruising state (active time).

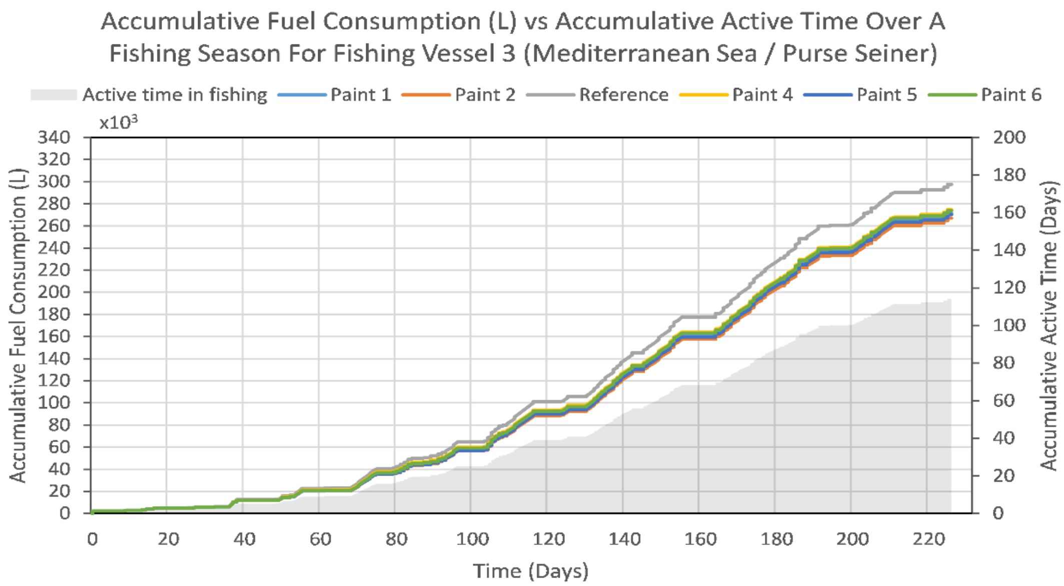


Figure 5-29: Accumulative Fuel Consumption (Litres) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 3 (Purse Seiner Fishing in the Mediterranean Sea Region) Over a Fishing Season with the Accumulative Active (Cruising) Time.

Looking at Figure 5-29, it can be seen that a purse seiner, coated with the selected antifouling coatings (and the uncoated reference coating) operating in the Mediterranean Sea region can consume between 267.11 and 297.65 thousand litres of fuel when a fishing season is considered. In addition, as shown in Figure 5-29, the accumulative active time and the accumulative fuel consumption increase shows similar trends. However, looking at in detail, it can be seen that the increase in the accumulative fuel consumption becomes faster in comparison to the accumulative active time by the end of the fishing year. Therefore, it can be seen that whilst the trends between accumulative active time and the accumulative fuel consumption are closer to each other at the beginning of the fishing season, the trends become further apart by the end of the fishing season. For that reason, a comment may be suitable as this gap increases over time can be directly linked to the biofouling growth over time.

In addition, a further bar chart was plotted to detail total fuel consumption (L) over a fishing season for fishing vessel 3 coated with the selected antifouling coatings. Figure 5-30 shows the total fuel consumption (litres) of the selected SPC coatings and Reference (uncoated) applied on the fishing vessel 3 (purse seiner fishing in the Mediterranean Sea region) over a fishing season.

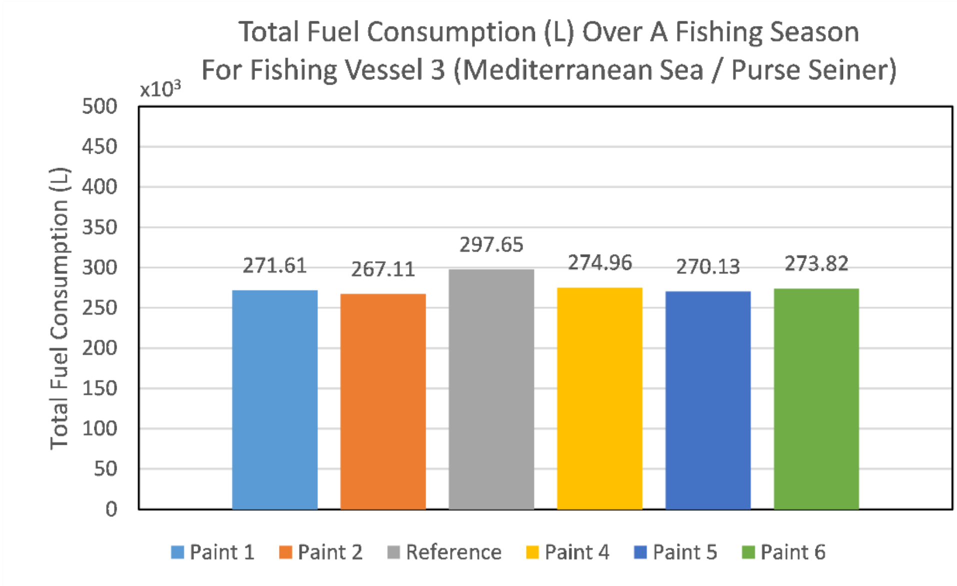


Figure 5-30: Total Fuel Consumption (Litres) of the Selected SPC Coatings and Reference (Uncoated) Applied on Fishing Vessel 3 (Purse Seiner Fishing in the Black Sea Region) Over a Fishing Season.

Looking at Figure 5-30, it can be seen that coating a purse seiner with the selected SPC coatings or Reference (uncoated) can consume up to 297.65 thousand of litres fuel in a fishing season. More specifically, fishing vessel 3 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4 and Reference (Uncoated) respectively consume 267.11, 270.13, 271.61, 273.82, 274.96, and 297.65 thousand of fuel in litres in a fishing season. In addition to that, it can be seen from Figure 5-30, a simple antifouling coating selection decision for a purse seiner fishing in the Black Sea can save up to 7850 litres of fuel (when Paint 2 and Paint 4 are compared) for the fishing vessel 3 by the end of a fishing season. Moreover, by only coating fishing vessel 3 with any of the selected antifouling coatings, up to 30540 litres of fuel (when Paint 2 and Reference coating are compared) can be saved in a fishing season. It should be noted that these numbers represent fuel consumption with the biofouling accumulation on the selected antifouling coatings by the end of the fishing season, which were applied on the fishing vessel 3. Therefore, in order to illustrate how coating fishing vessel 3 with any of the selected antifouling coatings would save in comparison to each other in fuel consumption by the end of the fishing season, a further figure was plotted and presented in Figure 5-31. Figure 5-31 shows total fuel consumption savings (%) for the selected SPC coatings in comparison to Reference (uncoated) applied on the fishing vessel 3 (purse seiner fishing in the Mediterranean Sea region) over a fishing season.

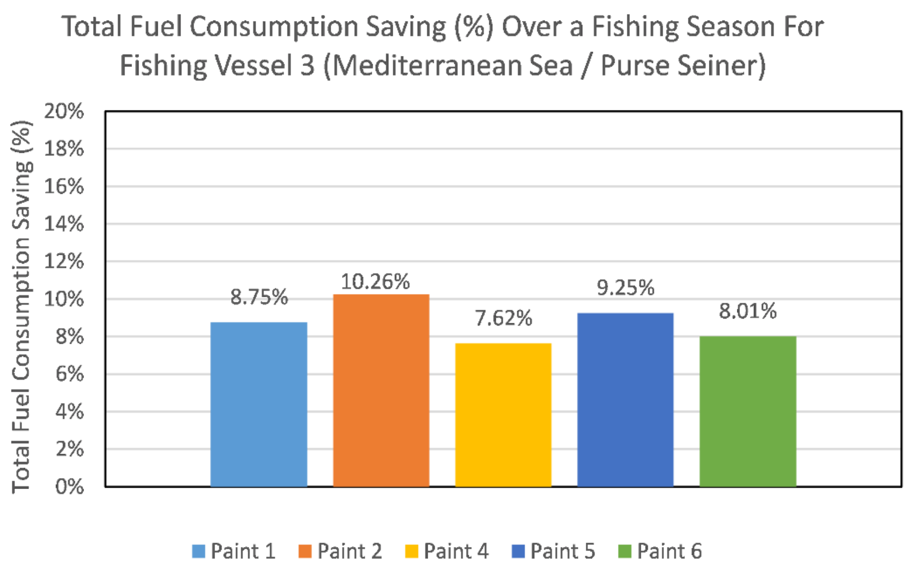


Figure 5-31: Total Fuel Consumption Savings (%) for the Selected SPC Coatings in Comparison to Reference (Uncoated) Applied on the Fishing Vessel 3 (Purse Seiner Fishing in the Mediterranean Sea Region) Over a Fishing Season.

As shown in Figure 5-31, coating fishing vessel 3 with any of the selected antifouling coatings in comparison to Reference (uncoated) can save from 7.62% to 10.26% in total fuel consumption. More specifically, if the fishing vessel 3 is coated with Paint 2, Paint 5, Paint 1, Paint 6, and Paint 4, respectively, 10.26%, 9.25%, 8.75%, 8.01%, and 7.62% in fuel consumption can be saved in comparison to Reference (uncoated) by the end of a fishing season. Demonstrating these percentages is essential to underline the vital role of antifouling coatings in preventing the penalties caused by biofouling. More importantly, when the selected antifouling coatings are compared with each other, it can be seen that making a simple antifouling coating selection decision for a purse seiner fishing in the Black Sea can save up to 2.63% (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) of the fuel consumed by the end of a fishing season. Further saving derivations can be made by comparing other selected antifouling coatings illustrated in Figure 5-31. It should be noted that due to having a direct link between the fuel consumption, fuel cost, and CO_2 emissions released into the atmosphere, the saving (%) presented in Figure 5-31 is valid for the total fuel cost and total CO_2 emission savings by the end of fishing season for the fishing vessel 3.

In addition to the total fuel consumption of the fishing vessel 3 coated with the selected SPC coatings and Reference (uncoated) shown in Figure 5-32, a bar chart showing the total fuel cost for the fishing vessel 3 by the end of the fishing year is plotted and presented in Figure 5-32.

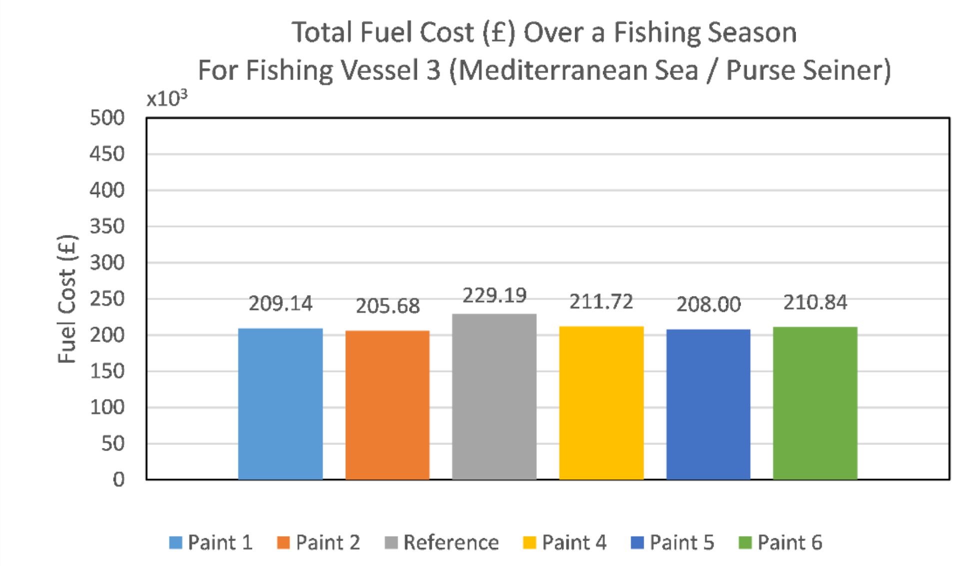


Figure 5-32: Total Fuel Cost (£) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 3 (Purse Seiner Fishing in the Mediterranean Sea Region) Over a Fishing Season.

Looking at Figure 5-32, it can be seen that coating a purse seiner with the selected SPC coatings and Reference (uncoated) can cost up to 229.19 thousands GBP fuel cost in a fishing season. More specifically, the total fuel cost for the fishing vessel 3 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4 and Reference (uncoated), respectively, can be 205.68, 208, 209.14, 210.84, 211.72 and 229.19 thousands of GBP. It should be noted that the fuel costs presented in Figure 5-32 are the most recent fuel prices, as detailed in Section 5.4. Moreover, these costs may be too much when considering the countries surrounding the Black Sea fishing region for a yearly based fuel cost. However, considering that the fishing vessels benefit from fuel subsidies in varying amounts in different countries, the amount that the fishermen spent for the fuel cost may be lower than estimated and presented in Figure 5-32. Because the fuel subsidies that a fishing vessel receives depend on many factors, such as LOA, country, and type of fisheries, these numbers are estimated without considering the fuel subsidies as a simpler approach (Schuhbauer et al., 2020). It should also be noted that it would be easier to calculate the fuel costs if the carbon tax, which has been discussed among the authorities, is introduced as subsidies will disappear. In addition to that, it can be seen from Figure 5-32, by only coating fishing vessel 3 with any of the selected antifouling coatings, up to 23.51 thousands of GBP for fuel cost (when Paint 2 and Reference paint are compared) can be saved in a fishing season. More importantly, a simple antifouling coating selection decision for a purse seiner fishing in the Black Sea can save up to 6.04 thousands GBP for fuel cost (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) by the end of a fishing season.

In addition, a further bar chart was plotted to detail total CO_2 emission (tonnes) over a fishing season for fishing vessel 3 coated with the selected SPC coatings and Reference coating (uncoated). Figure 5-33 shows the total CO_2 emission (tonnes) of the selected SPC coatings and Reference (uncoated) applied on the fishing vessel 3 (purse seiner fishing in the Mediterranean Sea region) over a fishing season.

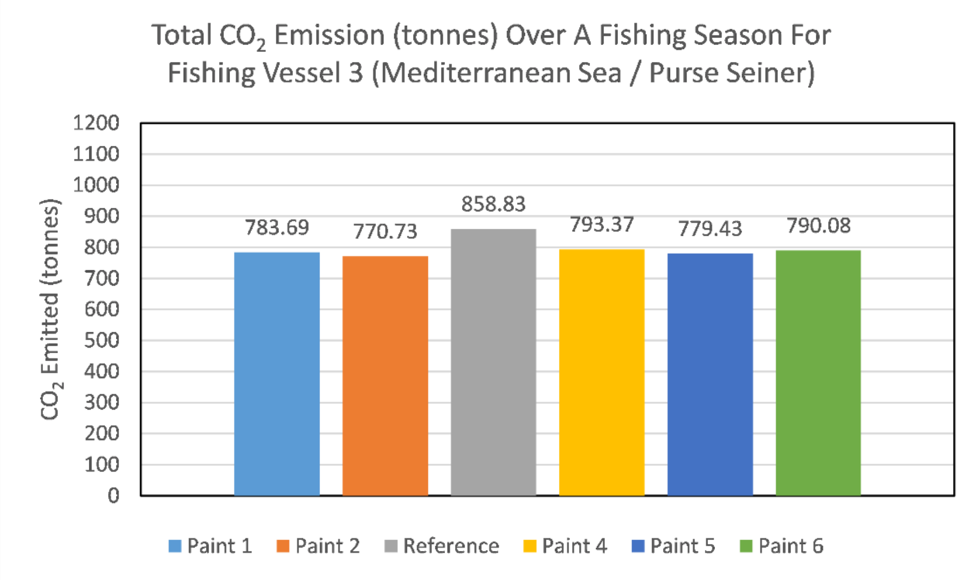


Figure 5-33: Total CO_2 emission (tonnes) of the Selected SPC coatings and Reference (Uncoated) Applied on Fishing Vessel 3 (Purse Seiner Fishing in the Mediterranean Sea Region) Over a Fishing Season.

Looking at Figure 5-33, it can be seen that coating a purse seiner with the selected SPC coatings or Reference (uncoated) can emit up to 858.83 tonnes of CO_2 into the atmosphere. More specifically, fishing vessel 3 coated with Paint 2, Paint 5, Paint 1, Paint 6, Paint 4 and Reference (Uncoated) respectively emit 770.73, 779.43, 783.69, 790.08, 793.37 and 858.83 tonnes of CO_2 into the atmosphere by the end of a fishing season. More importantly, it can also be seen from Figure 5-33, a simple antifouling coating selection decision for a purse seiner fishing in the Mediterranean Sea can stop up to 22.64 tonnes of CO_2 emitted into the atmosphere (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) for the fishing vessel 3 by the end of a fishing season. Moreover, by only coating fishing vessel 3 with any of the selected antifouling coatings, up to 88.1 tonnes of CO_2 emission into the atmosphere (when Paint 2 and Reference are compared) can be prevented by the end of a fishing season in comparison to uncoated (Reference) fishing vessel 3.

5.7 Case Study Results Comparisons

5.7.1 Performance Comparisons Between Different Antifouling Strategies

As a result of the case studies with the selected SPC coatings applied on the fishing vessels, it can be seen that the selected antifouling coating strategies (SPC coatings) show different results. The study demonstrated that Paint 2 is the most efficient antifouling coating, followed by Paint 5, Paint 1, Paint 6 and Paint 4. Furthermore, as stated before in Table 4-1, Paint 2, Paint 5, and Paint 1 are produced by the local companies, yet Paint 6 with Paint 4 are made by the more prominent and global companies. Because the most successful coatings are branded by the locally available companies, a generalisation can be made as the large antifouling companies seem to put in more effort to address the needs for the regional industrial fishing vessels' fight with the biofouling.

When considering the biocide contents of the coatings, certain biocides can be specified as more successful for the industrial fisheries against the fight with biofouling. It can be seen that every antifouling coating, except Paint 5 (which is the paint with no contents specified), has the biocide Cuprous Oxide (CO) as typical content. However, checking the most efficient antifouling coatings from the case studies, it can be said that coatings containing Diuron (Di) and "N-cyclopropyl-N'-(1,1- dimethylethyl)-6- (methylthio)-1,3,5- Triazine-2,4-diamine" (CY) biocides are among the most successful coatings. Besides that, coatings containing Zinc Pyrithione (ZP) and Copper Pyrithione (CP) biocides are insufficient against fouling accumulation for the industrial fishing vessels.

5.7.2 Comparison Between Different Fishing Methods in the Same Region

A perfect comparison to show the effects of biofouling on two different fishing vessels, which are equipped with different fishing gears, would be only possible when certain conditions are matched, such as ship characteristics, power requirements, engine specs, operational profiles, antifouling coating characteristics, and fishing activity's location. Nonetheless, because there are many parameters affecting biofouling accumulation on a ship, comparing the impacts of biofouling on two fishing vessels equipped with two different fishing gears is a complex and somewhat difficult task to overcome.

Furthermore, because trawlers and purse seiners are the two fishing activities considered in the case studies of this thesis, it is essential to compare these purse seiner and trawler fishing methods operating in the same region in terms of the effects of the different antifouling technologies. However, before starting to compare the impacts of the biofouling on two fishing vessels with two different fishing gears in detail, it is important to re-state the characteristics of fishing vessel 1 and fishing vessel 2 with the operational and engine characteristics. Table 5-2 shows operational and main engine characteristics of the fishing vessels used in the case studies.

Table 5-2: Operational and Engine Characteristics of the Fishing Vessels Used in the Case Studies

Parameter	*Symbols*	*Units*	*Fishing Vessel 1*	*Fishing Vessel 2*	*Fishing Vessel 3*
Fishing Gear	N/A	N/A	Purse Seine	Trawl	Purse Seine
Fishing Region			Black Sea	Black Sea	Mediterranean Sea
Installed Main Engine Power	N/A	kW	551	551	551
Main Engine Fuel Consumption	MEFC	l/h	88.13	76	88.13
A Fishing Season	N/A	days	221	225	225
Total Idle (Stationary) Time Spent in a Fishing Season	N/A	days	95	145	111
Total Active Time (Cruising) Spent in a Fishing Season	N/A	days	126	80	114

Table 5-2 shows that both the operational profile and the ship characteristics of fishing vessel 1 and fishing vessel 2 show differences. Therefore, when the fouling ratings of fishing vessel 1 and fishing vessel 2 are considered, fishing vessel 1 and fishing vessel 2 coated with the same SPC coatings are expected to show different fouling ratings by the end of the fishing season. Figures showing total fouling ratings of the fishing vessel 1 and fishing vessel 2 by the end of fishing seasons (Figure 5-7 and Figure 5-16) were thus put together and illustrated in Figure 5-34. Figure 5-34 shows accumulative fouling rating comparisons between fishing vessel 1 and fishing vessel 2 coated with the selected SPC coatings by the end of fishing seasons.

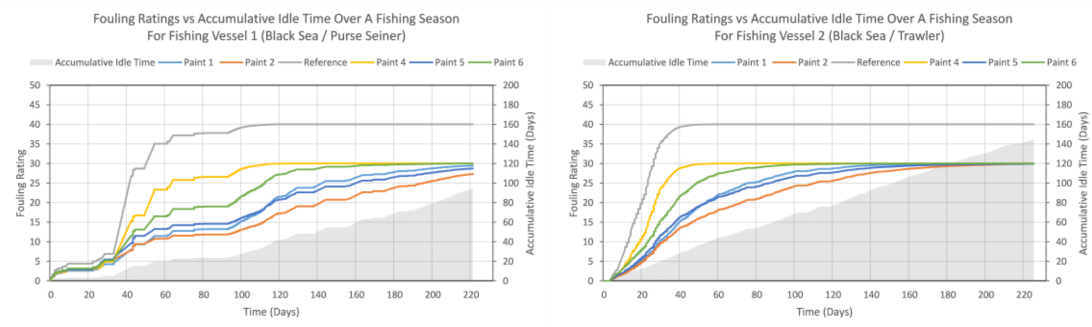


Figure 5-34: Accumulative Fouling Rating Comparisons by the End of Fishing Seasons Between Fishing Vessel 1 and Fishing Vessel 2 Coated with the Selected SPC coatings.

From Figure 5-34, it can be seen that, by the end of a fishing season, fouling ratings of some of the selected SPC coatings applied on the fishing vessel 1 and fishing vessel 2 (Paint 2, Paint 5, and Paint 1) show differences. Additionally, it can also be seen from Figure 5-34 and Table 5-2 that the idle time spent in a fishing season for each fishing vessel show significant differences. To be more specific, whilst fishing vessel 1 spent 95 days in idle condition, fishing vessel 2 spent 145 days in idle condition over a fishing season. Therefore, although there are several reasons behind these differences in fouling ratings between the fishing vessels (such as having different ship characteristics and operational profiles), the idle time spent in a fishing season can be attributed as the main reason behind this fouling rating differences of the selected SPC coatings applied on two different fishing vessels operating in the Black Sea fishing region. Due to the higher idle times in a fishing season, fouling growth on fishing vessel 2 shows earlier growth in comparison to fishing vessel 1. This assumption can also be confirmed with the SPC antifouling coatings' field test results, as detailed in Section 4.5.

As explained before in this thesis, in Section 5.2, the operation profiles of the selected fishing vessels, ship speed, idle times, and cruising times were determined and used as inputs into Uzun (2019)'s time-based biofouling model. In Uzun (2019)'s research, fouling accumulation on a ship was assumed to increase only when the ship is in idle condition. Furthermore, although the fouling ratings at the end of their fishing seasons show differences, looking at the idle times spent and their equivalent fouling ratings, a great match on the fouling ratings can be seen between the fishing vessels coated with the same SPC coatings. For example, after approximately 80 days of accumulative idle time spent in a fishing season, fouling ratings of Paint 2 on fishing vessel 1 and fishing vessel 2 show the approximate value of 26.

Last but not least, as both of the fishing vessels operates in the same fishing region (Black Sea), fouling growth trends are expected to show similarities. Therefore, as shown in Figure 5-34, this great match on the fouling ratings also proves the practicability of Uzun (2019)'s assumption on the sea surface temperature's dominance in fouling growth rate relation. In conclusion, when a trawler and a purse seiner which are operating in the Black Sea fishing region and the impacts of the biofouling on them are compared, there seems to be no difference between two fishing vessels when each fishing vessel is coated with the same SPC coating. In other words, biofouling's impact on different fishing vessels equipped with different fishing gears (such as trawl and purse seine) show no difference when the operation zones are the same.

Furthermore, to illustrate the antifouling performances of the selected antifouling coatings between fishing vessel 1 and fishing vessel 2, an additional graph is plotted. Therefore, Figure 5-35 shows accumulative fouling rating comparisons of each selected SPC coatings between fishing vessel 1 and fishing vessel 2 by the end of their fishing seasons.

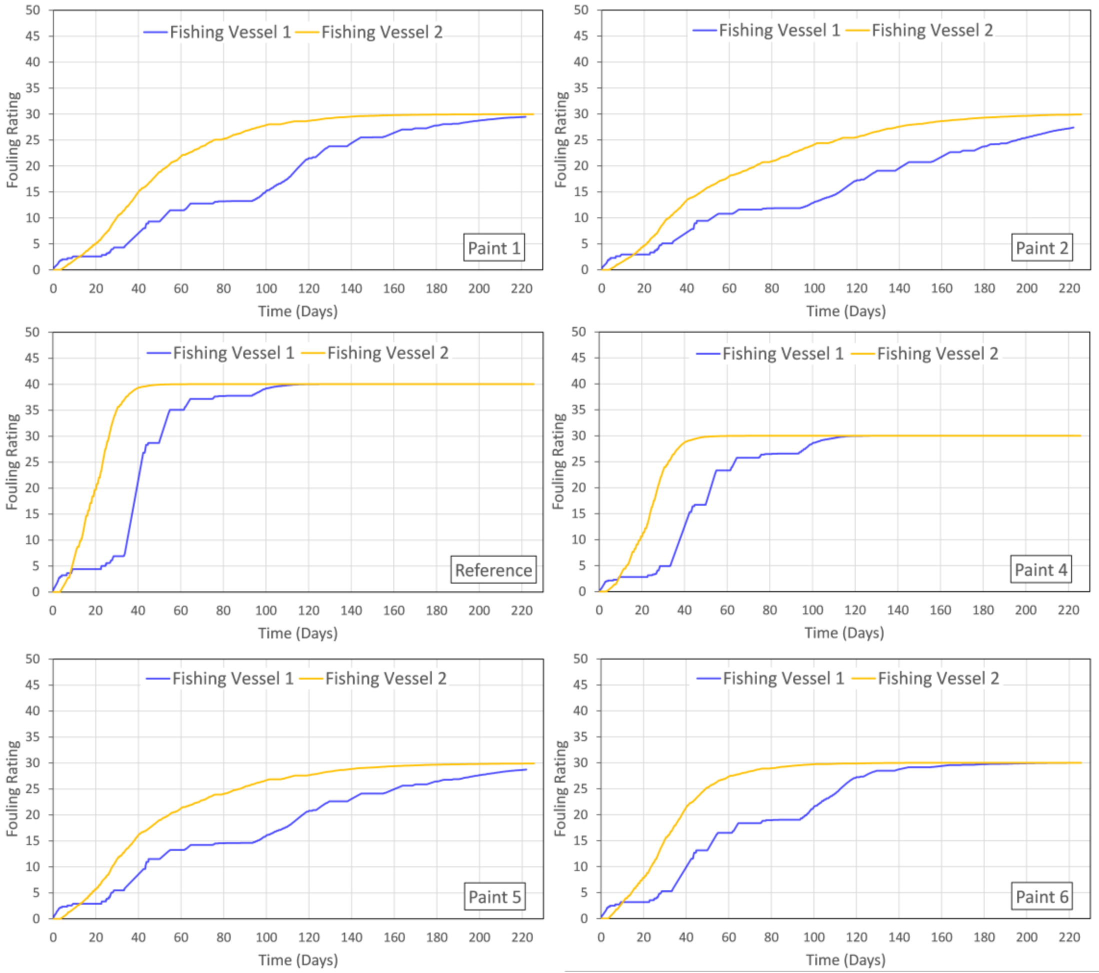


Figure 5-35: Accumulative Fouling Rating Comparisons of the Each Selected SPC Coatings Between Fishing Vessel 1 And Fishing Vessel 2 by the End of their Fishing Seasons

As can be seen from Figure 5-35, each SPC coating shows different antifouling performance trends by the end of their fishing seasons. More specifically, it can be seen that, whilst Reference, Paint 4 and Paint 6 show the same fouling ratings (fouling rating of 30), Paint 1, Paint 2 and Paint 5 show different fouling ratings when each coating applied on the fishing vessel 1 and fishing vessel 2 are compared by the end of their fishing season. Within this point, a further comment on the fouling rating comparisons between fishing vessel 1 and fishing vessel 2 can be made as; each antifouling coating applied on the fishing vessel 2 shows either higher or quicker fouling rating accumulation, due to having more idle times spent in a fishing season, as can be seen in Figure 5-34 and Figure 5-35.

As detailed in sections 6.6.1 and 6.6.2, antifouling performances order from the best to worst were the same when fishing vessel 1 and fishing vessel 2 were taken into consideration. In other words, a list can be made from the best to the worst antifouling coating performance as Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (uncoated). Within this point, it is important to give examples for the best and the worst antifouling coatings and their performance comparisons on two different fishing vessels operating in the same region (Black Sea).

Therefore, starting from the best antifouling coating (Paint 2), it can be seen that whilst the fouling rating reaches a fouling rating of 30 for the fishing vessel 2, the fouling rating of the same coating (Paint 2) on the fishing vessel 1 stays at slightly lower fouling rating. In other words, when a trawler (fishing vessel 2) is coated with the best antifouling coating (Paint 2), the fouling rating reaches the fouling rating of 30 at the end of the fishing season. Moreover, when a purse seiner (fishing vessel 1) is coated with the best antifouling coating (Paint 2), fouling ratings reach a fouling rating of 27.3. In other words, Paint 2 applied on the fishing vessel 2 shows a poorer performance than Paint 2 applied on the fishing vessel 1.

On the other hand, when the worst antifouling coating (Paint 4) is taken into consideration for fishing vessel 1 and fishing vessel 2, it can be seen from Figure 5-35 that Paint 4 reaches the fouling rating of 30 for both of fishing vessels by the end of their fishing seasons. In other words, when a trawler (fishing vessel 2) and a purse seiner (fishing vessel 1) is coated with the worst antifouling coating (Paint 4), there seem to be no fouling rating differences at the end of their fishing seasons. However, a note has to be taken into consideration here. Due to reaching the fouling rating of 30 quicker in comparison to the fishing vessel 1, the worst antifouling coating (Paint 4) applied on the fishing vessel 2 (trawler) shows poorer performance than Paint 4 applied on the fishing vessel 1 (purse seiner).

Another point that has to be taken into consideration when comparing accumulative fouling ratings of each selected SPC coatings applied on a purse seiner (fishing vessel 1) and a trawler (fishing vessel 2) is that the differences between the fouling ratings might vary depending on the duration of the fishing season. In other words, if the fishing seasons taken into consideration lasted shorter, fouling rating differences between fishing vessel 1 and fishing vessel 2 would show differences. To give an example for the best antifouling coating (Paint 2), if the fishing seasons lasted after 100 days for fishing vessel 1 and fishing vessel 2, the fouling differences between the fouling ratings of the Paint 2 applied on the fishing vessel 1 and Paint 2 applied on the fishing vessel 1 would show differences. In short, if the fishing seasons lasted after 100 days, the fouling rating differences for the same coating (Paint 2) applied on two different fishing vessels operating in the same region would go from 2.7 up to approximately 10 fouling. Further comparisons can be made for the rest of the antifouling coatings for the two fishing vessels.

To sum up, the case study results show that differences between the same coatings applied on a purse seiner and a trawler can make slight differences by the end of their fishing seasons. However, the differences may be significantly higher when considering the fishing season's duration. Hence the penalties caused by biofouling can be vastly different for the same antifouling coating applied on different fishing vessels with different fishing gears operating in the same region.

Next, when the total fuel consumption (L) in a fishing season is considered, fishing vessel 1 and fishing vessel 2 are expected to show different fuel consumptions due to having different operational profiles, ship characteristics and power requirements. For that reason, figures showing the total fuel consumptions of fishing vessel 1 and fishing vessel 2 (Figure 5-12 and Figure 5-21) were thus put together and illustrated in Figure 5-36. Figure 5-36 shows total fuel consumption (L) comparisons between fishing vessel 1 and fishing vessel 2 coated with the selected SPC coatings by the end of a fishing season.

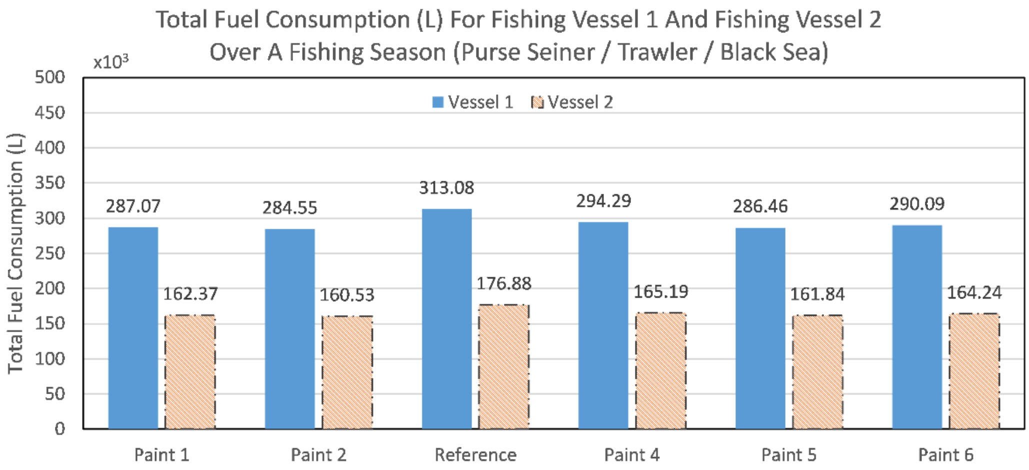


Figure 5-36: Total Fuel Consumption (L) Comparisons Between Fishing Vessel 1 and Fishing Vessel 2 Coated with the Selected SPC Coatings Operating in the Black Sea.

As shown in Figure 5-36, there is a vast difference between the total fuel consumption of fishing vessel 1 (purse seiner) and fishing vessel 2 (trawler) operating in the same region (Black Sea) in general. Furthermore, as explained before in Section 5.6, total fuel consumption was directly linked to total cruising time (active time), main engine output power (kW) and % increase in the effective power for the penalties caused by biofouling in a fishing season. Thus, due to spending more active time in a fishing season and having higher MEFC values, fishing vessel 1 (purse seiner) spends almost double the amount of fuel compared to fishing vessel 2 (trawler)'s total fuel consumption (L) in a fishing season.

Furthermore, looking at Figure 5-36, a comparison can be made for the total fuel consumption savings (L) of the two fishing vessels when each fishing vessel is coated with the best (Paint 2) and the worst (Paint 4) antifouling coatings. Furthermore, it can be seen that, whilst fishing vessel 1 saves 9740 litres, fishing vessel 2 saves 4660 litres of fuel by the end of their fishing season. In other words, whilst a simple antifouling coating selection decision for a purse seiner (fishing vessel 1) coated with any of the selected SPC coatings can save up to 9740 litres of fuel, up to 4660 litres of fuel can be saved for a trawler (fishing vessel 2) operating in the same region (Black Sea).

A further comparison can be given between the reference coatings and the SPC coatings for fishing vessel 1 and fishing vessel 2, as this case very clearly demonstrates the necessity of antifouling coating usage. Furthermore, coating a purse seiner with any of the selected antifouling coatings can save from a minimum of 18790 up to 28530 litres of fuel compared to an uncoated purse seiner. Moreover, coating a trawler with any of the selected antifouling coatings can save from a minimum of 11690 litres to 16350 litres of fuel compared to an uncoated trawler. Within this point, a note has to be pointed out. It is not realistic to calculate and show an uncoated fishing vessel's total fuel consumption as no fishing vessel operates with an uncoated hull. However, considering the fact that one of the aims of this research is "to train the fishermen on selecting the most suitable antifouling coating", showing the worst-case scenario (as the uncoated vessel) would be necessary in order to emphasise antifouling coatings' abilities in preventing the penalties caused by biofouling. In other words, with the aim of emphasising the importance and efficiency of the antifouling coatings in the fight with the biofouling for the fishing vessels coated with the selected antifouling coatings, an uncoated fishing vessel scenario (with reference coating) was also included in the case studies.

In addition to the fuel consumption values of fishing vessel 1 and fishing vessel 2 in a fishing season, it is essential to illustrate and compare the total fuel consumption savings in % when a fishing season is considered. In addition to that, as stated before in this section, demonstrating these percentages is essential to underline the vital role of antifouling coatings in preventing the penalties caused by biofouling. For that reason, with the aim of comparing the SPC coatings with each other for the two fishing vessels by the end of their fishing seasons, figures showing the total fuel consumptions of the fishing vessel 1 and fishing vessel 2 (Figure 5-13 and Figure 5-22) were put together and illustrated in Figure 5-37. Figure 5-37 shows total fuel consumption savings (%) for the selected SPC coatings compared to reference (uncoated) coating applied on fishing vessel 1 and fishing vessel 2.

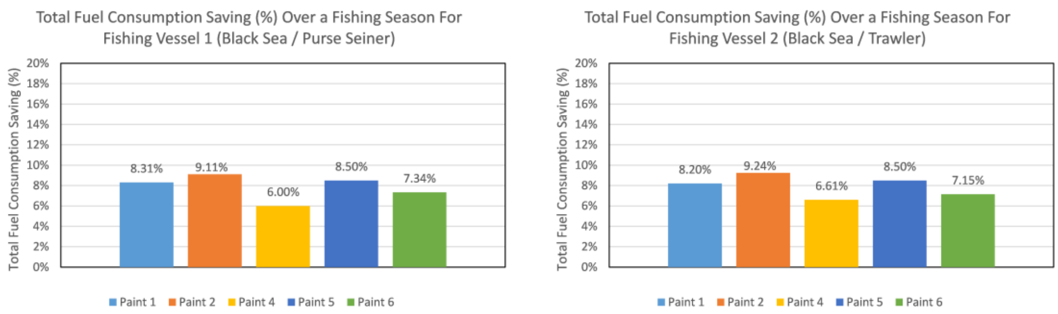


Figure 5-37: Total Fuel Consumption Savings (%) for the Selected SPC Coatings in Comparison to Reference (Uncoated) Coating Applied on the Fishing Vessel 1 and Fishing Vessel 2.

As shown in Figure 5-37, coating fishing vessel 1 and fishing vessel 2 with any of the selected antifouling coatings can save from 0.19% to 3.11% in total fuel consumption by the end of a fishing season regardless of the fishing method used. Furthermore, when selected antifouling coatings applied on fishing vessel 1 and fishing vessel 2 are compared with each other, it can be seen that making a simple antifouling coating selection decision for a purse seiner (fishing vessel 1) fishing in the Black Sea can save up to 3.11% (when the best antifouling coating Paint 2 and the worst antifouling coating Paint 4 are compared) of the fuel consumed by the end of a fishing season. Similarly, when the selected antifouling coatings are compared with each other, it can be seen that making a simple antifouling coating selection decision for a trawler (fishing vessel 2) fishing in the Black Sea can save up to 2.63% (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) of the fuel consumed by the end of a fishing season.

Overall, the examples given above support the view that when the total fuel consumption savings of each SPC antifouling coatings applied on two different fishing vessels are compared to the vessels coated with any other selected antifouling coatings, it can be seen that the % savings for each coating show similarities on fishing vessel 1 and fishing vessel 2. That is to say, with a simple antifouling coating selection decision, the total fuel consumption savings for a purse seiner and trawler operating in the same region show similarities. In other words, when the two antifouling coatings are compared in two different fishing vessels, total fuel consumption savings in % would only show slight differences. For example, it can be seen from Figure 5-37 that, when Paint 2 and Paint 6 coatings are compared on fishing vessel 1 and fishing vessel

2, whilst Paint 2 can save 1.77% for the fishing vessel 1; similarly, it saves 2.09% for the fishing vessel 2 when compared to fishing vessels coated with Paint 6.

It might be expected that when the same antifouling coatings are applied on two different fishing vessels and compared with a specific antifouling coating's performance, there would not be any difference in the total fuel consumption savings between the fishing vessels operating in the same region. However, due to having different operational profiles and so that cruising times, the amount of the total fuel consumption savings will differ. For example, in comparison to the worst antifouling coating (Paint 4), applying the best antifouling coating (Paint 2) on each vessel shows differences in terms of total fuel consumption savings among the fishing vessels. Finally, similar comments are possible for total fuel cost savings and CO_2 emission savings.

5.7.3 Comparison Between Different Fishing Regions

After comparing two different fishing vessels with two different fishing methods in the same region, vessels fishing with the same fishing methods in different fishing zones were considered. For that reason, the performances of two purse seiners used in the case studies were compared. Figures showing total fouling ratings of fishing vessel 1 and fishing vessel 3 by the end of fishing seasons (Figure 5-7 and Figure 5-25) were thus put together and illustrated in Figure 5-38. Figure 5-38 shows accumulative fouling rating comparisons between fishing vessel 1 and fishing vessel 3 coated with the selected SPC coatings by the end of fishing seasons.

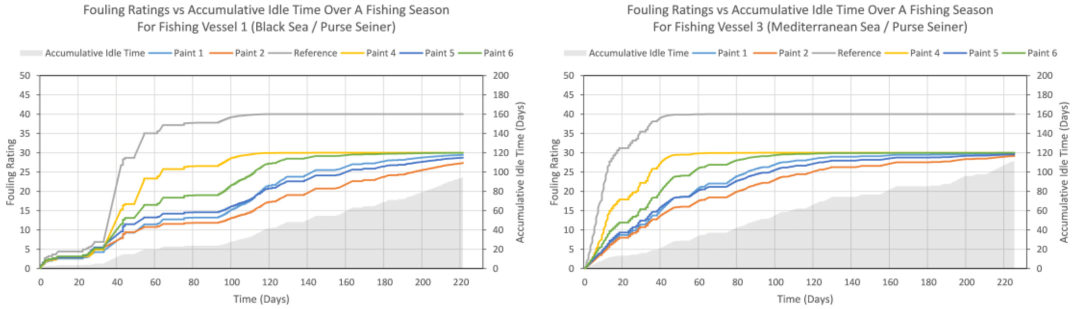


Figure 5-38: Accumulative Fouling Rating Comparisons by the End of Fishing Seasons Between Fishing Vessel 1 and Fishing Vessel 3 Coated with the Selected SPC coatings.

From Figure 5-38, it can be seen that, by the end of a fishing season, fouling ratings of some of the selected SPC coatings applied on the fishing vessel 1 and fishing vessel 3 (Paint 2, Paint 5, and Paint 1) show differences. Additionally, it can also be seen from Figure 5-37 and Table 5-2 that the idle time spent in a fishing season for each fishing vessel show significant differences. To be more specific, whilst fishing vessel 1 spent 95 days in idle condition, fishing vessel 3 spent 111 days idle in a fishing season. Last but not least, fishing vessel 1 and fishing vessel 3 operates in different fishing regions where the sea surface temperatures show differences. Therefore, the idle time spent in a fishing season and the location difference where the fishing vessels operate can be attributed as the main reasons behind this fouling rating differences of the selected SPC coatings applied on two different fishing vessels operating in the two different fishing regions (the Black Sea and the Mediterranean Sea). Due to having higher idle times in a fishing season, the fouling rating on fishing vessel 3 shows further growth in comparison to fouling rating growth on fishing vessel 1. In addition to that, due to using different fouling rating data as detailed in Section 4.5, fouling ratings of the coatings applied on the fishing vessel operating in the Mediterranean Sea (Fishing vessel 3) shows a faster fouling growth in comparison to the fishing vessel operating in the Black Sea (Fishing vessel 1). This assumption can also be confirmed with the SPC antifouling coatings' field test results, as detailed in Section 4.5.

Furthermore, due to having higher sea surface temperatures, fouling ratings are expected to show higher values for fishing vessel 3 than fishing vessel 1. However, looking at Figure 5-37, it can be seen that although some of the SPC antifouling coatings applied on the fishing vessel 3 show higher fouling ratings (when the same accumulative idle time is taken into consideration), some of the paints show the same fouling ratings (such as Reference, Paint 4, Paint 6) with the fishing vessel 1. The reason behind having the same fouling ratings is due to the required idle time that the coating needs to continue increasing in terms of fouling ratings. This approach can be understood better when comparing the immersion test results in the Black Sea and the Mediterranean Sea. As shown in Figure 4-19, it can be seen that once the fouling ratings reach a certain fouling rating, no increase is observed in the fouling rating. Therefore, once the particular SPC coatings reach fouling ratings, they show no increase.

Furthermore, an additional graph is plotted to illustrate the antifouling performances of the selected antifouling coatings between fishing vessel 1 and fishing vessel 3. Therefore, Figure 5-39 shows accumulative fouling rating comparisons of each selected SPC coatings between fishing vessel 1 and fishing vessel 3 by the end of their fishing seasons.

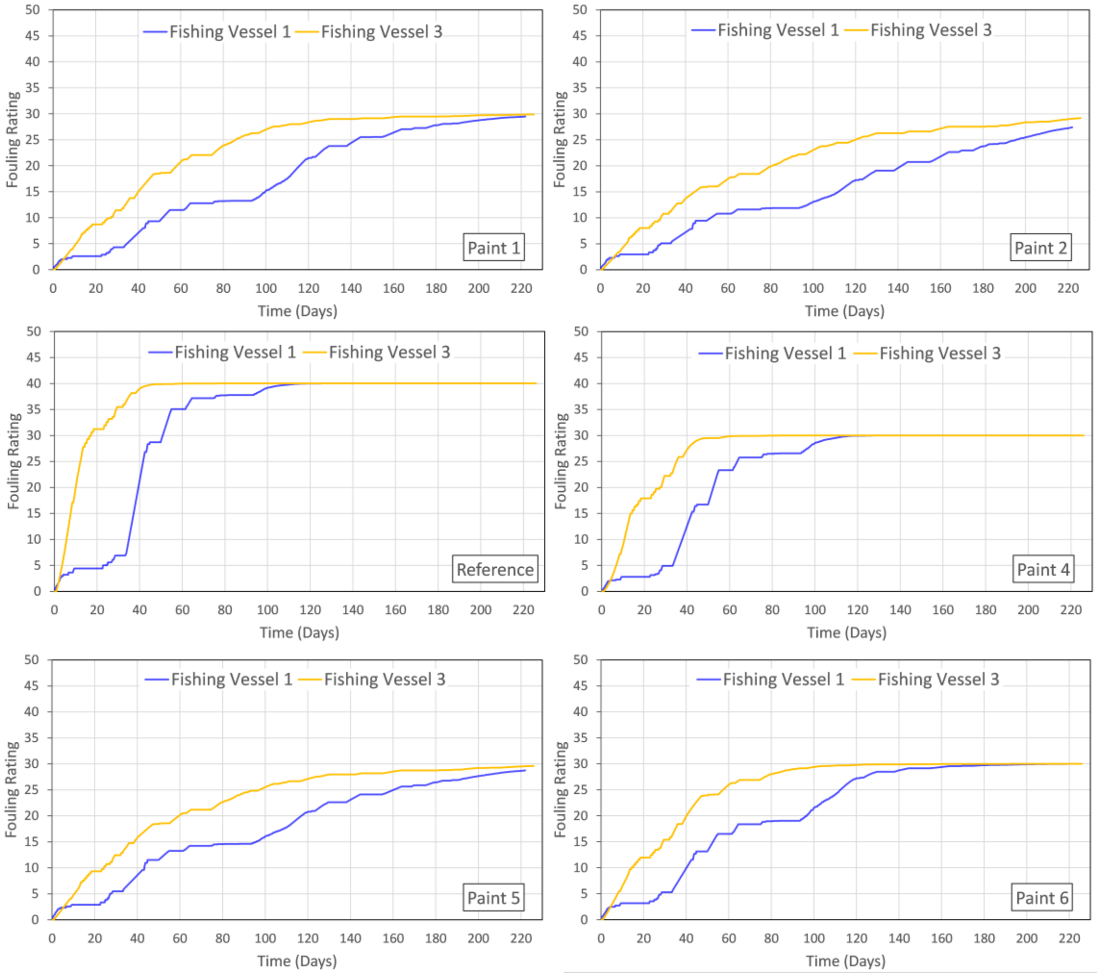


Figure 5-39: Accumulative Fouling Rating Comparisons of the Each Selected SPC Coatings Between Fishing Vessel 1 And Fishing Vessel 3 by the End of their Fishing Seasons

As can be seen from Figure 5-39, each SPC coating shows different antifouling performance trends by the end of their fishing seasons. More specifically, it can be seen that, whilst Reference, Paint 4 and Paint 6 show the same fouling ratings (fouling rating of 30), Paint 1, Paint 2 and Paint 5 show different fouling ratings when each coating applied on the fishing vessel 1 and fishing vessel 3 are compared by the end of their fishing season. Within this point, a further comment on the fouling rating comparisons between fishing vessel 1 and fishing vessel 3 can be made. Moreover, each antifouling coating applied on the fishing vessel 3 shows either higher or quicker fouling rating accumulation due to having more idle times spent in a fishing season and operating in warmer sea surface temperatures, as can be seen in Figure 5-38 and Figure 5-39.

As detailed in sections 6.6.1 and 6.6.3, antifouling performances order from the best to worst were the same when fishing vessel 1 and fishing vessel 3 were taken into consideration. In other words, a list can be made from the best to the worst antifouling coating performance as Paint 2, Paint 5, Paint 1, Paint 6, Paint 4, and Reference (uncoated). Within this point, it is important to give examples for the best and the worst antifouling coatings and their performance comparisons on two different fishing vessels operating in two different regions (the Black Sea and the Mediterranean Sea).

Therefore, starting from the best antifouling coating (Paint 2), it can be seen that whilst the fouling rating reach to fouling rating of 29.1 for the fishing vessel 3, the fouling rating of the same coating (Paint 2) on the fishing vessel 1 stays at slightly lower fouling rating (fouling rating of 27.3). In other words, when a purse seiner operating in the Mediterranean Sea (fishing vessel 3) is coated with the best antifouling coating (Paint 2), the fouling rating reaches the fouling rating of 29.1 at the end of the fishing season. Moreover, when a purse seiner operating in the Black Sea (fishing vessel 1) is coated with the best antifouling coating (Paint 2), fouling ratings reach a fouling rating of 27.3. In other words, Paint 2 applied on fishing vessel 3 shows a poorer performance than Paint 2 applied on fishing vessel 1.

On the other hand, when the worst antifouling coating (Paint 4) is taken into consideration for fishing vessel 1 and fishing vessel 3, it can be seen from Figure 5-39 that Paint 4 reaches the fouling rating of 30 for both fishing vessels by the end of their fishing seasons. In other words, when a purse seiner operating in the Mediterranean Sea (fishing vessel 3) and a purse seiner operating in the Black Sea (fishing vessel 1) is coated with the worst antifouling coating (Paint 4), there seem to be no fouling rating differences at the end of their fishing seasons. However, a note has to be taken into consideration here. Due to reaching the fouling rating of 30 quicker in comparison to the fishing vessel 1, the worst antifouling coating (Paint 4) applied on the fishing vessel 3 (purse seiner operating in the Mediterranean Sea) shows poorer performance than

Paint 4 applied on the fishing vessel 1 (purse seiner operating in the Black Sea). That is to say, the penalties caused due to biofouling for fishing vessel 3 will be higher in comparison to fishing vessel 1.

Another point that has to be taken into consideration when comparing accumulative fouling ratings of each selected SPC coatings applied on a purse seiner operating in the Black Sea (fishing vessel 1) and a purse seiner operating in the Mediterranean Sea (fishing vessel 3) is that the differences between the fouling ratings might vary depending on the duration of the fishing season. In other words, if the fishing seasons ended earlier, the differences between fouling ratings of the same antifouling coating on different fishing vessels would change.

For example, when the best antifouling coating (Paint 2) is applied on fishing vessel 1 and fishing vessel 3, and if the fishing seasons ended after 100 days, the differences between the fouling ratings would show a change. In short, if the fishing seasons ended after 100 days, the fouling rating differences for the same coating (Paint 2) applied on two different fishing vessels operating in the different regions would go from 1.8 fouling rating up to approximately 9.89 fouling rating. Further comparisons can be made for the rest of the antifouling coatings for the two fishing vessels.

To sum up, the case study results show that differences between the same coatings applied on a purse seiner operating in the Black Sea and a purse seiner operating in the Mediterranean Sea can make slight differences by the end of their fishing seasons. However, the differences may be significantly higher when considering the duration of the fishing season and sea surface temperature. Hence the penalties caused by biofouling can be vastly different for the same antifouling coating applied on the fishing vessels with the same fishing gears operating in the different regions.

Next, when the total fuel consumption (L) in a fishing season is considered, fishing vessel 1 and fishing vessel 3 are expected to show different fuel consumptions due to having different operational profiles. For that reason, figures showing total fuel consumptions of fishing vessel 1 and fishing vessel 3 (Figure 5-12 and Figure 5-30) were thus put together and illustrated in Figure 5-40. Figure 5-40 shows total fuel consumption (L) comparisons between fishing vessel 1 and fishing vessel 3 coated with the selected SPC coatings by the end of a fishing season.

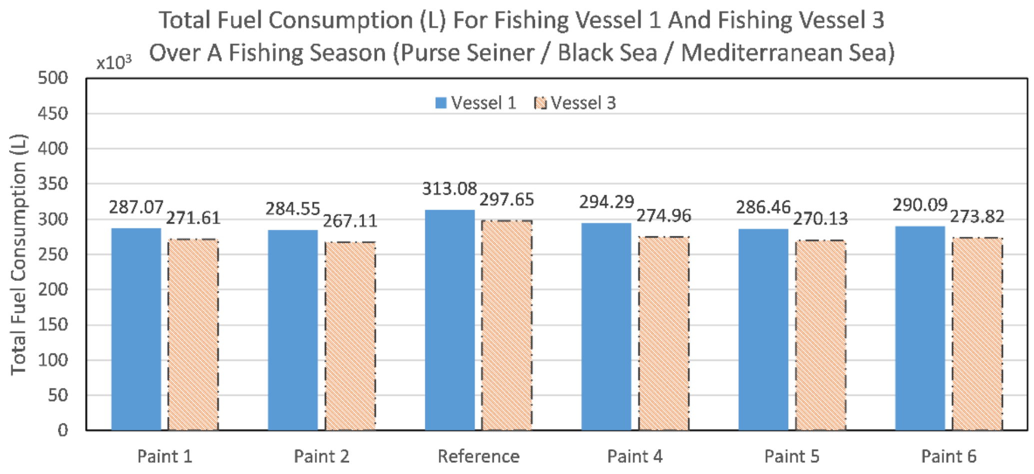


Figure 5-40: Total Fuel Consumption (L) Comparisons Between Fishing Vessel 1 and Fishing Vessel 3 Coated with the Selected SPC coatings.

As shown from Figure 5-40, the total fuel consumption of fishing vessel 3 (purse seiner operating in the Mediterranean Sea) is lower than fishing vessel 1 (purse seiner operating in the Black Sea). Furthermore, as explained before in Section 5.6, total fuel consumption was directly linked to total cruising time, engine power (kW), and % increase in the effective power in a fishing season. Thus, as a result of spending more cruising time (active time) in a fishing season, fishing vessel 1 spends more fuel than fishing vessel 3 in a fishing season.

Furthermore, looking at Figure 5-40, a comparison can be made for the total fuel consumption savings (L) of the two fishing vessels when each vessel is coated with the best (Paint 2) and the worst (Paint 4) antifouling coatings. Furthermore, it can be seen from Figure 5-40 that, whilst the Paint 2 coated fishing vessel 1 saves 9740 litres of fuel compared to Paint 4 coated fishing vessel 1, Paint 2 coated fishing vessel 3 saves 7850 litres of fuel compared to Paint 4 coated fishing vessel 3 by the end of their fishing seasons. In other words, whilst a simple antifouling coating selection decision for a purse seiner operating in the Black Sea (fishing vessel 1), which is coated with any of the selected SPC coatings, can save up to 9740 litres of fuel, up to 7850 litres of fuel can be saved for a purse seiner operating in the Mediterranean Sea.

As stated previously in Section 5.7, a perfect comparison to show the effects of biofouling on two different fishing vessels, even if equipped with the same fishing gears, would be only possible when certain conditions are matched, such as ship characteristics, power requirements, engine specs, operational profiles, antifouling coating characteristics, and fishing activity's location. Nonetheless, because many parameters affect biofouling accumulation on a ship, comparing the impacts of biofouling on two fishing vessels operating in different locations with the same fishing gears is a complex and somewhat difficult task to overcome. For that reason, if Table 5-2 is examined, it can be seen that fishing vessel 1 and fishing vessel 3 are the sister fishing vessels operating in different locations, as one in the Black Sea and the other in the Mediterranean Sea. Furthermore, a comment may be suitable to make as fishing vessel 1 and fishing vessel 3 are almost the perfect match to compare and show the effects of the biofouling with only one exception, which is the operational profile. Therefore, if the operational profile of the two vessels were the same, the impact of the biofouling would be higher for fishing vessel 3, so that the total fuel consumption for fishing vessel 3 would be higher in comparison to fishing vessel 1 due to higher sea surface temperatures in the Mediterranean Sea. However, looking at the comparison results between case study 1 and case study 3, it can be seen that having more cruising time (active time) in a fishing season for fishing vessel 1, fuel consumptions for case study 1 show higher results than case study 3. In other words, operational differences between two sister fishing vessels dominate the difference that may occur due to geographical differences when the impact of biofouling is in concern.

A further comparison can be given between the reference coating and the SPC coatings for fishing vessel 1 and fishing vessel 3 as this case clearly demonstrates the necessity of the antifouling usage and significance in preventing the biofouling for the fishing vessels. Furthermore, coating a fishing vessel 1 with any of the selected antifouling coatings can save from a minimum of 18790 up to 28530 litres of fuel compared to uncoated fishing vessel 1. Moreover, coating fishing vessel 3 with any of the selected antifouling coatings can save from a minimum of 22690 litres to 30540 litres of fuel compared to uncoated fishing vessel 3.

In addition to the fuel consumption values of fishing vessel 1 and fishing vessel 3 in a fishing season, it is essential to illustrate and compare the total fuel consumption savings in % when a fishing season is considered. In addition to that, as stated before in this section, demonstrating these percentages is essential to underline the vital role of antifouling coatings in preventing the penalties caused by biofouling. For that reason, with the aim of comparing the SPC coatings with each other for the two fishing vessels by the end of their fishing seasons, figures showing total fuel consumptions of fishing vessel 1 and fishing vessel 3 (Figure 5-13 and Figure 5-31) were thus put together and illustrated in Figure 5-41. Figure 5-41 shows total fuel consumption savings (%) for the selected SPC coatings compared to reference (uncoated) coating applied on fishing vessel 1 and fishing vessel 3.

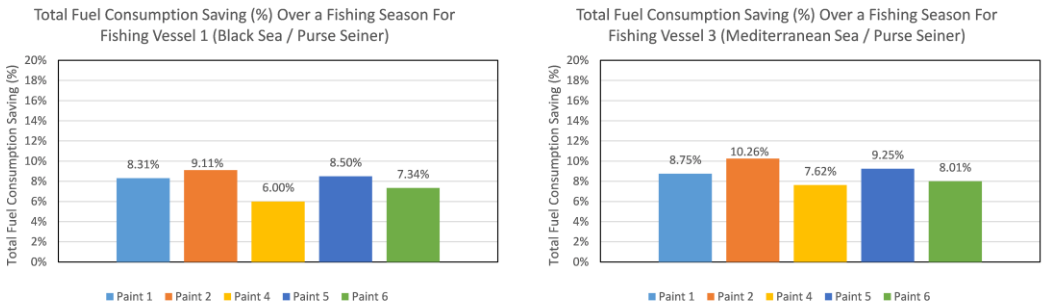


Figure 5-41: Total Fuel Consumption Savings Between a Purse Seiner (Fishing Vessel 1) and a Purse Seiner (Fishing Vessel 3) after a Fishing Year of Operation

As shown in Figure 5-41, coating fishing vessel 1 and fishing vessel 3 with any of the selected antifouling coatings can save from 0.19% to 3.11% in total fuel consumption by the end of a fishing season regardless of where the fishing operation is conducted. Furthermore, when selected antifouling coatings applied on fishing vessel 1 and fishing vessel 3 are compared with each other, it can be seen that making a simple antifouling coating selection decision for a purse seiner (fishing vessel 1) fishing in the Black Sea can save up to 3.11% (when the best antifouling coating Paint 2 and the worst antifouling coating Paint 4 are compared) of the fuel consumed by the end of a fishing season. Similarly, when the selected antifouling coatings are compared with each other, it can be seen that making a simple antifouling coating selection decision for a purse seiner fishing in the Black Sea (fishing vessel 3) can save up to 2.64% (when the best antifouling coating: Paint 2 and the worst antifouling coating; Paint 4 are compared) of the fuel consumed by the end of a fishing season. In other words, when the antifouling performances of the SPC coatings are compared to each other for the different fishing vessels, it can be seen that a simple antifouling coating decision can save up to 3.11% for the fishing vessel 1 and 2.64% for the fishing vessel 3 in fuel consumptions.

Overall, examples given above support the view that, when the total fuel consumption savings of each SPC antifouling coatings applied on two fishing vessels operating in different locations are compared to the vessels that are coated with any other selected antifouling coatings, the % savings for each coating show slight differences on fishing vessel 1 and fishing vessel 3. That is to say, with a simple antifouling coating selection decision, the total fuel consumption savings for fishing vessel 1 and fishing vessel 3 show slight differences. In other words, when the two antifouling coatings are compared in two different fishing vessels operating in different fishing regions, total fuel consumption savings in % would only show slight differences. To give another example from case study 1 and case study 3's comparison, it can be seen from Figure 5-41 that, when Paint 2 and Paint 6 coatings are compared on the fishing vessel 1 and fishing vessel 2 separately, whilst Paint 2 can save 1.77% for the fishing vessel 1; similarly, it saves 2.25% for the fishing vessel 3 when compared to fishing vessels coated with Paint 6. Furthermore, a note has to be taken into consideration. As seen from the comparison results, fuel consumption savings for fishing vessel 3 is lower than that of fishing vessel 1. This is simply because fishing vessel 3 has either faster or higher fouling accumulation growth in the Mediterranean Sea compared to fishing vessel 1 operating in the Black Sea. This assumption can also be confirmed by examining Figure 5-38. Finally, similar comments are possible for total fuel cost savings and CO_2 emission savings.

Within this point, a comparison among the 3 cases should be pointed. As stated before in Chapter 2, the number of motorized fishing vessels with at least 24 m or larger LOA is estimated as 67800 globally, and there are 15000 industrial fishing vessels operating in the Black Sea and the Mediterranean Sea. Moreover, as aforementioned before in Section 5.4, the global diesel oil price is taken 0.77 GBP per litre in this thesis. What is more, for a litre of diesel oil, 2.8854 kg of CO_2 is emitted into the atmosphere. Therefore, having the possibility of saving thousands of fuel in litres would not only benefit the fishermen economically but also help the fight against climate change. Thus, considering the number of industrial fishing vessels in the GFCM region (the Black Sea and the Mediterranean Sea) and globally, both economic and environmental impacts of biofouling could be better understood. If a simple calculation is carried out depending on the case studies and the numbers of estimated industrial fishing vessels:

- Up to “9740 litres fuel per and industrial fishing vessel” x “15000 industrial fishing vessels in the GFCM region” = 146.1M litres of fuel can be saved in the GFCM region. Furthermore, up to “9740 litres fuel per an industrial fishing vessel” x “67800 industrial fishing vessels in the globe” = 660.37M litres of fuel can be saved globally.

- Up to “146.1M litres of fuel consumption saving in GFCM region” x “0.77GBP” = 112.5M GBP can be saved in the GFCM region. Furthermore, up to “660.37M litres of fuel consumption saving globally” x “0.77GBP” = 508.48M GBP can be saved globally.

- Up to “146.1M litres of fuel consumption saving in GFCM region” x “ 2.8854 kg of CO_2 emitted per litre of diesel oil” = 0.42M tonnes of CO_2 emission can be prevented in the GFCM region. Furthermore, up to “660.37M litres of fuel consumption savings globally” x “2.8854 kg of CO_2 emitted per litre of diesel oil” = 1.9M tonnes of CO_2 emission can be prevented globally.

A simple antifouling coating selection decision for the industrial fishing vessels operating in the GFCM region, regardless of the fishing gear used and where the fishing operation is conducted, can decrease, or increase industrial fishing vessel fleet’s fuel consumption up to 146.1M litres, fuel costs up to £112.5M, and CO_2 emission up to 0.42M tonnes. In addition to that, a simple antifouling coating selection decision for the industrial fishing vessels, regardless of the fishing gear used and where the fishing operation is conducted, can decrease, or increase the global industrial fishing vessel fleet’s fuel consumption up to 660.37M litres, fuel costs up to £508.48M, and CO_2 emission up to 1.9M tonnes. It should be noted that these numbers were calculated through a simple approach, and therefore, the results might vary when different case studies are in concern.

5.8 Chapter Summary

In this chapter, the results of the case studies were detailed and presented in figures step by step. Firstly fishing vessels were determined, and characteristics were stated. Following that, hydrodynamic analyses for each case study were plotted. Following that, economic analysis and environmental analysis were conducted and presented systematically. Finally, comparisons between the case studies were conducted and presented.

6 Discussion

6.1 Chapter Introduction

Chapter 6 presents the discussions on the research carried out in this thesis. First, the achievement of research aims and objectives are stated. Following that, novelties and the contributions to state of the art is stated. Finally, a summary of the thesis is given.

6.2 Achievement of Research Aim and Objectives

This PhD thesis was set out to contribute to the roughness database due to biofouling of fishing vessel hulls and investigate the impacts of biofouling on ships frictional resistance and fuel consumption “in real” conditions, specifically for industrial fishing vessels, as described in Chapter 1. In order to achieve the aim mentioned above, experimental research was conducted with principal objectives in mind.

The first objective listed in Chapter 1 was:

- *To conduct a literature review on the impact of biofouling and hull surface conditions on ships’ hydrodynamic performance and resistance, current antifouling strategies, antifouling coating test methodologies, fisheries importance, classification of the fisheries, and current fishing methods to determine the gaps in the literature.*

In Chapter 2, this objective was achieved by a comprehensive critical literature review on the relevant subjects within this PhD thesis, including the nutritional and economic importance of the fisheries, classifications of the fisheries around the world, the most common fishing fleets with characteristic behaviours, fishery types around the world, marine biofouling, impacts of biofouling on ship performance, antifouling strategies, antifouling coating performance tests, theoretical backgrounds for the calculation of the ship resistance, boundary layer, determination of the roughness function.

The following objectives were achieved in Chapter 3:

- *To perform a field survey together with the regulatory framework introduced by authorities to manage fishing stocks with the aim of determining the operating profiles of the industrial fishing vessels.*

- *To survey fishermen about how they maintain their vessels, how they select the coating types, what are the most common coating application chosen etc.*

- *To determine fouling characteristics of fishing vessels in selected fishing zones together with antifouling coatings applied on the hull (if applied) by inspecting the vessels at the end of their annual fishing operation.*

- *To select the most appropriate commercially available antifouling coatings while considering the fouling characteristics in collaboration with coating manufacturers,*

- *To select the most suitable fishing vessel with the aim of this thesis*.

A questionnaire was prepared with the help of 4 experts in their fields. Furthermore, including owners/operators of 41 industrial fishing vessels, 61 fishermen participated in the survey. The results of the survey are presented in detail in Section 3.2. Later, the most common fishing vessel types, together with the fishing methods used, were determined. This information was used to determine the operational profile of the fishing vessels from AIS(marinetraffic.com) in addition to the survey results. Next, the most commonly used antifouling coating types and brands were determined in order to be used for the field and ship tests. Following that, underwater hulls of three fishing vessels operating in the Black Sea were inspected to determine the fouling characteristics of the fishing vessels and the fouler organisms by using a force gauge. Fouling characteristics and the fouler organisms were presented in Section 3.3.

Following objectives were achieved in Chapter 4:

- *To apply these coatings as patches on a fishing vessel to determine the comparative performance of these coating under the same working and weather conditions. Inspect the patches between two maintenance periods to determine the time-based fouling.*

- *To place similar patches (coated panels) in the sea statically and observe the fouling patterns in regular intervals. Inspect the patches regularly to determine the time-based fouling,*

- *To compare antifouling coatings' performance in terms of biofouling, between ship tests and static test patches and between different coatings.*

Flat panels were coated with the selected antifouling coatings, which were identified from the survey conducted with the industrial fishing vessel owners/stakeholders in the Black Sea region. In addition, flat panels were also coated with new antifouling coatings with the help of one of the leading paint companies in the sector. Each coated panel was systematically observed. The time-dependent fouling accumulation under the same working and weather conditions for the flat panels was determined. Then, fouling patterns were rated according to the NSTM standards and fitted in the logistic growth model. Following that, with the cooperation of a fishing vessel's owner, selected antifouling coatings from the survey results were applied on the ship hull and investigated at the end of the fishing season. Fouling patterns were rated according to NSTM standards, and both the field test and ship test results were compared and presented in tables and plots.

Following objectives were achieved in Chapter 5:

- *To establish various case studies for typical fishing vessels to investigate the impacts of determined coating/roughness/fouling on powering requirements of these boats, based on analysis of the coating/roughness/fouling data collected from the field tests,*

- *To determine the most suitable coating in terms of fouling performance and in terms of energy efficiency, environmentally friendliness and costs,*

- *To analyse the performance data to guide specified fishing vessels communities to change or improve their current practice to get the best performance out of their vessels as well as making the least undesirable impact to the environment,*

The first step was to determine the fishing vessels to be used in the case studies. Three fishing vessels fishing in either the Black Sea or the Mediterranean Sea were selected depending on the fishing methods. After that, operation profiles of the fishing vessels were obtained with the help of the Automatic Identification System on marinetraffic.com. Then, Uzun (2019)'s time-based biofouling model was used in order to estimate the fouling ratings of the selected antifouling coatings on selected fishing vessels. Next, fouling ratings over time for each case study were converted into equivalent sand roughness heights (k_s values). And then, added resistance data was generated using diagrams presented in Demirel et al. (2019). Later, the effects of biofouling on resistance and powering for each case study was presented. Then, the impacts of biofouling in terms of fuel consumption, fuel cost, and CO_2 emission were calculated at each vessel's design speed. Finally, the impact of the biofouling on fuel consumption and CO_2 was compared in terms of antifouling coating performances, fishing methods and fishing regions.

6.3 Novelties and Contributions

Within this PhD study, a number of novelties have been achieved and introduced to state of art. The main novelties achieved within this PhD study are given as follows:

- *To the best of the author's knowledge, this is the first-time biofouling's impacts were systematically investigated and then demonstrated on industrial fishing vessels that have different fishing practices within the Black Sea and the Mediterranean Sea.*

This was achieved by conducting surveys with the fishermen, underwater hull inspections, field and ship tests, and case studies conducted in the Black Sea and the Mediterranean Sea region. Impacts of biofouling change depending on many parameters, and so that different scenarios have to be investigated separately. Moreover, considering the number of people who earn their living directly or indirectly from fisheries, improving the industrial fisheries would benefit thousands of people's lives only in the Mediterranean and the Black Sea, as stated in Chapter 2. Therefore, investigating the impacts of biofouling on industrial fishing vessels may assist authorities in reconsidering the regulations related to hull protections for the fishing vessels to improve the energy efficiency and potential financial benefits in the industrial fisheries.

What is more, although the use of non-toxic based antifouling coatings is encouraged by the authorities, survey results showed that the majority of the fishermen still use toxic based SPC antifouling coatings rather than FR coatings. The surveys conducted in the field with the end-users (fishermen) are essential to create awareness among the various stakeholders and demonstrate the realistic strategies used to fight biofouling in the determined industries (such as industrial fisheries). Moreover, this may also highlight the importance of training when misleading information spreads in communities such as industrial fishermen.

In addition, presenting biofouling's impacts may help the end-users (fishermen) to understand that a simple antifouling coating selection can make a significant contribution to their economy and reduce CO_2 emissions, which is important to reach IMO's Sustainable Development Goals: zero hunger, good health and well-being, quality education, affordable and clean energy, sustainable cities and communities, responsible consumption and production, and climate action (IMO, 2017). Last but not least, fishing vessels with different fishing practices show different biofouling characteristics for the SPC antifouling coatings. This was also supported by presenting the financial benefits for fishing vessels in Chapter 5. Additionally, this study may influence the researchers to conduct industry-based research when biofouling is of concern.

- *To the best of the author's knowledge, this is the first time that biofouling data over time was presented for eight different antifouling coatings and two different antifouling coatings (Foul release and Self-Polishing-Copolymer) in the Black Sea region.*

This was achieved by taking two different antifouling coating strategies (SPC and FR) into account and conducting field and ship tests presented in Chapter 4. Five SPC and three FR antifouling coatings were tested and compared. Field tests were investigated over a year, and the fouling characteristics of each coating were determined. SPC antifouling coatings showed a better performance in fighting with biofouling compared to FR coatings. In addition to that, locally available SPC antifouling coatings showed a better performance than internationally available SPC antifouling coatings.

What is more, when the biocide components and the antifouling coating success is compared, SPC coatings that have particular biocides showed better antifouling performances. To be more specific, Diuron (Di) and N-cyclopropyl-N'-(1,1-dimethylethyl)-6- (methylthio)-1,3,5- Triazine-2,4-diamine (CY) showed better antifouling performances than Zinc Pyrithione (ZP) and Cuprous Oxide (CP) biocides. Although each biocide has its thread and health risks for various species, it should be noted that, this data may be helpful for a decision-making tool to limit the impacts of biofouling on the ships operating in the Black Sea by the end-users. Furthermore, these fouling conditions of different antifouling coatings may be used to calculate and estimate the added resistance and so fuel consumption, economic and environmental penalties of the ships under particular fouling conditions at varying ship speeds by the engineers and researchers. In addition, these fouling conditions of the coatings may be used to identify the impacts of biofouling in alternative industries such as aquaculture in the Black Sea. Furthermore, these fouling ratings can encourage further experiments to show the differences between varying antifouling strategies.

- *To the best of the author's knowledge, this is the first time a survey was conducted with the stakeholders of the industrial fishing vessels, demonstrating their knowledge about biofouling, marine coatings, and antifouling strategies.*

This was achieved by directing 34 open- and close-ended questions to the fishermen/stakeholders of 41 industrial fishing vessels. Survey results showed the common antifouling application choice and habits together with the fishermen's awareness of the penalties caused by the biofouling. Such data help the recent practices used by the relevant industries more visible to the public. Therefore, any further step can be taken when necessary, such as encouraging authorities to focus on educational training to increase awareness about the importance of biofouling in industrial fisheries.

Other main contributions to the field within this PhD study are listed below:

- *To the best of the author's knowledge, this is the first-time underwater hull inspections of three different fishing vessels were conducted, and the fishing vessels' fouling characteristics in the Black Sea were presented in Chapter 3. Thus, the results of these inspections can help authorities and the companies to focus on specific fouler organisms in the fight with biofouling.*

This was achieved by selecting fishing vessels randomly and then investigating their underwater hull fouling accumulations when the vessels were drydocked. This data shows the fouler organisms under different operational profiles and ship characteristics. Even if there is no detailed data available for the operational profiles of the ships whose underwater hulls were examined, it is important to understand the type of biofouling and species that would be encountered when any immersion test is conducted in the region. It is also important to see that what possible penalties are faced when the underwater hulls of similar ships are not cleaned at varying times. One of the critical findings obtained from the investigations is that, although a variety of fouler organisms exist, most of them accumulate on certain parts of the fishing vessels. This heterogenous fouling behaviour of the species can help the antifouling coating manufacturers to reconsider the working mechanism or the efficacy of their antifouling coatings in certain underwater spots of the ship hulls.

- *To the best of the author's knowledge, this is the first time that adhesion strengths of the specified organisms adhered on different fishing vessels with different operational profiles in the Black Sea were presented and illustrated in Chapter 3.*

This was achieved by using a force gauge to measure the peak applied force required for the calcareous fouler organism to release itself from the adhered surface. Although a limited number of organisms were available to measure adhesion strengths, the most difficult organisms to remove was barnacles reaching up to 0.521 MPa. Moreover, adhesion strength values show similar results with the data available in the literature (Oliveira and Granhag, 2016). In addition to that, there might be significant differences in the adhesion strengths of different species, regardless of their size or the adhered surface area. This data may be helpful for learning the necessary forces to remove certain species from desired surfaces to prevent deformation of the hull surface for the ships.

- *In Chapter 5, the impacts of antifouling coatings were compared in terms of biocide ingredients and availability.*

This was achieved by comparing the biocide contents and availability of the antifouling coatings. Furthermore, results showed that certain biocides show better antifouling performances compared to others. Therefore, this data may be helpful for marine antifouling coating designers so that specific target antifouling coatings can be manufactured in various industries. Furthermore, collaborating with the local paint manufacturers may contribute to help internationally available coating manufacturers for preventing penalties caused by biofouling more efficiently on global scale.

6.4 General Discussion

There are three main sections in this thesis. The first section is the survey conducted with the fishermen and stakeholders to determine the characteristics of the common antifouling practices in the fishing industry to address the knowledge that the stakeholders/fishermen have about the impacts of biofouling. The second section is the investigation of the effects of biofouling with the help of field and ship tests conducted and presented in Chapter 4. The third section is the case studies which are presented in Chapter 5.

As stated in Chapter 3, a survey was conducted with the fishermen to capture the technical and operational aspects of the fishing vessels in the Black Sea. The survey conducted with the fishermen measures the knowledge of the end-users and provides real insight for the authorities to reconsider the current situation regarding the topic. Therefore, looking at the survey results detailed in Section 3.4, it can be seen that although regulations are becoming stricter to improve the energy efficiency of a ship, there are still poor (or traditional in some cases) practices in use that negatively impacts the antifouling capabilities of a fishing vessel, so that negatively effects ship performance and environment.

At this point, giving examples from what survey results show would be beneficial. Fishermen still use a roller brush to coat their vessels. Moreover, some fishermen do not prefer coating their vessel's propeller. Next, there are fishermen who do not let professional antifouling coating applications be conducted for their fishing vessels, and the majority of the fishermen use biocide based SPC coatings. These examples can be broadened by examining the survey results detailed in Chapter 3. It should be noted that the given examples represent a realistic perspective rather than ideal conditions, particularly after considering the regulations, which impose limitations.

Nevertheless, this is important to show that although the authorities set limitations for more energy and economically efficient shipping, the practice in use still does not match the aimed goals. Field tests and case studies were conducted based on the practices used and learnt as a result of survey results. Fishing vessels, regulations, and fishing seasons might change for different fishing regions. Therefore, increasing the number of fishermen from certain different regions would offer a better understanding of the penalties that might be caused by determining the impractical habits that the regions would have.

As stated in Chapter 4, immersion test panels were used to test the antifouling performance of the coatings over time in the Black Sea. Two different immersion test panels were set for two different antifouling coating technologies representing the SPC and FR type coatings. Having two different antifouling strategies tested in the same region over time is essential to compare the current most commonly used antifouling strategies (biocide based SPC) and the futuristic antifouling strategies (Foul release) due to ongoing restrictions made by IMO. Interestingly, results showed that the most common antifouling coatings (SPC) currently show better performance than the futuristic antifouling coating strategies (Foul release).

Furthermore, it was seen that the first two months after immersion of the surfaces coated with the relevant antifouling coatings is crucially essential to prevent fouling accumulation. Moreover, both the SPC and foul release coatings showed calcareous fouling by the end of their immersion test times. However, looking at the reason behind the difference of two antifouling coatings immersion test results in detail, it can be seen that working mechanisms of the foul release coatings are the reasons behind the poorer performances in the immersion test results. As stated before in Section 2.4, foul release coatings offer a smooth surface, and the working mechanism is designed to degrade the adhesion strengths of the colonisers with the increasing speed of the coated surface or the seawater current. In short, immersion test results showed that foul release coatings show poorer performance than SPC antifouling coatings; however, considering the cruising condition for the surfaces that foul release coatings applied, the efficiency of the foul release coatings would significantly increase. Therefore, foul release coatings coated ship tests would be helpful to make a comparison of the FR coatings under cruising conditions as further research.

Next, when the immersion test results were obtained for the Black Sea region, fouling ratings of the SPC coatings were generated for the Mediterranean Sea. Having said that, conducting immersion tests for the same coatings in more locations would not only show the fouling growth differences under different environments but would also be helpful to generate new data for any antifouling coating depending on the immersion tests. Last but not least, immersion test results were further used to show the impact of biofouling on fishing vessels, as presented in case studies in Chapter 5.

In Chapter 5, three case studies representing two fishing methods operating in two different regions were conducted to show the impacts of biofouling and the importance of the antifouling coating selection for the industrial fishing vessels. Case studies were performed by surveying results from Chapter 3 and using immersion test results from Chapter 4. Furthermore, SPC antifouling coatings were deployed in the case studies. Results showed that a significant amount of fuel (L) consumption could be saved, and so that a significant amount of CO_2 emission can be prevented considering a fishing vessel operating in either the Black Sea or the Mediterranean Sea.

To be more specific, considering the number of fishing vessel fleets in the GFCM area, it was estimated that with a simple antifouling coating selection among the determined SPC coatings, 146.1M litres of fuel consumption can be reduced and so that up to £112.5M can be saved due to fuel cost reduction. In addition, up to 0.42M tonnes of CO_2 emission can be prevented. What is more, considering the number of fishing vessel fleets globally, it was estimated that with a simple antifouling coating selection among the determined SPC coatings, 660.37M litres fuel consumption can be reduced. In addition, £508.48M can be saved due to the fuel cost reduction and yet to up to 1.9M tonnes CO_2 emission can be prevented. Although these numbers might look smaller compared to the global shipping industry, examining the number of people related to industrial fisheries who would possibly be affected would make it easier to understand its significance.

Furthermore, considering that the fishing vessels operate near coastal zones, it is expected that reducing the CO_2 emission would directly improve millions of people's health. Next, considering the fuel prices, any deduction on the total fuel consumption costs would contribute to reducing the seafood prices so that many millions of people can have easier access to healthier food globally. In addition, considering the total number of people whose job is directly or indirectly related to industrial fisheries, any saving in the costs would positively affect many people's income. Moreover, the case studies presented in Chapter 5 are also important to show how the fishermen would benefit by improving their knowledge (regarding to the importance of antifouling coatings) in terms of fuel consumption, fuel consumption costs and CO_2 emissions.

6.5 Chapter Summary

This chapter summarises the achieved research aims and objectives and provides a general discussion on the limitations, assumptions, and difficulties faced within this PhD research. In addition, novelties and contributions made by this research were also clearly presented.

7 Conclusions and Recommendations

7.1 Chapter Introduction

This chapter presents the conclusions of the studies performed within this PhD. Moreover, recommendations are presented for future research as a further study of the work presented in the main chapters of this thesis.

7.2 Main Conclusions

The main conclusions of this PhD thesis are listed below:

- The survey study presented in Chapter 3 concluded that although biofouling is a widespread phenomenon in shipping and maritime industries, the importance of fighting the biofouling accumulation is not understood very well among the fishermen/stakeholders.

- From the hull inspections presented in Chapter 3, it was concluded that the longer the fishing vessel's underwater hull inspections are neglected, the more species accumulated on the ship hull. Nevertheless, each accumulated fouling organisms have different adhesion strength depending on the species and its dimensions. Furthermore, adhesion strength test results showed that barnacles are the most difficult to remove once they attach themselves to a surface.

- From the field tests presented in Chapter 4, different antifouling coatings using the same antifouling strategies (SPC coatings) show significant differences in fighting biofouling. Furthermore, locally available SPC antifouling coatings showed a better performance than internationally available SPC antifouling coatings. What is more, when the biocide components and the antifouling coating success is compared, SPC coatings that have particular biocides showed better antifouling performances. To be more specific, Di and CY showed better antifouling performances in comparison to ZP and CP biocides.

- From the field test presented in Chapter 4, fouling organisms are directly affected by weather conditions, currents, waves, and predators feeding with the fouler organisms (such as piper fish). Although it is difficult to measure which one is the most important, waves and the predators showed that they are efficient enough to remove some of the organisms that had already adhered to the surface.

- From the field tests presented in Chapter 4, differences between SPC and Foul release coatings show that FR coatings had poor performance compared to SPC coatings. In other words, the worst effective SPC antifouling coating showed better performance than foul release coatings in the Field test results. Looking at the reason behind the poorer performance of the FR coatings, the working mechanisms of FR coatings can be attributed to the poor performance. In other words, because FR coatings are designed to work under cruising conditions, immersion test results for the FR coatings showed poorer antifouling performance compared to SPC coatings. In addition to that, generated immersion test results of the SPC coatings in the Mediterranean Sea showed poorer performance than immersion test results of the SPC coatings in the Black Sea due to having warmer sea surface temperatures.

- From the field and ship tests presented in Chapter 4, ship test results showed that coatings applied on selected fishing vessel's underwater hull have relatively lower fouling rates in comparison with the SPC immersion test Panel's results as expected. The reason behind this is due to the assumption made in Uzun (2019)'s study as "the biofouling growth during the static conditions (idle times) overweigh the biofouling growth in dynamic conditions". For that reason, Uzun (2019)'s time-dependant biofouling model results, in terms of fouling ratings, show reasonable outcomes in comparison to the ship test results.

- From the Case studies presented in Chapter 5, it was shown that impacts of biofouling on industrial fishing vessels are significant both financially and environmentally. To give an example, coating a purse seiner fishing in the Black Sea with any of the SPC antifouling coatings can save up to 9.11% in fuel consumption in comparison to the uncoated. Therefore, up to 9.11% of the fuel cost and the CO_2 emission can be deducted in a fishing season.

- From the case studies presented in Chapter 5, due to mainly having different operational profiles required for different fishing techniques, it was shown that the impact of biofouling in terms of ship frictional resistance and effective power is higher in trawlers than the purse seiners fishing in the same region.

- From the case studies presented in Chapter 5, it was shown that the antifouling coatings branded by the local companies are more successful in comparison to the internationally available antifouling coating brands. In other words, all the case studies showed that the impacts of biofouling on industrial fishing vessels are less for the locally branded antifouling companies. Within this point, that should be noted that the local companies do not use internationally banned biocides such as TBT. However, it is still a question of whether the local companies comply with the international standards. Nevertheless, results show that large and internationally available companies should cooperate with the local brands so that the penalties caused by the biofouling can be minimised for the industrial fishing vessels.

- From the case studies presented in Chapter 5, it was shown that the biocide contents of the SPC antifouling coatings show a significant difference in avoiding the penalties caused by the biofouling for the industrial fishing vessels. In other words, specific biocides are more successful with the fight against biofouling in industrial fishing vessels. To be more specific, Di and CY biocides containing coatings showed better antifouling performances in comparison to ZP and CP biocides containing coatings.

- From the Case studies presented in Chapter 5, it was shown that geographical differences directly impact the performances of the antifouling coatings regardless of the fishing methods. Nevertheless, in the warmer regions, biofouling accumulation occurs faster so that the impacts of the biofouling on industrial fishing vessels are observed more severe. Furthermore, generated fouling data results for the Mediterranean Sea show approving results.

7.3 Recommendations for Future Work

Following listings are the recommended work for future studies in order to take this work forward.

- In Chapter 3, a survey was conducted with the fishermen/stakeholders to learn the understanding from the point of end users' view for the industrial fisheries in the Black Sea region. A further survey investigation in different regions within different sectors might fill the gap between the antifouling coating companies and the end users' knowledge and expectations as each sector, region, and industry have different localised problems.

- In Chapter 3, underwater hull inspections of the industrial fishing vessels were conducted, and the fouling characteristics of the vessels in the region were determined. In addition to that, further underwater hull inspections for the industrial fishing vessels could be conducted for other locations such as the Mediterranean Sea. Another further study could be conducted for the artisanal, small scale, and recreational fisheries to understand the impacts of the biofouling together with the fouling patterns as the fishing vessels in these fisheries classes are expected to be less yet significant due to often drydocking and hull cleaning periods.

- In Chapter 4, antifouling field tests were conducted and investigated. A further study can be considered as increasing the number of locations of the field tests. Thus, geographical differences and the parameters affecting biofouling, such as salinity, pH, temperature, can be investigated thoroughly. To give an example, the Caspian Sea would be an excellent example due to its unique marine environment characteristics.

- In Chapter 4, a ship test was conducted for the SPC antifouling coatings selected as a result of the survey conducted with the fishermen/stakeholders. A future study can be applying the selected antifouling coatings to the fishing vessels fishing with varying fishing methods. Thus, the differences between fishing methods and suitable fishing vessels' fouling patterns can be learnt, and the impacts of biofouling on different fishing methods can be compared.

- In addition, applying antifouling coatings on the ship hulls fully for the ship tests can be regarded as a future study. Further investigation could be conducted for the impacts of the light over the ship hull and the self-grooming due to fishing activities.

- In Chapter 4, a ship test was conducted for SPC antifouling coatings selected as a result of the survey conducted with fishermen/stakeholders. A further application can be made by coating the fishing vessels with foul release coatings (FR) to compare the field tests, and the ship tests as the working mechanism of the foul release are dependent on surface adhesion of the fouler organisms rather than exposure to toxic biocides.

- In Chapter 4, field tests and ship tests were conducted. As a result, fouling ratings were appointed for each coating over time in Black Sea Region according to NSTM standards to be converted to equivalent surface roughness heights. A further study could be conducted to enhance the fouling ratings by combining the surface coverage of each fouler organism and equivalent sand roughness heights.

- In Chapter 5, Case studies show that power requirements increase, fuel consumption increases, and the CO_2 emission increase due to biofouling. Therefore, considering that the number of small-scale fishing vessels is higher, similar calculations showing the impacts of biofouling for the small scale / artisanal / subsidence / recreational fisheries can be considered a future work.

- A simple antifouling coating selection decision among the determined SPC antifouling coatings can decrease industrial fishing vessel fleet's fuel consumption up to 146.1M litres, fuel costs up to £112.5M, and CO_2 emission up to 0.42M tonnes in the GFCM area. Moreover, a simple antifouling coating selection decision among the determined SPC antifouling coatings can decrease the global industrial fishing vessel fleet's fuel consumption up to 660.37M litres, fuel costs up to £508.48M, and CO_2 emission up to 1.9M tonnes when a purse seiner operating in the Black Sea is taken into consideration. Therefore, increasing the number of fishing methods and suitable fishing vessels such as long liners fishing in the open ocean can be considered as a further study. Thus, a comparison between fishing vessels near coastal zones and fishing vessels fishing in open ocean waters can be made.

- In Chapter 5, field test results were converted in equivalent sand roughness heights using Schultz (2007)'s NSTM rating and equivalent sand roughness height conversion table. A future study is regarded as using the towing tank tests by obtaining the relevant total resistant coefficients (C_T) and so that Schultz (2007)'s NSTM rating and equivalent sand roughness height conversion table can be validated. In addition, mimicking the fouling environment in a controlled environment by using a slime farm and analysis of the skin friction characteristics by measuring the pressure drop in a friction pipe for the selected SPC antifouling coatings can be considered as a further works.

- The importance of antifouling coating selection was systematically investigated, and benefits were presented both environmentally and financially for the fishermen. Another future study, therefore, can be considered as developing a practical decision support system and guidelines to train the fishermen on selecting the most suitable antifouling coating and maintaining it for maximum performance. Thuswise, improvements in the fishermen's community can make profits and reduce GHG emissions in their local regions.

7.4 Chapter Summary

This chapter gives the main conclusions in this PhD thesis. Furthermore, recommendations for future work were outlined.

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Research Outputs

The following publications were generated throughout the timespan of the PhD studies related to this thesis.

Journal papers (SCI / SCI Expanded):

1. Uzun, D., **Ozyurt, R.**, Demirel, Y.K., Turan, O., 2020. Does the barnacle settlement pattern affect ship resistance and powering? Appl. Ocean Res. 95, 102020. https://doi.org/10.1016/j.apor.2019.102020

2. Uzun, D., Sezen, S., **Ozyurt, R.**, Atlar, M., Turan, O., 2021. A CFD study: Influence of biofouling on a full-scale submarine. Appl. Ocean Res. 109, 102561. https://doi.org/10.1016/j.apor.2021.102561

3. Sezen, S., Uzun, D., **Ozyurt, R.**, Turan, O., Atlar, M., 2021. Effect of biofouling roughness on a marine propeller's performance including cavitation and underwater radiated noise (URN). Appl. Ocean Res. 107, 102491. https://doi.org/10.1016/j.apor.2020.102491

Conference papers:

- Uzun, D., **Ozyurt, R.**, Demirel, Y.K., Turan, O., 2018. Time based ship added resistance prediction model for biofouling, in: Marine Design XIII. pp. 971–979.

Appendix A: Survey

1. What kind of vessel do you use; motorised or non-motorised vessel ? If motorised; What is your vessel's lenth overall, engine's horsepower and is it an inboard or outboard?

   ☐ Non-motorised Vehicle

   ☐ Motor Boat;

   LOA = ...
   HP = ...
   Engine's age = ...
   Inboard / Outboard Motor

2. Do you own the vessel? If Your answer is NO, please spesify your situation.

   ☐YES ☐NO :......................... ....

3. What is the hull of your vessel made of?

   ....

4. How old is your vessel?

   ....

5. How often do you go fishing?

   ....

6. How many years of experience do you have in fishing?

   ....

7. What type of fuel do you use?

   ....

8. What is your normal daily / monthly fuel consumption in litres?

   ....

9. How far is your operational range from the coast? Please specify

....

10. Are you aware of the penalties posed by biofouling? If Your answer is YES, please spesify.

☐ NO ☐YES;

✎

11. Have you got any training information by any organisation about minimising the accumulation of biofouling? If your answer is YES, please specify.

☐ NO ☐YES;

✎

12. Do you conduct the hull cleaning (docking) process for biofouling?

☐ NO ☐ YES

13. How often do you conduct the hull cleaning (docking) process for biofouling?

✎

14. How often do you dry-dock your vessel?

....

15. Do you drydock your vessel only for cleaning biofouling? If your answer is NO, please specify what the other reasons are?
☐ YES ☐NO;

16. Where do you conduct the hull cleaning (docking) process for biofouling?

17. What kind of methods do you use to conduct the hull cleaning (docking) process for biofouling ?

18. How much do that hull cleaning (docking) process cost? Please specify in detail.

19. How long does it take to to conduct the hull cleaning (docking) process for biofouling ?

....

20. How do you choose the method used in conducting the hull cleaning (docking) process for biofouling? Please Specify.

21. Do you use hull coating? If your answer is YES, please specify which brand you use?

☐NO ☐ YES ;

22. Where do you buy the hull coating from?

23. How do you choose the coating applied on the hull?

24. How do you conduct the coating?

25. Do you conduct the coating yourself? If your answer is NO, Please detail who does.

☐YES ☐ NO ;

26. Where do you conduct the coating?

27. How long does it take to apply the hull coating ?

28. What is the common paint application practice amongst typical fishermen communities?

29. How often do you coat your vessel?

30. How much does it cost you to paint the vessel hull?

31. How many litres of coatings do you use to coat your vessel?

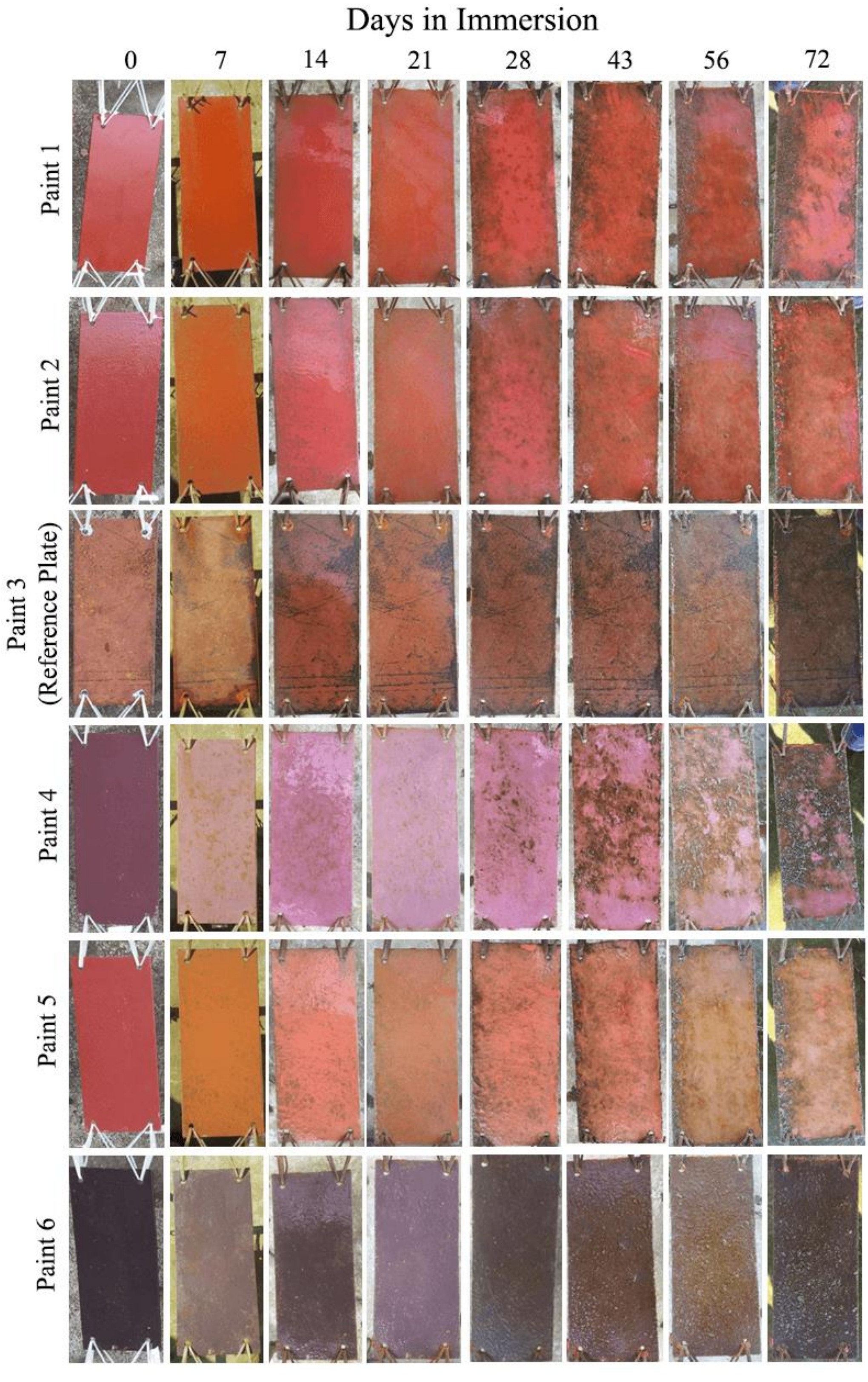
32. Does your propeller get fouled?

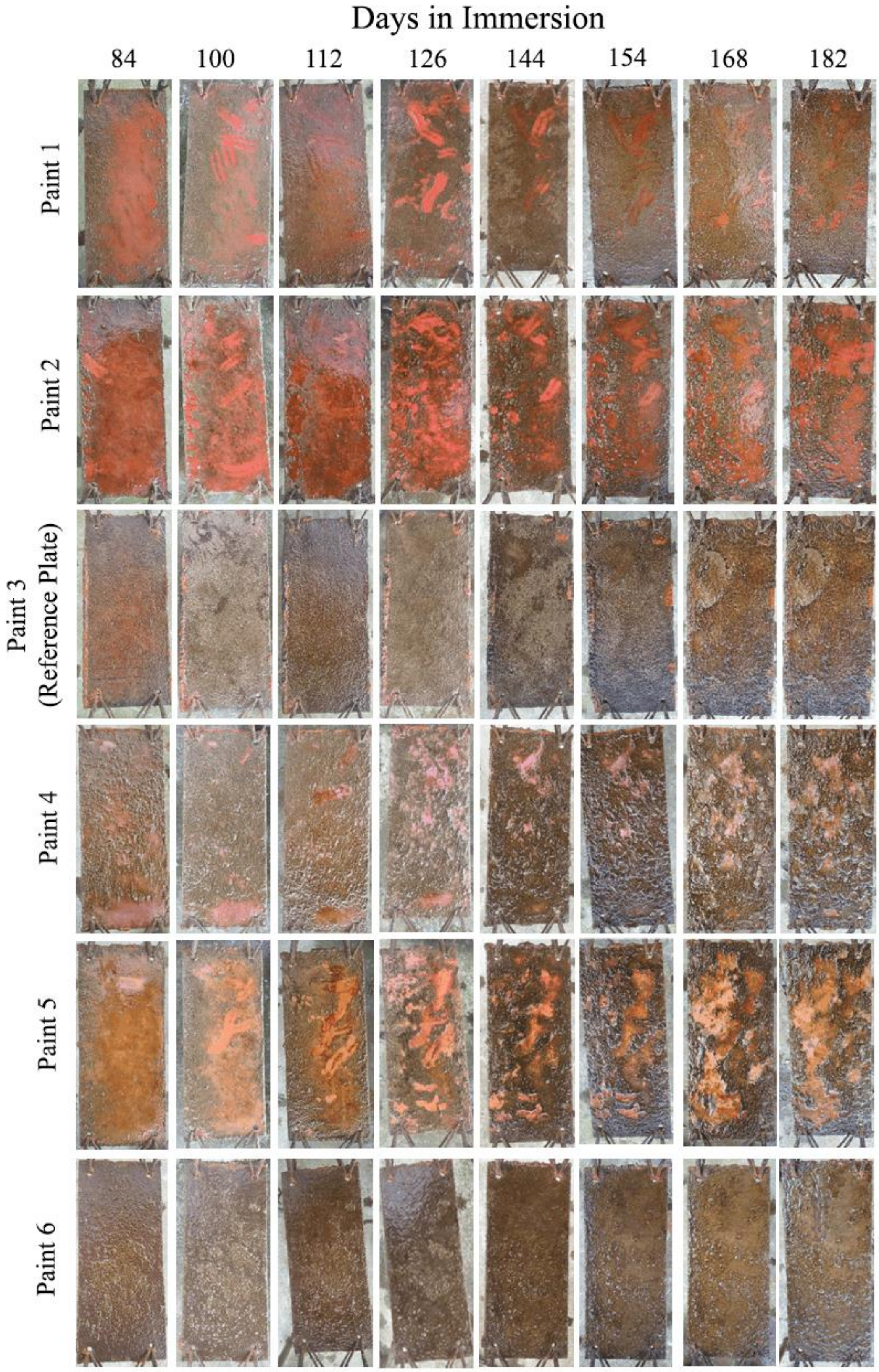
33. Have you ever coated your propeller? Would you like to do it, if it keeps propeller clean?

34. Please specify your average time and average speed in nautical miles for different operational profiles separately.

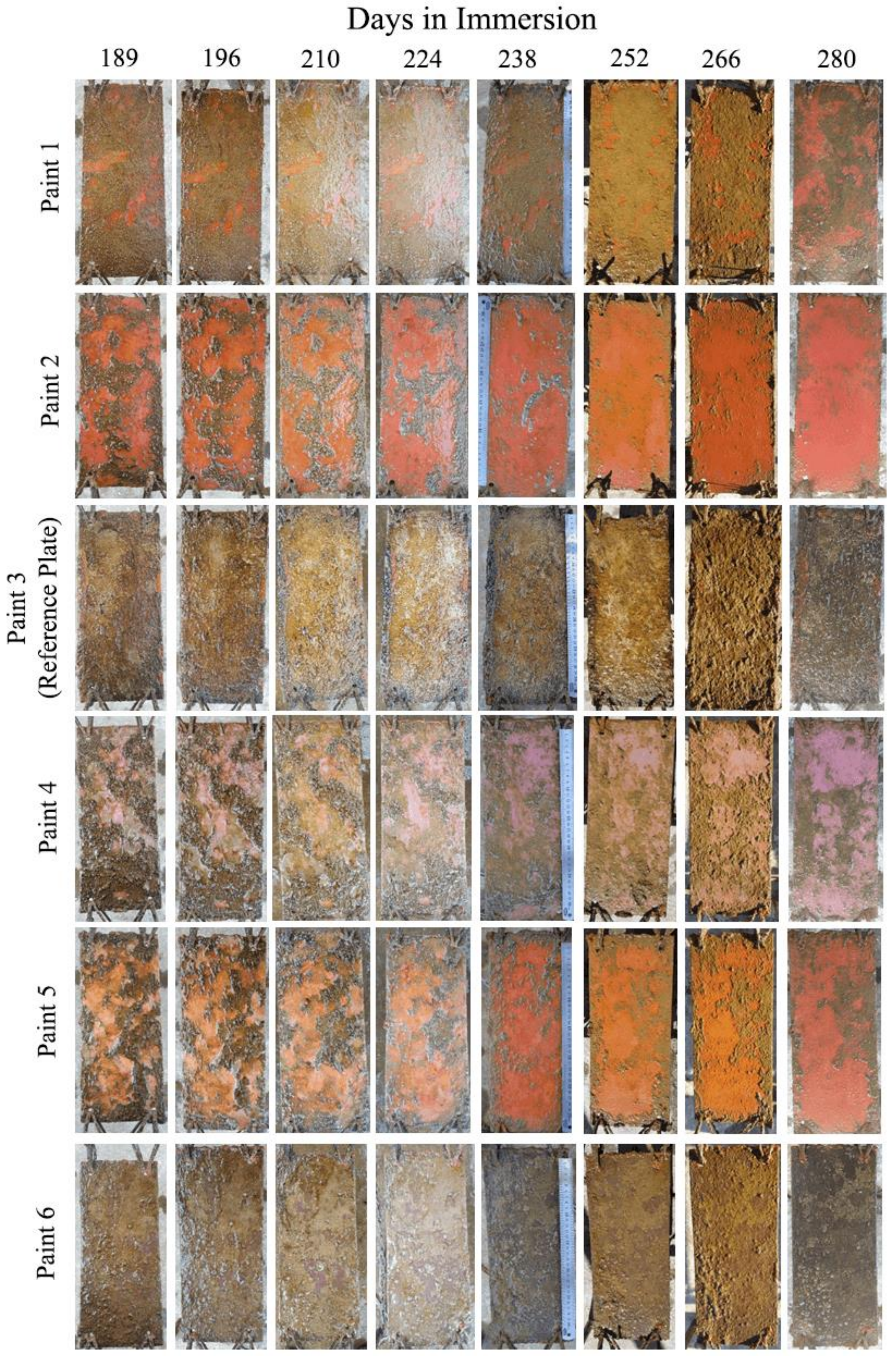
	Average Time	Average Speed (Nm)
Navigation to Fishing Zone:		
Multiple Hauling And back to the next line		
Navigation back to port		
Discharging fish in port		

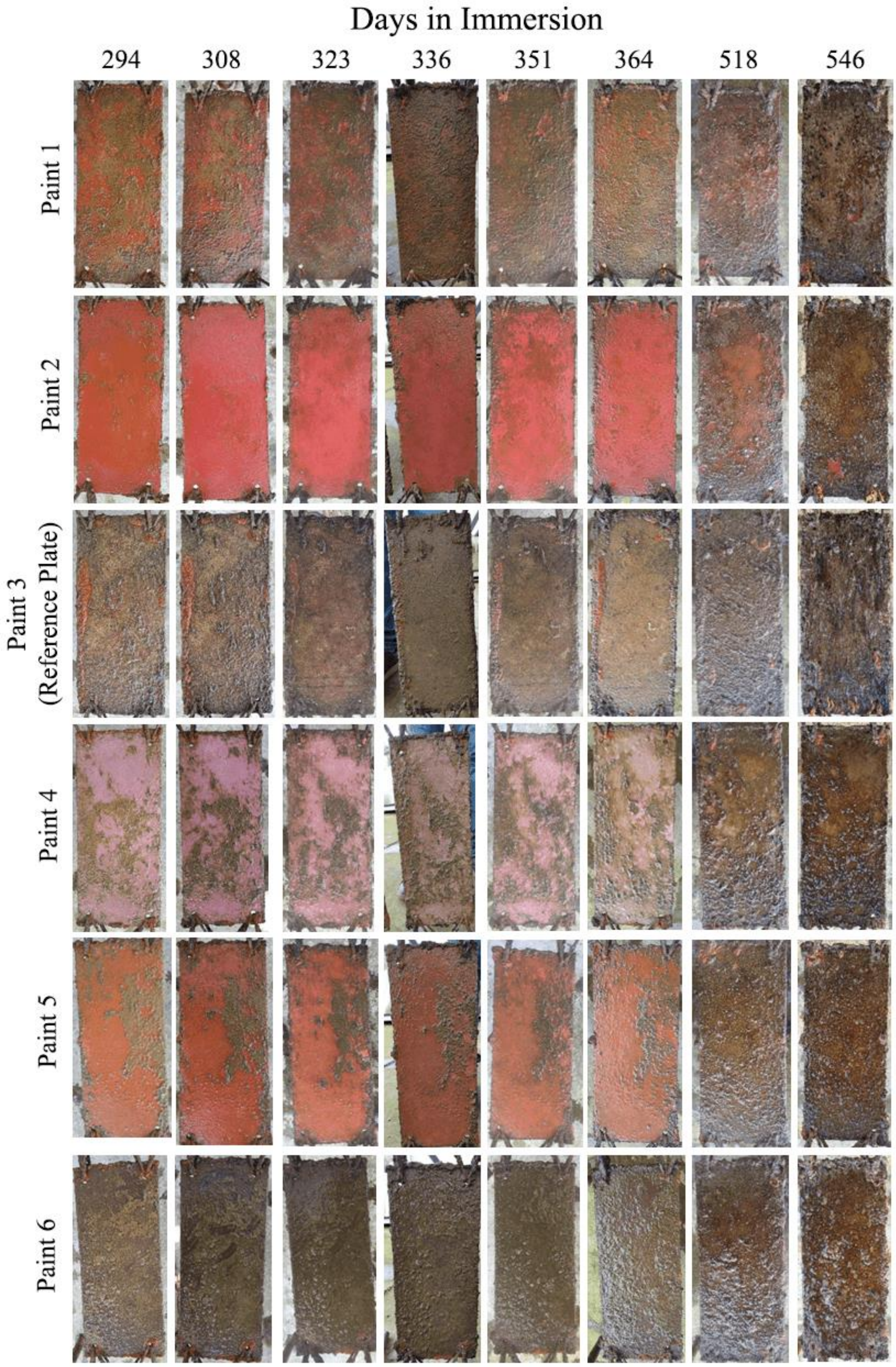
Appendix B: SPC Immersion Test



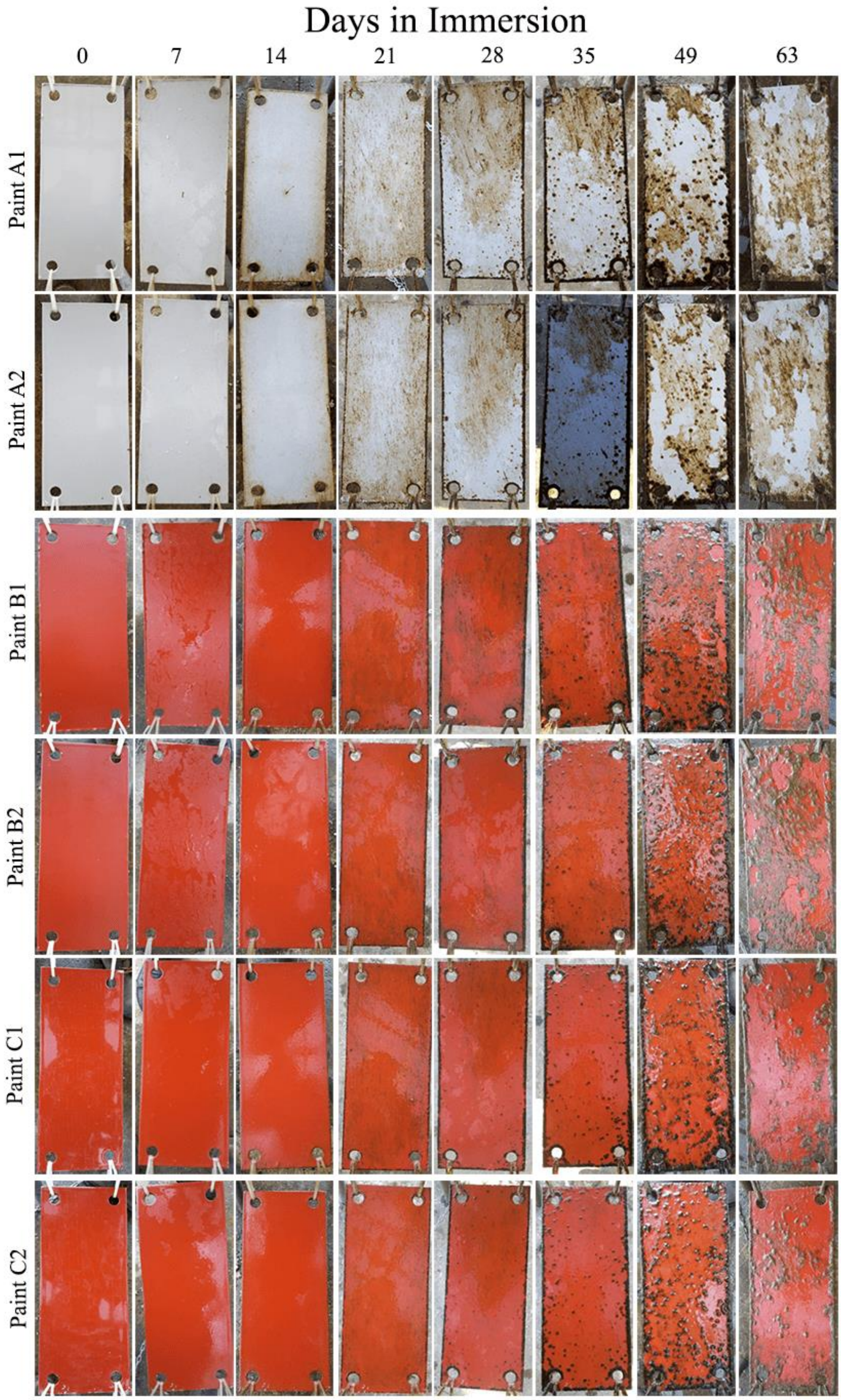


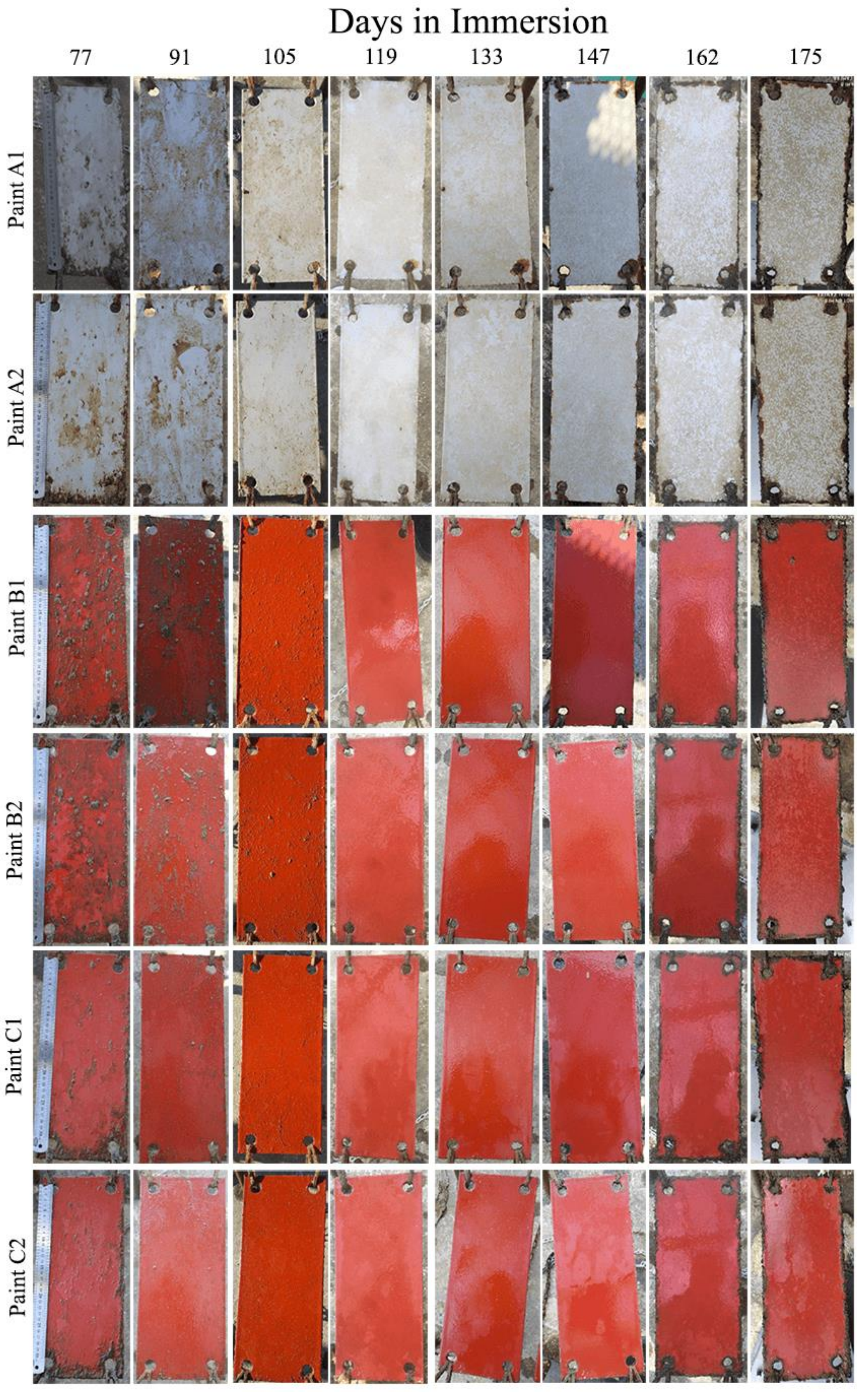
Days in Immersion
84
100
112
126
144
154
168
182
Paint 1
Paint 2
Paint 3
(Reference Plate)
Paint 4
Paint 5
Paint 6

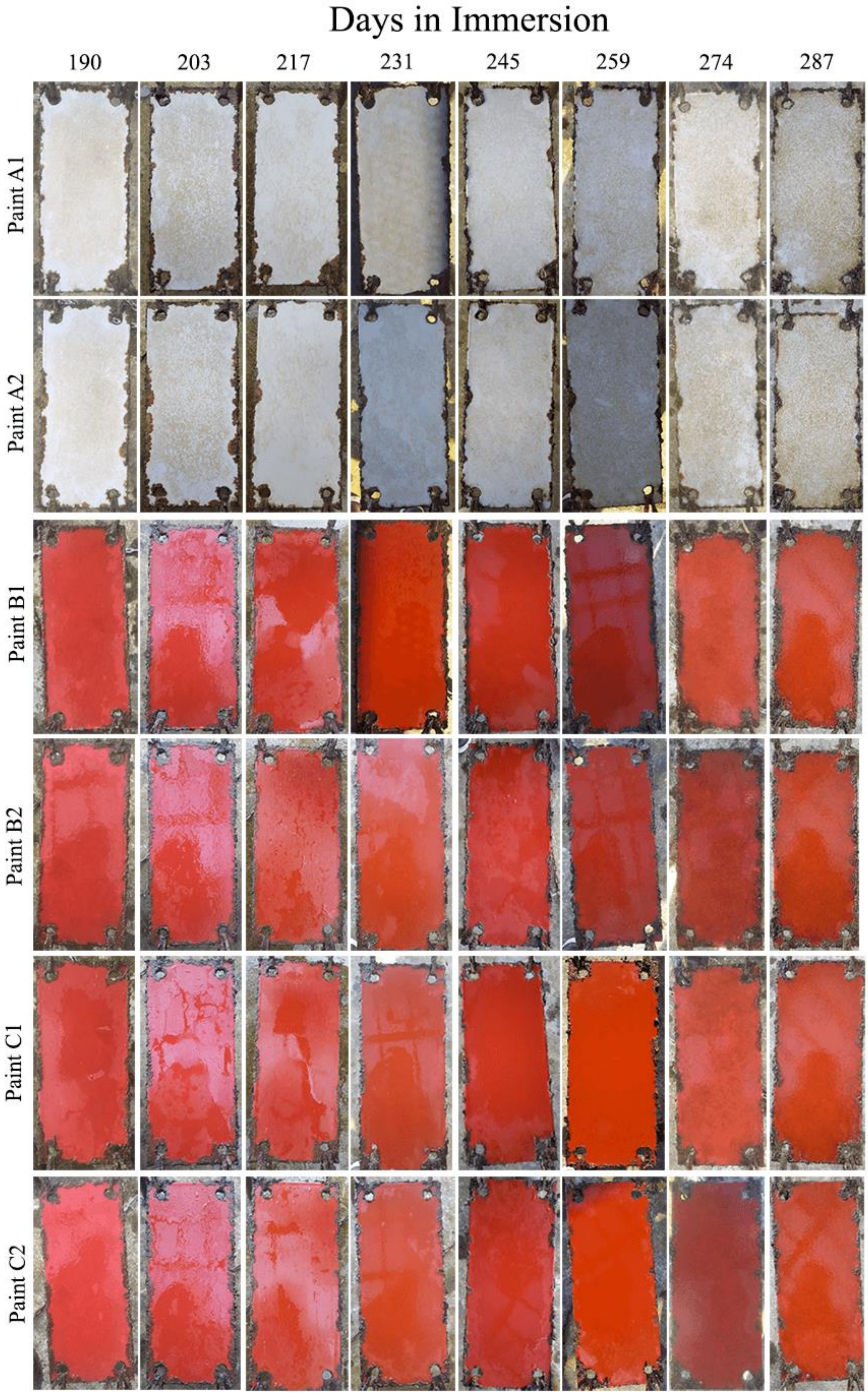

Days in Immersion
189
196
210
224
238
252
266
280
Paint 1
Paint 2
Paint 3 (Reference Plate)
Paint 4
Paint 5
Paint 6


Days in Immersion
294
308
323
336
351
364
518
546
Paint 1
Paint 2
Paint 3 (Reference Plate)
Paint 4
Paint 5
Paint 6

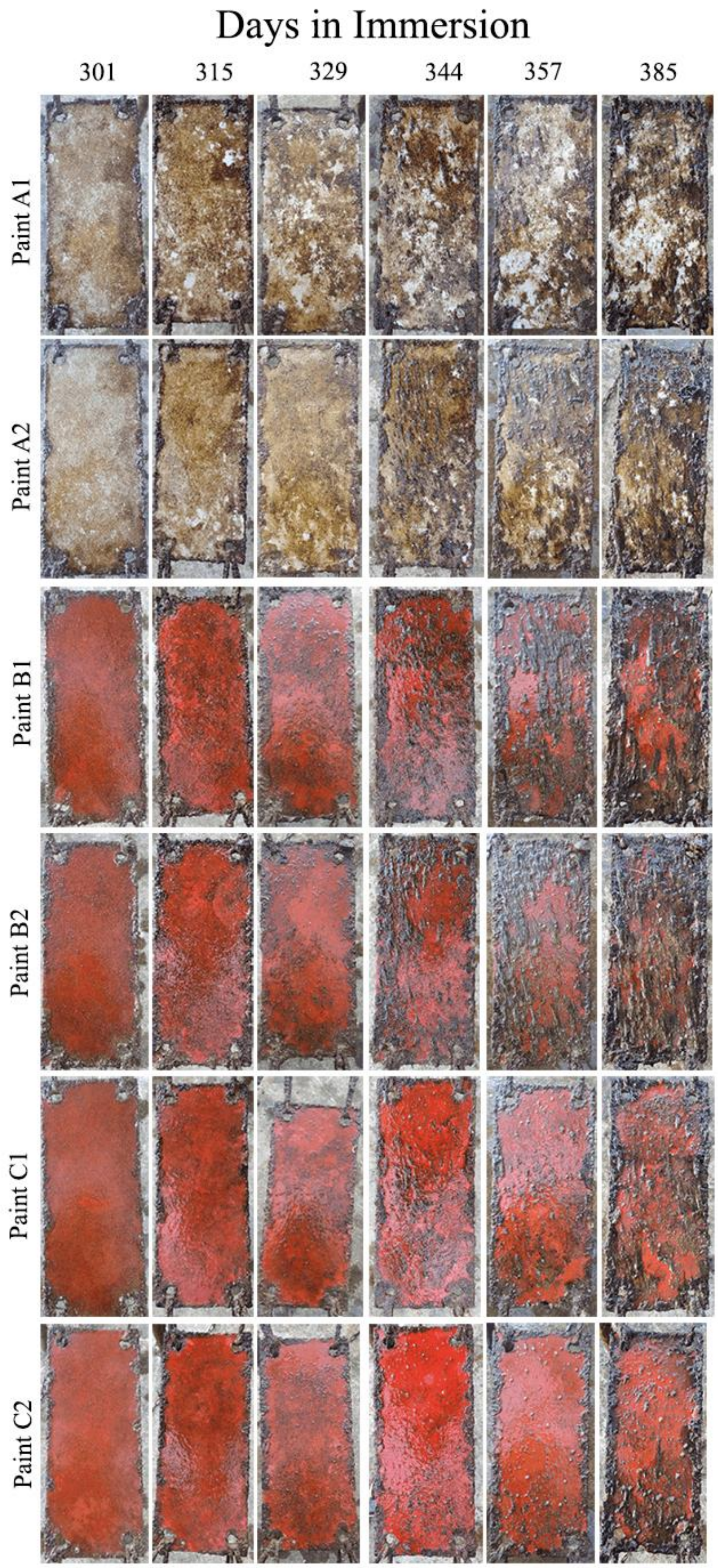
Appendix C: FR Immersion Test




Days in Immersion
77
91
105
119
133
147
162
175
Paint A1
Paint A2
Paint B1
Paint B2
Paint C1
Paint C2



Days in Immersion
190
203
217
231
245
259
274
287
Paint A1
Paint A2
Paint B1
Paint B2
Paint C1
Paint C2


Days in Immersion
301
315
329
344
357
385
Paint A1
Paint A2
Paint B1
Paint B2
Paint C1
Paint C2

Appendix D: Fouling Rating Assessment of SPC Coatings

Paint 1 - Fouling Rating Assessment

Appx-Table.1: Appx-Table. 1: Appx-Table.1: NSTM Fouling Ratings for Paint1

	Paint 1	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ The antifouling coating was used and defined as Paint 1. Paint 1 is a bottom paint with a high content of cuprous oxide. ➢ The panel is painted with roller brush paint and immersed on 4th September 2018 in a fishing port. ➢ According to NSTM standards, “a clean, foul-free surface; red and/or black AF paint or a bare metal surface” is rated as 0. Hence Paint 1’s immersion day fouling rating is 0.
7 Days in Immersion		➢ 1st week’s accumulation results of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, there is no visible fouling, but a close inspection indicates that incipient slime accumulation can be seen as light green shades on the panel. ➢ According to NSTM standards; “A clean, foul-free surface; red and/or black AF paint or a bare metal surface” is rated as 0 and “Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.” is rated as 10. Hence Paint 1’s 1st week’s fouling rating can be identified between 0 and 10.

Appx-Table 1. NSTM Fouling Ratings for Paint1 (cont.)

	Paint 1	Fouling Ratings According to NSTM Standards
14 Days in Immersion		➢ 2nd week's accumulation results of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, the panel's surface is still visible. Additionally, incipient slime accumulations as in light green shades can be observed over the panel. ➢ According to NSTM standards, "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence, Paint 1's 2nd week's fouling rating can be identified as 10.
21 Days in Immersion		➢ 3rd week's accumulation results of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation starts becoming visible compared to 2nd week's accumulation results; however, it is easy to notice that the bare panel is still visible. ➢ According to NSTM standards, "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence, Paint 1's 3rd week's fouling rating can be identified as 10.
28 Days in Immersion		➢ 4th week's accumulation result of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, unlike the previous weeks' accumulation results, advanced slime accumulation starts to be visible as green/red spots over the panel in the fourth week. It can be seen that advanced slime accumulation obscure the panel surface partially. However, it can be noticed that the paint surface is still visible, and the paint surface can still be identified. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10 and "Slime as dark green patches with yellow or brown colored areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. As 4th week's result show both early stages of fouling rating 20 and advanced stages of fouling rating 10. Therefore with reference to NSTM standards, it can be said that Paint 1's 4th week's fouling rating can be identified with a rating between 10 and 20.

Appx-Table 1. NSTM Fouling Ratings for Paint1 (cont.)

	Paint 1	Fouling Ratings According to NSTM Standards
84 Days in Immersion		➢ 12th week's accumulation results of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, the grass filaments coverage area increases compared to the previous week's accumulation results. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 1's 12th week's fouling rating can be identified between 20 and 30.
182 Days in Immersion		➢ 26th week's accumulation results of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 1's 26th week's fouling rating can be identified as 30.

Appx-Table 1. NSTM Fouling Ratings for Paint1 (cont.)

	Paint 1	Fouling Ratings According to NSTM Standards
266 Days in Immersion		➢ 38th week's accumulation results of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous foulers. However, it can be noticed that the coverage area of the grass filaments decreased together with the soft non-calcareous fouling compared to the previous week's fouling condition. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 1's 38th week's fouling rating can be identified as 30.
364 Days in Immersion		➢ 52nd week's accumulation results of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 1's 52nd week's fouling rating can be identified as 30.

Appx-Table 1. NSTM Fouling Ratings for Paint1 (cont.)

	Paint 1	Fouling Ratings According to NSTM Standards
546 Days in Immersion		➢ 78th week's accumulation results of Paint 1 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation covers all of the panel's surface. In addition, grass filaments and soft non-calcareous fouler organisms keep growing one on top of another. Although early stages of calcareous fouling appear on the panel, among the grass, tubeworm and *Spirorbis pusilla* accumulation can be hardly identified. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. For that reason, with reference to NSTM standards, Paint 1's 78th week's fouling rating can be identified as 40.

Paint 2 - Fouling Rating Assessment

Appx-Table.2: NSTM Fouling Ratings for Paint 2

	Paint 2	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ The antifouling coating was used and defined as Paint 2. Paint 2 is a bottom paint with a high content of cuprous oxide. ➢ The panel is painted with roller brush paint and immersed on 4th September 2018 in a fishing port. ➢ According to NSTM standards; “a clean, foul-free surface; red and/or black AF paint or a bare metal surface” is rated as 0. Hence Paint 2’s immersion day fouling rating is 0.
7 Days in Immersion		➢ 1st week’s accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, there is no visible fouling; however, looking at it closer, incipient slime accumulation can be seen. ➢ According to NSTM standards; “A clean, foul-free surface; red and/or black AF paint or a bare metal surface” is rated as 0 and “Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.” is rated as 10. Hence, it can be said that Paint 2’s 1st week’s fouling rating can be identified between 0 and 10.
14 Days in Immersion		➢ 2nd week’s accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, bare panel is still visible, and there seems to be only incipient slime accumulation can be observed over the panel. ➢ According to NSTM standards; “Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.” is rated as 10. Hence Paint 2’s 2nd week’s fouling rating can be identified as 10.

Appx-Table.2: NSTM Fouling Ratings for Paint 2 (cont.)

	Paint 2	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3^{rd} week's accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation becomes more visible in the third week and light-slime intensity, compared to 2^{nd} week, is higher; however, the coated surface is still visible beneath the fouling. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence Paint 2's 3^{rd} week's fouling rating can be identified as 10.
28 Days in Immersion		➢ 4^{th} week's accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, unlike the previous weeks' accumulation results, advanced slime starts to be visible as dark green/red spots on the panel in 4^{th} week. Although the paint surface is still visible and the paint can still be identified, advanced slime accumulation starts to obscure the paint surface partially over the panel. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10 and "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Therefore, it can be said that 4^{th} week's fouling rating for Paint 2 can be identified between 10 and 20.
84 Days in Immersion		➢ 12^{th} week's accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulations keep expanding over the panel. The majority of the surface is obscured by dark green and red slime spots. According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Therefore, with reference to NSTM standards, Paint 2's 12^{th} week's fouling rating can be identified as 20.

Appx-Table.2: NSTM Fouling Ratings for Paint 2 (cont.)

	Paint 2	Fouling Ratings According to NSTM Standards
182 Days in Immersion		➢ 27th week's accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, grass filaments keep growing in height over the panel along with heavy slime accumulation and projections. However, in comparison with the previous weeks' accumulation results, it can be seen that some of the panel's surface starts becoming visible with almost no biofouling on the panel in some of the parts. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 2's 27th week's fouling rating can be identified as 30.
266 Days in Immersion		➢ 38th week's accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation can be observed over the panel. Additionally, the early stages of projections are still visible. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 2's 38th week's fouling rating can be identified between 20 and 30.

Appx-Table.2: NSTM Fouling Ratings for Paint 2 (cont.)

	Paint 2	Fouling Ratings According to NSTM Standards
364 Days in Immersion		➢ 52^{nd} week's accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation can be observed over the panel. Additionally, the early stages of projections are still visible. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 2's 52^{nd} week's fouling rating can be identified between 20 and 30.
546 Days in Immersion		➢ 78^{th} week's accumulation results of Paint 2 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation covers all of the panel's surface. In addition, grass filaments and soft non-calcareous fouler organisms keep growing one on top of another. Although early stages of calcareous fouling appear on the panel, among the grass, tubeworm and *Spirorbis pusilla* accumulation can be hardly identified. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. For that reason, with reference to NSTM standards, Paint 2's 78^{th} week's fouling rating can be identified as 40.

Paint 3 - Fouling Rating Assessment

Appx-Table.3: NSTM Fouling Ratings for Paint 3

	Paint 3 (Ref. Panel)	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ Reference Panel was used and defined as Paint 3 (Ref. Panel). Paint 3 represents the reference panel. ➢ Reference panel immersed on 4^{th} September 2018 in a fishing port. ➢ According to NSTM standards; “a clean, foul-free surface; red and/or black AF paint or a bare metal surface” is rated as 0. Hence Paint 3’s immersion day fouling rating is 0.
7 Days in Immersion		➢ 1^{st} week’s accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, early stages of slime accumulation can be seen in light green areas over the panel with limited coverage surface area. ➢ According to NSTM standards; “Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.” is rated as 10. Hence, it can be said that 1^{st} week’s fouling rating for Paint 3 can be identified as 10.
14 Days in Immersion		➢ 2^{nd} week’s accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, limited slime accumulation areas can be observed with almost similar slime intensity compared to 1^{st} week’s, and the coated surface is still visible beneath the fouling. However, looking closer, it can be seen that calcareous fouling in the form of *Spirorbis pusilla* accumulation can be clearly seen over the surface. ➢ According to NSTM standards; “Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height.” is rated as 40. Hence Paint 3’s 2^{nd} week’s fouling rating can be identified as 40.

Appx-Table.3: NSTM Fouling Ratings for Paint 3 (cont.)

	Paint 3 (Ref. Panel)	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, the coverage area of calcareous fouling in the forms of *Spirorbis pusilla* accumulation increases in comparison with the previous week's accumulation results. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Hence Paint 3's 3rd week's fouling rating can be identified as 40.
28 Days in Immersion		➢ 4th week's accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation spreads all over the panel, and the panel's surface is still visible. Additionally, early stages of calcareous fouling in the form of *Spirorbis pusilla* together with tubeworms less than ¼ inch (6.4 mm) in diameter or height can be seen as in very early stages. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Hence Paint 3's 4th week's fouling rating can be identified as 40.
84 Days in Immersion		➢ 12th week's accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, the majority of the panel surface is covered with grass filaments. Additionally, the number of tubeworms, as well as their sizes, keep increasing increases. Additionally, it can be seen that a flat network of grass filaments covers all over the surface area. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint 3's 12th week's fouling rating can be identified as 40.

Appx-Table.3: NSTM Fouling Ratings for Paint 3 (cont.)

	Paint 3 (Ref. Panel)	Fouling Ratings According to NSTM Standards
182 Days in Immersion		➢ 26th week's accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, soft non-calcareous foulers keep growing one on top of another. It is still difficult to recognise the species in the accumulation; however, an early appearance of an overlay with slime or grass accumulation can be seen over the panel. Among the grass, tubeworm and *Spirorbis pusilla* accumulation can be hardly identified. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint 3's 26th week's fouling rating can be identified as 40.
266 Days in Immersion		➢ 38th week's accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous foulers. However, it can be noticed that the coverage area of the grass filaments decreased together with the soft non-calcareous fouling compared to the previous week's fouling condition. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc. Additionally, looking closer, early stages of barnacle accumulations less than ¼ inch (6.4 mm) becomes visible with this week's accumulation results. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40, and "Combination of tubeworms and barnacles, less than ¼ inch (6.4mm) in diameter or height." is rated as 60. Therefore, with reference to NSTM standards, Paint 3's 38th week's fouling rating can be identified between 40 and 60.

Appx-Table.3: NSTM Fouling Ratings for Paint 3 (cont.)

	Paint 3 (Ref. Panel)	Fouling Ratings According to NSTM Standards
364 Days in Immersion		➢ 52nd week's accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing over the panel. Additionally, it can be seen that a combination of barnacle and tubeworm accumulation is visible over the panel. ➢ According to NSTM standards, "Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height." is rated as 60. Therefore, with reference to NSTM standards, Paint 3's 52nd week's fouling rating can be identified as 60.
546 Days in Immersion		➢ 78th week's accumulation results of Paint 3 (Ref. Panel) is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation covers all of the panel's surface. In addition, grass filaments and soft non-calcareous fouler organisms keep growing one on top of another. Furthermore, although adult stages of calcareous fouling appear on the panel, among the grass, tubeworm, *Spirorbis pusilla* and barnacle accumulation can be hardly identified. ➢ According to NSTM standards, "Combination of tubeworms and barnacles, greater than ¼ inch (6.4 mm) in diameter or height." is rated as 70. For that reason, with reference to NSTM standards, Paint 3's 78th week's fouling rating can be identified as 70.

Paint 4 - Fouling Rating Assessment

Appx-Table.4: NSTM Fouling Ratings for Paint 4

	Paint 4	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ The antifouling coating was used and defined as Paint 4. Paint 4 is a bottom paint with a high content of Cuprous Oxide and Zinc Pyrithione. ➢ The panel is painted with a roller brush paint and immersed on 4th September 2018 in a fishing port. ➢ According to NSTM standards; "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0. Hence Paint 3's immersion day fouling rating is 0.
7 Days in Immersion		➢ 1st week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, the early stages of biofouling can be seen as very limited slime in light green areas on the panel, and the coated surface is still visible beneath the fouling. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence, it can be said that 1st week's fouling rating for Paint 4 can be identified as 10.
14 Days in Immersion		➢ 2nd week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, limited slime accumulation areas can be observed with higher slime intensity compared to 1st week; however, the coated surface is still visible beneath the fouling. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence Paint 4's 2nd week's fouling rating can be identified as 10.

Appx-Table.4: NSTM Fouling Ratings for Paint 4 (cont.)

	Paint 4	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation becomes more visible in 3rd week. Early stages of advanced slime accumulation becoming visible; however, the coated surface is still visible beneath the fouling. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10 and "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Hence Paint 4's 3rd week's fouling rating can be identified between 10 and 20.
28 Days in Immersion		➢ 4th week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, unlike the previous weeks' accumulation results, advanced slime starts to be visible as dark green/red spots on the panel in 4th week. However, bare paint is still visible, and the paint can still be identified on most of the surface area. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. As 4th week's results show advanced slime accumulation, 4th week's fouling rating for Paint 4 can be identified with a rating of 20.
84 Days in Immersion		➢ 12th week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation together with projections is expanded over the panel; and the majority of the coated surface is obscured with soft, non-calcareous foulers. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 4's 12th week's fouling rating can be identified as 30.

Appx-Table.4: NSTM Fouling Ratings for Paint 4 (cont.)

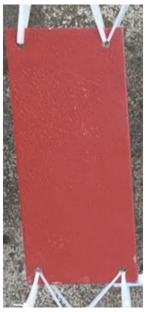
	Paint 4	Fouling Ratings According to NSTM Standards
182 Days in Immersion		➢ 26th week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 4's 26th week's fouling rating can be identified as 30.
266 Days in Immersion		➢ 38th week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 4's 38th week's fouling rating can be identified as 30.
364 Days in Immersion		➢ 52nd week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 4's 52nd week's fouling rating can be identified as 30.

Appx-Table.4: NSTM Fouling Ratings for Paint 4 (cont.)

	Paint 4	Fouling Ratings According to NSTM Standards
546 Days in Immersion		➢ 78th week's accumulation results of Paint 4 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation covers all of the panel's surface. In addition, grass filaments and soft non-calcareous fouler organisms keep growing one on top of another. Although early stages of calcareous fouling appear on the panel, among the grass, tubeworm and *Spirorbis pusilla* accumulation can be hardly identified. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. For that reason, with reference to NSTM standards, Paint 4's 78th week's fouling rating can be identified as 40.

Paint 5 - Fouling Rating Assessment

Appx-Table.5: NSTM Fouling Ratings for Paint 5

	Paint 5	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ The antifouling coating was used and defined as Paint 5. Paint is a bottom paint with a high content of cuprous oxide. ➢ The panel is painted with a roller brush paint and immersed on 4^{th} September 2018 in a fishing port. According to NSTM standards; “a clean, foul-free surface; red and/or black AF paint or a bare metal surface” is rated as 0. Hence Paint 5’s immersion day fouling rating is 0.
7 Days in Immersion		➢ 1^{st} week’s accumulation results of Paint 5 is illustrated in the picture. ➢ As can be seen from the picture, the early stages of biofouling can be seen as very limited slime in light green areas on the panel, and the coated surface is still visible beneath the fouling. ➢ According to NSTM standards; “Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.” is rated as 10. Hence Paint 5’s 1^{st} week’s fouling rating can be identified as 10.
14 Days in Immersion		➢ 2^{nd} week’s accumulation results of Paint 5 is illustrated in the picture. ➢ As can be seen from the picture, limited slime accumulation areas can be observed with higher slime intensity compared to 1^{st} week. However, the coated surface is still visible beneath the fouling. ➢ According to NSTM standards; “Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.” is rated as 10. Hence Paint 5’s 2^{nd} week’s fouling rating can be identified as 10.

Appx-Table 5: NSTM Fouling Ratings for Paint 5 (cont.)

	Paint 5	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint 5 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation becomes more visible in 3rd week and light-slime intensity compared to 2nd week is higher; however, the coated surface is still visible beneath the fouling. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence Paint 5's 3rd week's fouling rating can be identified as 10.
28 Days in Immersion		➢ 4th week's accumulation results of Paint 5 is illustrated in the picture. ➢ As can be seen from the picture, unlike the previous weeks' accumulation results, advanced slime starts to be visible as dark green/red spots on the panel in 4th week. However, bare paint is still visible, and the paint can still be identified. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10 and "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. As 4th week's result show both early stages of Fouling Rating 20 and advanced stages of Fouling Rating 10, it can be said that 4th week's fouling rating for Paint 5 can be identified with a rating between 10 and 20.

Appx-Table 5: NSTM Fouling Ratings for Paint 5 (cont.)

<table>
<tr><th></th><th>Paint 5</th><th>Fouling Ratings According to NSTM Standards</th></tr>
<tr><td>84 Days in Immersion</td><td></td><td>➢ 12th week's accumulation results of Paint 5 is illustrated in the picture.
➢ As can be seen from the picture, incipient grass filaments keep expanding and dominate the surface panel along with heavy slime accumulation. Dark green and red slime spots dominate the panel's surface as well. Additionally, it can be seen that the soft non-calcareous accumulation start to become visible with projections.
➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 1's 12th week's fouling rating can be identified between 20 and 30.</td></tr>
<tr><td>182 Days in Immersion</td><td></td><td>➢ 26th week's accumulation results of Paint 5 is illustrated in the picture.
➢ As can be seen from the picture, advanced slime accumulation keeps growing in the form of grass filaments and soft non-calcareous fouling. However, it can be noticed that the coverage area of the grass filaments decreased together with the soft non-calcareous fouling compared to the previous week's fouling condition. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc.
➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 5's 26th week's fouling rating can be identified as 30.</td></tr>
</table>

Appx-Table 5: NSTM Fouling Ratings for Paint 5 (cont.)

	Paint 5	Fouling Ratings According to NSTM Standards
266 Days in Immersion		➢ 38th week's accumulation results of Paint 5 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing in the form of grass filaments and soft non-calcareous fouling. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 5's 38th week's fouling rating can be identified as 30.
364 Days in Immersion		➢ 52nd week's accumulation results of Paint 5 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing in the form of grass filaments and soft non-calcareous fouling. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 5's 52nd week's fouling rating can be identified as 30.

Appx-Table 5: NSTM Fouling Ratings for Paint 5 (cont.)

	Paint 5	Fouling Ratings According to NSTM Standards
546 Days in Immersion		➢ 78th week's accumulation results of Paint 5 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation covers all of the panel's surface. In addition, grass filaments and soft non-calcareous fouler organisms keep growing one on top of another. Although early stages of calcareous fouling appear on the panel, among the grass, tubeworm and *Spirorbis pusilla* accumulation can be hardly identified. ➢ According to NSTM standards, "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30 and "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. For that reason, with reference to NSTM standards, Paint 5's 78th week's fouling rating can be identified between 30 and 40.

Paint 6 - Fouling Rating Assessment

Appx-Table.6: NSTM Fouling Ratings for Paint 6

	Paint 6	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ The antifouling coating was used and defined as Paint 6. Paint 6 is a bottom paint with a high content of Cuprous Oxide and Cuprous Pyrithione. ➢ The panel is painted with roller brush paint and immersed on 4th September 2018 in a fishing port. According to NSTM standards; "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0. Hence Paint 6's immersion day fouling rating is 0.
7 Days in Immersion		➢ 1st week's accumulation result of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, the early stages of biofouling can be seen as very limited slime in light green areas on the panel, and the coated surface is still visible beneath the fouling. According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence, it can be said that 1st week's fouling rating for Paint 6 can be identified as 10.
14 Days in Immersion		➢ 2nd week's accumulation result of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, limited slime accumulation areas can be observed with higher slime intensity compared to 1st week. However, the coated surface is still visible beneath the fouling. According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence Paint 6's 2nd week's fouling rating can be identified as 10.

Appx-Table.6: NSTM Fouling Ratings for Paint 6 (cont.)

	Paint 6	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation result of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, the coverage area of slime accumulation increases in 3rd week compared to 2nd week, and the coated surface is still visible beneath the fouling. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10 and "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Hence Paint 6's 3rd week's fouling rating can be identified between 10 and 20.
28 Days in Immersion		➢ 4th week's accumulation result of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation appears in the form of dark green patches, which starts partially obscuring the coated surface. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. As 4th week's results show both early stages of Fouling Rating 20, it can be said that 4th week's fouling rating for Paint 5 can be identified with a rating of 20.
84 Days in Immersion		➢ 12th week's accumulation results of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 6's 12th week's fouling rating can be identified as 30.

Appx-Table.6: NSTM Fouling Ratings for Paint 6 (cont.)

	Paint 6	Fouling Ratings According to NSTM Standards
182 Days in Immersion		➢ 26th week's accumulation results of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. Additionally, a flat network of filaments can be seen covering the panel surface. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 6's 26th week's fouling rating can be identified as 30.
266 Days in Immersion		➢ 38th week's accumulation results of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. Additionally, a flat network of filaments can be seen covering the panel surface. However, it can be noticed that the coverage area of the grass filaments decreased together with the soft non-calcareous fouling compared to the previous week's fouling condition. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 6's 38th week's fouling rating can be identified as 30.

Appx-Table.6: NSTM Fouling Ratings for Paint 6 (cont.)

	Paint 6	Fouling Ratings According to NSTM Standards
364 Days in Immersion		➢ 52nd week's accumulation results of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing as grass filaments and soft non-calcareous fouling. Additionally, a flat network of filaments can be seen covering the panel surface. However, it can be noticed that the coverage area of the grass filaments decreased together with the soft non-calcareous fouling compared to the previous week's fouling condition. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc. ➢ According to NSTM standards; "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint 6's 52nd week's fouling rating can be identified as 30.
546 Days in Immersion		➢ 78th week's accumulation results of Paint 6 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation covers all of the panel's surface. In addition, grass filaments and soft non-calcareous fouler organisms keep growing one on top of another. Although early stages of calcareous fouling appear on the panel, among the grass, tubeworm and *Spirorbis pusilla* accumulation can be hardly identified. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. For that reason, with reference to NSTM standards, Paint 6's 78th week's fouling rating can be identified as 40.

Appendix E: Fouling Rating Assessment of Foul Release Coatings

Paint A1 - Fouling Rating Assessment

Appx-Table.7: NSTM Fouling Ratings for Paint A1

	Paint A1	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ A-type fouling release antifouling coating was used and defined as Paint A1 for this panel. ➢ The panel was grit blasted and then coated with a paint gun professionally by IP's experts and immersed on 12th February 2019 in a fishing port in the Black Sea. ➢ According to NSTM standards, "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0. Hence Paint A1's immersion day fouling rating is 0.
7 Days in Immersion		➢ 1st week's accumulation results of Paint A1 is illustrated in the picture. ➢ As can be seen from the picture, the panel is still clear and visible for a fouled paint. ➢ According to NSTM standards; "A clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0 and "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence, it can be said that Paint A1's 1st week's fouling rating can be identified between 0 and 10.
14 Days in Immersion		➢ 2nd week's accumulation results of Paint A1 is illustrated in the picture. ➢ As can be seen from the picture, early stages of incipient slime accumulation can be observed with light shades. Additionally, it can be seen that the paint surface is still visible. ➢ According to NSTM standards, "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint A1's 2nd week's fouling rating can be identified as 10.

Appx-Table.7: NSTM Fouling Ratings for Paint A1 (cont.)

	Paint A1	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint A1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation covers all over the panel as red/green spots. ➢ According to NSTM standards, "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Therefore, with reference to NSTM standards, Paint A1's 3rd week's fouling rating can be identified as 20.
28 Days in Immersion		➢ 4th week's accumulation results of Paint A1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation keeps expanding over the panel. In addition to the previous week's accumulation results, it can be noticed that dark green/brown spots start becoming visible and projecting over the panel. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint A1's 4th week's fouling rating can be identified between 20 and 30.
91 Days in Immersion		➢ 13th week's accumulation result of Paint A1 is presented in the picture. ➢ As can be seen from the picture, the coverage area of the grass filaments decreased together with the soft non-calcareous fouling compared to the previous week's fouling condition. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc. Looking closer, it can be seen that calcareous fouling in the form of *Spirorbis pusilla*. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint A1's 13th week's fouling rating can be identified as 40.

Appx-Table.7: NSTM Fouling Ratings for Paint A1 (cont.)

	Paint A1	Fouling Ratings According to NSTM Standards
175 Days in Immersion		➢ 25^{th} week's accumulation result of Paint A1 is illustrated in the picture. ➢ As can be seen from the picture, the panel surface area is covered by the green slime accumulation together with calcareous fouling in the form of *Spirorbis pusilla*. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint A1's 25^{th} week's fouling rating can be identified as 40.
274 Days in Immersion		➢ 39^{th} week's accumulation result of Paint A1 is illustrated in the picture ➢ As can be seen from the picture, the panel surface is covered by green slime accumulation together with calcareous in the form of *Spirorbis pusilla*. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint A1's 39^{th} week's fouling rating can be identified as 40.
357 Days in Immersion		➢ 51^{st} week's accumulation result of Paint A1 is illustrated in the picture. ➢ As can be seen from the picture, the panel surface is covered with heavy slime accumulation. In addition to that, barnacles less than ¼ inch (6.4 mm) and *Spirorbis pusilla* accumulation is visible over the panel. ➢ According to NSTM standards, "Calcareous fouling in the form of barnacles less than ¼ inch (6.4 mm) in diameter or height" is rated as 50. Therefore, with reference to NSTM standards, Paint A1's 51^{st} week's fouling rating can be identified as 50.

Paint A2 - Fouling Rating Assessment

Appx-Table.8: NSTM Fouling Ratings for Paint A2

	Paint A2	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ A-type fouling release antifouling coating was used and coated on this panel and defined as Paint A2. ➢ The panel was grit blasted and then coated with a paint gun professionally by IP's experts and immersed on 12th February 2019 in a fishing port in the Black Sea. ➢ According to NSTM standards, "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0. Hence Paint A2's immersion day fouling rating is 0. ➢
7 Days in Immersion		➢ 1st week's accumulation results of Paint A2 is illustrated in the picture. ➢ As can be seen from the picture, the panel is still clear and visible for a fouled paint. ➢ According to NSTM standards; "A clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0 and "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling." is rated as 10. Hence, it can be said that Paint A2's 1st week's fouling rating can be identified between 0 and 10.
14 Days in Immersion		➢ 2nd week's accumulation results of Paint A2 is illustrated in the picture. ➢ As can be seen from the picture, early stages of incipient slime accumulation can be observed with light shades. However, it can be seen that the majority of the panel surface is still visible. ➢ According to NSTM standards, "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint A2's 2nd week's fouling rating can be identified as 10.

Appx-Table.8: NSTM Fouling Ratings for Paint A2 (cont.)

	Paint A2	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint A2 is illustrated in the picture. ➢ As can be seen from the picture, advanced slime accumulation covers the majority of the panel. Additionally, it can be seen that fouling starts obscuring the panel surface. ➢ According to NSTM standards, "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Therefore with reference to NSTM standards, Paint A2's 3rd week's fouling rating can be identified as 20.
28 Days in Immersion		➢ 4th week's accumulation results of Paint A2 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation spreads over the panel. Additionally, there are dark spots in brown/green, which starts covering the panel surface obscured. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint A2's 4th week's fouling rating can be identified between 20 and 30.
91 Days in Immersion		➢ 13th week's accumulation results of Paint A2 is presented in the picture. ➢ As can be seen from the picture, slime accumulation covers the majority of the surface panel. In addition to the previous week's accumulation result, there seems to be calcareous fouling in the form of *Spirorbis pusilla* become visible. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint A2's 13th week's fouling rating can be identified as 40.

Appx-Table.8: NSTM Fouling Ratings for Paint A2 (cont.)

	Paint A2	Fouling Ratings According to NSTM Standards
175 Days in Immersion		➢ 25th week's accumulation result of Paint A2 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation in the form of dark green covers the majority of the panel. Additionally, looking closer to the panel, calcareous accumulation in the form of *Spirorbis pusilla* can be seen over the panel. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint A2's 25th week's fouling rating can be identified as 40.
274 Days in Immersion		➢ 39th week's accumulation result of Paint A2 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation covers the majority of the panel in light shades. Additionally, although there are calcareous fouling in the form of *Spirorbis pusilla* due to the reason that the applied coating's colour and *Spirorbis pusilla*'s colour are similar to each other, it is difficult to notice *Spirorbis pusilla* accumulation over the panel. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint A2's 39th week's fouling rating can be identified as 40.
357 Days in Immersion		➢ 51st week's accumulation result of Paint A2 is illustrated in the picture. ➢ As can be seen from the picture, the panel surface is covered with heavy slime accumulation. In addition to that, barnacles are less than ¼ inch (6.4 mm) and *Spirorbis pusilla* accumulation is visible over the panel. ➢ According to NSTM standards, "Calcareous fouling in the form of barnacles less than ¼ inch (6.4 mm) in diameter or height" is rated as 50. Therefore, with reference to NSTM standards, Paint A2's 51st week's fouling rating can be identified as 50.

Paint B1 - Fouling Rating Assessment

Appx-Table.9: NSTM Fouling Ratings for Paint B1

	Paint B1	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ B-type fouling release antifouling coating was used and defined as Paint B1 for this panel. ➢ The panel was grit blasted and then coated with a paint gun professionally by IP's experts and immersed on 12th February 2019 in a fishing port in the Black Sea. ➢ According to NSTM standards; "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0. Hence Paint B1's immersion day fouling rating is 0.
7 Days in Immersion		➢ 1st week's accumulation results of Paint B1 is illustrated in the picture. ➢ As can be seen from the picture, there are early stages of incipient slime accumulations over the panel; however, the majority of the panel is still clear and visible for a fouled paint. ➢ According to NSTM standards; "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0 and "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint B1's 1st week's fouling rating can be identified between 0 and 10.
14 Days in Immersion		➢ 2nd week's accumulation results of Paint B1 is illustrated in the picture. ➢ As can be seen from the picture, early stages of incipient slime accumulation can be observed with light shades. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint B1's 2nd week's fouling rating can be identified as 10.

Appx-Table.9: NSTM Fouling Ratings for Paint B1 (cont.)

	Paint B1	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint B1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation in dark patches becomes visible over the panel. However, it can be seen that the panel surface is still visible. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Hence Paint B1's 3rd week's fouling rating is 20.
28 Days in Immersion		➢ 4th week's accumulation results of Paint B1 is illustrated in the picture. ➢ As can be seen from the picture, this week's accumulation result shows that the advanced slime accumulation starts obscuring the panel surface in dark patches. In addition to this, there seem to be early stages of non-calcareous fouling in the form of dark spots. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Hence Paint B1's 4th week's fouling rating can be identified between 20 and 30.
91 Days in Immersion		➢ 13th week's accumulation result of Paint B1 is illustrated in the picture. ➢ As can be seen from the picture, the percentage of fouled area decreased in comparison with the previous week's accumulation result. However, looking closer, it can be seen that calcareous fouling in the form of *Spirorbis pusilla* is still visible over the panel. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint B1's 13th week's fouling rating can be identified as 40.

Appx-Table.9: NSTM Fouling Ratings for Paint B1 (cont.)

	Paint B1	Fouling Ratings According to NSTM Standards
175 Days in Immersion		➢ 25th week's accumulation results of Paint B1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation covers the panel surface. Additionally, non-calcareous soft foulers and calcareous fouling in the form of *Spirorbis pusilla* are visible over the panel. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint B1's 25th week's fouling rating can be identified as 40.
274 Days in Immersion		➢ 39th week's accumulation result of Paint B1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation covers the majority of the surface area. In addition to that, calcareous fouling in the form of *Spirorbis pusilla* is still visible. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint B1's 39th week's fouling rating can be identified as 40.
357 Days in Immersion		➢ 51st week's accumulation result of Paint B1 is illustrated in the picture. ➢ As can be seen from the picture, the panel surface is covered with heavy slime accumulation. In addition to that, barnacles less than ¼ inch (6.4 mm) and tubeworms appear over the panel. ➢ According to NSTM standards, "Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height." is rated as 60. Therefore, with reference to NSTM standards, Paint B1's 51st week's fouling rating can be identified as 60.

Paint B2 - Fouling Rating Assessment

Appx-Table.10: NSTM Fouling Ratings for Paint B2

<table>
<tr><td></td><td>Paint B2</td><td>Fouling Ratings According to NSTM Standards</td></tr>
<tr><td>0 Days in Immersion</td><td></td><td>➢ B-type fouling release antifouling coating was used and defined as Paint B2 for this panel.
➢ The panel was grit blasted and then coated with a paint gun professionally by IP's experts and immersed on 12th February 2019 in a fishing port in the Black Sea.
➢ According to NSTM standards, "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0. Hence Paint B2's immersion day fouling rating is 0.</td></tr>
<tr><td>7 Days in Immersion</td><td></td><td>➢ 1st week's accumulation results of Paint B2 is illustrated in the picture.
➢ As can be seen from the picture, there are early stages of incipient slime accumulations over the panel; however, the majority of the panel is still clear and visible for a fouled paint.
➢ According to NSTM standards; "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0 and "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint B2's 1st week's fouling rating can be identified between 0 and 10.</td></tr>
<tr><td>14 Days in Immersion</td><td></td><td>➢ 2nd week's accumulation results of Paint B2 is illustrated in the picture.
➢ As can be seen from the picture, early stages of incipient slime accumulation can be observed with light shades.
➢ According to NSTM standards, "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint B2's 2nd week's fouling rating can be identified as 10.</td></tr>
</table>

Appx-Table.10: NSTM Fouling Ratings for Paint B2 (cont.)

	Paint B2	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint B2 is illustrated in the picture. ➢ As can be seen from the picture, incipient slime accumulation can be observed with light shades. ➢ According to NSTM standards, "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Hence Paint B2's 3rd week's fouling rating is 20.
28 Days in Immersion		➢ 4th week's accumulation result of Paint B2 is illustrated in the picture. ➢ As can be seen from the picture, non-calcareous foulers projecting over the panel together with the calcareous fouling in forms of *Spirorbis pusilla* cover the majority of the panel. However, looking closer, it can be seen that the coverage area of fouled area decreased in comparison with the previous week's accumulation result. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint B2's 4th week's fouling rating can be identified as 40.
91 Days in Immersion		➢ 13th week's accumulation result of Paint B2 is illustrated in the picture. ➢ As can be seen from the picture, the percentage of fouled area decreased in comparison with the previous week's accumulation result. However, looking closer, it can be seen that calcareous fouling in the form of *Spirorbis pusilla* is still visible over the panel. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint B2's 13th week's fouling rating can be identified as 40.

Appx-Table.10: NSTM Fouling Ratings for Paint B2 (cont.)

	Paint B2	Fouling Ratings According to NSTM Standards
175 Days in Immersion		➢ 25th week's accumulation results of Paint B2 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation covers the panel surface. Additionally, non-calcareous soft foulers and calcareous fouling in the forms of *Spirorbis pusilla* are visible over the panel. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint B2's 25th week's fouling rating can be identified as 40.
274 Days in Immersion		➢ 39th week's accumulation result of Paint B2 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation covers the majority of the surface area. In addition to that, calcareous fouling in the forms of *Spirorbis pusilla* is still visible. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint B2's 39th week's fouling rating can be identified as 40.
357 Days in Immersion		➢ 51st week's accumulation result of Paint B2 is illustrated in the picture. ➢ As can be seen from the picture, the panel surface is covered with heavy slime accumulation. In addition to that, barnacles less than ¼ inch (6.4 mm) and tubeworms appear over the panel. ➢ According to NSTM standards, "Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) (6.4 mm) in diameter or height." is rated as 60. Therefore, with reference to NSTM standards, Paint B2's 51st week's fouling rating can be identified as 60.

Paint C1 - Fouling Rating Assessment

Appx-Table.11: NSTM Fouling Ratings for Paint C1

	Paint C1	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ C-type fouling release antifouling coating was used and defined as Paint C1 for this panel. ➢ The panel was grit blasted and then coated with a paint gun professionally by IP's experts and immersed on 12th February 2019 in a fishing port in the Black Sea. ➢ According to NSTM standards; "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0. Hence Paint C1's immersion day fouling rating is 0.
7 Days in Immersion		➢ 1st week's accumulation results of Paint C1 is illustrated in the picture. ➢ As can be seen from the picture, there seems to be almost no visible fouling over the panel. However, looking closer, early stages of biofouling can be seen over the panel. ➢ According to NSTM standards; "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0 and "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint C1's 1st week's fouling rating can be identified between 0 and 10.
14 Days in Immersion		➢ 2nd week's accumulation results of Paint C1 is illustrated in the picture. ➢ As can be seen from the picture, early stages of incipient slime accumulation can be observed with light shades. ➢ According to NSTM standards; "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint C1's 2nd week's fouling rating can be identified as 10.

Appx-Table.11: NSTM Fouling Ratings for Paint C1 (cont.)

	Paint C1	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint C1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation can be observed over the panel in addition to early stages of advanced slime accumulation as dark shades over the panel. Additionally, it can be seen that the surface area is obscured in a low percentage. ➢ According to NSTM standards, "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Hence Paint C1's 3rd week's fouling rating can be identified as 20.
28 Days in Immersion		➢ 4th week's accumulation results of Paint C1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation spreads over the panel. Additionally, there are dark spots in brown/green patches, which starts obscuring the panel surface. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore, with reference to NSTM standards, Paint C1's 4th week's fouling rating can be identified between 20 and 30.

Appx-Table.11: NSTM Fouling Ratings for Paint C1 (cont.)

	Paint C1	Fouling Ratings According to NSTM Standards
91 Days in Immersion		➢ 13th week's accumulation results of Paint C1 is presented in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing in the forms of grass filaments and soft non-calcareous fouling. However, it can be noticed that the coverage area of the grass filaments decreased together with the soft non-calcareous fouling compared to the previous week's fouling condition. There might be various reasons causing this drop, such as currents, waves, species feeding with fouler etc. Additionally, calcareous fouling in the form of *Spirorbis pusilla* is visible over the panel. ➢ According to NSTM standards, "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint C1's 13th week's fouling rating can be identified as 40.
175 Days in Immersion		➢ 25th week's accumulation results of Paint C1 is presented in the picture. ➢ As can be seen from the picture, there is calcareous fouling in the form of *Spirorbis pusilla* over the panel. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint C1's 25th week's fouling rating can be identified as 40.
274 Days in Immersion		➢ 39th week's accumulation result of Paint C1 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation covers the majority of the surface area. In addition to that, calcareous fouling in the form of *Spirorbis pusilla* is still visible. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint C1's 39th week's fouling rating can be identified as 40.

Appx-Table.11: NSTM Fouling Ratings for Paint C1 (cont.)

	Paint C1	Fouling Ratings According to NSTM Standards
357 Days in Immersion		➢ 51st week's accumulation result of Paint C1 is illustrated in the picture. ➢ As can be seen from the picture, the panel surface is covered with heavy slime accumulation. In addition to that, barnacles less than ¼ inch (6.4 mm) and tubeworms appear over the panel. ➢ According to NSTM standards, "Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height." is rated as 60. Therefore, with reference to NSTM standards, Paint C1's 51st week's fouling rating can be identified as 60.

Paint C2 - Fouling Rating Assessment

Appx-Table.12: NSTM Fouling Ratings for Paint C2

	Paint C2	Fouling Ratings According to NSTM Standards
0 Days in Immersion		➢ C-type fouling release antifouling coating was used and defined as Paint C2 for this panel. ➢ The panel was grit blasted and then coated with a paint gun professionally by IP's experts and immersed on 12th February 2019 in a fishing port in the Black Sea. ➢ According to NSTM standards, "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0. Hence Paint C2's immersion day fouling rating is 0.
7 Days in Immersion		➢ 1st week's accumulation results of Paint C2 is illustrated in the picture. ➢ As can be seen from the picture, there seems to be almost no visible fouling over the panel. However, looking closer, early stages of biofouling can be seen over the panel. ➢ According to NSTM standards; "a clean, foul-free surface; red and/or black AF paint or a bare metal surface" is rated as 0 and "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint C2's 1st week's fouling rating can be identified between 0 and 10.
14 Days in Immersion		➢ 2nd week's accumulation results of Paint C2 is illustrated in the picture. ➢ As can be seen from the picture, early stages of incipient slime accumulation can be observed with light shades. ➢ According to NSTM standards, "Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling" is rated as 10. Hence Paint C2's 2nd week's fouling rating can be identified as 10.

Appx-Table.12: NSTM Fouling Ratings for Paint C2 (cont.)

	Paint C2	Fouling Ratings According to NSTM Standards
21 Days in Immersion		➢ 3rd week's accumulation results of Paint C2 is illustrated in the picture. ➢ As can be seen from the picture, incipient slime accumulation can be observed with light shades. Additionally, early stages of advanced slime accumulation start becoming visible ➢ According to NSTM standards, "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20. Hence Paint C2's 3rd week's fouling rating can be identified as 20.
28 Days in Immersion		➢ 4th week's accumulation results of Paint C2 is illustrated in the picture. ➢ As can be seen from the picture, most of the surface is covered with slime accumulation. In addition to that, advanced slime accumulation becomes visible with dark spot projections over the panel. ➢ According to NSTM standards; "Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling" is rated as 20 and "Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling can not be easily wiped off by hand" is rated as 30. Therefore with reference to NSTM standards, Paint C2's 4th week's fouling rating can be identified between 20 and 30.
91 Days in Immersion		➢ 13th week's accumulation results of Paint C2 is presented in the picture. ➢ As can be seen from the picture, advanced slime accumulation keeps growing over the panel surface. Additionally, calcareous fouling in the form of *Spirorbis pusilla* is clearly visible over the panel. ➢ According to NSTM standards; "Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height." is rated as 40. Therefore, with reference to NSTM standards, Paint C2's 13th week's fouling rating can be identified as 40.

Appx-Table.12: NSTM Fouling Ratings for Paint C2 (cont.)

	Paint C2	Fouling Ratings According to NSTM Standards
175 Days in Immersion		➢ 25th week’s accumulation results of Paint C2 is presented in the picture. ➢ As can be seen from the picture, calcareous fouling in the form of *Spirorbis pusilla* is clearly visible over the panel. ➢ According to NSTM standards; “Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height.” is rated as 40. Therefore, with reference to NSTM standards, Paint C2’s 25th week’s fouling rating can be identified as 40.
274 Days in Immersion		➢ 39th week’s accumulation result of Paint C2 is illustrated in the picture. ➢ As can be seen from the picture, slime accumulation covers the majority of the surface area. In addition to that, calcareous fouling in the form of *Spirorbis pusilla* is still visible. ➢ According to NSTM standards; “Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height.” is rated as 40. Therefore, with reference to NSTM standards, Paint C2’s 39th week’s fouling rating can be identified as 40.
357 Days in Immersion		➢ 51st week’s accumulation result of Paint C2 is illustrated in the picture. ➢ As can be seen from the picture, the panel surface is covered with heavy slime accumulation. In addition to that, barnacles less than ¼ inch (6.4 mm) and tubeworms appear over the panel. ➢ According to NSTM standards, “Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height.” is rated as 60. Therefore, with reference to NSTM standards, Paint C2’s 51st week’s fouling rating can be identified as 60.