Integrating Industry 4.0 Technologies and Green Supply Chain Management for Sustainable Renewable Energy Supply Chains in Africa

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Previously Published and Presented Material

Some parts of this thesis have been published in peer reviewed journals and presented in conferences both on international stage and within the university community. These are detailed as follows:

Peer reviewed journal publications:

1. Labaran, M. J., and Masood, T. (2025). "From smart factories to sustainable futures: how Industry 4.0 enhances green supply chains". *Supply Chain Management: An International Journal*, Vol. 30, No. 6, pp. 854–871, doi: https://doi.org/10.1108/SCM-07-2025-0750.

   Details: **This manuscript is based on the quantitative findings reported in Chapter 7 of this thesis.**

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Conferences

1. Labaran, M.J. and Masood, T., 2024, June. Industry 4.0 powered green supply chain management in renewable energy sector. In *2024 Production and Operations Management Society (POMS) International Conference: Operations Management and Information Systems in the Age of Analytics*. Istanbul, Turkey.

2. Labaran, M.J. and Masood, T., 2023, June. Industry 4.0 Driven Green Supply Chain Management to Tackle Sustainability and Supply Chain Problems within the Renewable Energy Sector. In *2023 University of Strathclyde Doctoral School Multidisciplinary Symposium: Horizons for Humanity.* Glasgow, United Kingdom.
3. Labaran, M.J. and Masood, T., 2023, August. Industry 4.0 Driven Green Supply Chain Management to Tackle Sustainability and Supply Chain Issues within the Renewable Energy Sector. In *2023 Department of Design, Manufacturing and Engineering Management LeoCon23 Conference.* Glasgow, United Kingdom.

Dedication

I dedicate this thesis to my dear father, whose unwavering support and commitment ensured that I received the best education and training. His encouragement has been a constant source of strength throughout every aspect of my life.

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ABSTRACT

As global attention intensifies around sustainability, renewable energy supply chains in emerging economies are under increasing pressure to enhance their environmental, economic, and social performance. Industry 4.0 technologies including blockchain, Internet of Things, and Artificial Intelligence alongside Green Supply Chain Management practices like eco-design and green procurement have been advocated as enablers of sustainable transformation. However, empirical evidence on how these two dimensions interact within resource-constrained African contexts remains sparse. Moreover, existing theories like the Resource-Based View and Natural Resource-Based View require further contextualization in emerging market supply chains to reflect the complexities of digital-sustainability integration. To address these conceptual and empirical gaps, this study adopted a sequential mixed-methods design, beginning with a qualitative phase involving semi-structured interviews with 8 managers and experts from renewable energy firms operating in sub-Saharan Africa. The qualitative insights uncovered key contextual factors influencing sustainability practices, including limited digital infrastructure, institutional weaknesses, and capability-related barriers. These findings informed the development of a conceptual model and survey instrument for the quantitative phase. Subsequently, the quantitative component employed a cross-sectional survey targeting 450 renewable energy experts across Africa and Partial Least Squares Structural Equation Modelling to test four hypotheses derived from Resource-Based View and Natural Resource-Based View frameworks. The results indicate that Industry 4.0 technologies do not directly improve sustainability performance but exert a significant positive effect on the adoption of Green Supply Chain Management practices, which in turn fully mediate the relationship between Industry 4.0 technologies and Sustainability Performance. These findings are suggestive of a nuanced extension of Resource-Based View, showing that digital resources alone may not meet the Resource-Based View's "valuable, rare, inimitable, and non-substitutable resources" criteria in sustainability contexts unless embedded in structured environmental capabilities. Similarly, the findings align with NRBV by

showing that environmental outcomes are achieved not through technology adoption per se, but through its integration with pollution prevention and product stewardship practices. This study contributes to theory by, first, clarifying how GSCM operates as a mediating environmental capability that activates the sustainability potential of digital resources; second, by extending the Resource-Based View/Natural Resource-Based View frameworks to better reflect the realities of renewable energy supply chains in African economies; and third, by emphasizing that in sustainability contexts, digital tools become strategically valuable only when paired with proactive, system-wide environmental management routines. Importantly, it contributes contextual nuance to existing theories by illustrating how structural and institutional constraints in African RESCs limit firms' ability to translate digital innovation into sustainability gains without targeted investments, capacity-building, and policy alignment. From a practical standpoint, the study highlights the need for governments, industry actors, and supply chain managers to pursue integrated digital–green strategies. Policy interventions including tax incentives, workforce upskilling, and digital infrastructure investments are vital to supporting Industry 4.0-enabled sustainability. The study suggests that firms should recognize that digital transformation is not a standalone solution, rather, should be deliberately aligned with green supply chain strategies.

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List of Abbreviations

AI - Artificial intelligence
AM - Additive manufacturing
AR - Augmented reality
AVE - Average variance extracted
BDA - Big Data Analytics
CB-SEM - Covariance-based structural equation modelling
CC - Cloud computing
CMB - Common method bias
CPS - Cyber-physical systems
CSR - Corporate social responsibility
EIA - Environmental Impact Assessment
EMS - Environmental management systems
ESIA - Environmental and Social Impact Assessment
GSCM - Green Supply Chain Management
GSCMP - Green Supply Chain Management practice
HTMT - Heterotrait-Monotrait Ratio
IoT - Internet of Things
NAPTIM - National Power Training Institute of Nigeria
NEMSA - Nigerian Electricity Management Services Agency
NRBV - Natural Resource-Based View
PLS-SEM - Partial Least Squares Structural Equation Modelling
PLS-SEM - Partial least squares structural equation modelling
PV - Photovoltaics
QAS - Questionnaire Appraisal System
R&D - Research and development
R^2 - R-square
RBV - Resource-Based View
RE - Renewable energy
RES - Renewable energy sector
RESCs - Renewable energy supply chains
ROI - Return on investment
SCM - Supply chain management
SDGs - Sustainable Development Goals
SEM - Structural equation modelling
SIA - Social Impact Assessment
SMEs - Small and medium-sized enterprises
VRIN - Valuable, rare, inimitable, and non-substitutable

1 Introduction

The aim of the introductory chapter is to establish a comprehensive foundation for the thesis by offering an in-depth overview of the research context. It begins by articulating the motivation that drives the investigation, followed by a clear presentation of the research problem. Subsequently, the chapter presents the study's aim and objectives, together with the research questions it intends to address. In addition, this section highlights the contributions of the research, underscoring its originality and potential impact. The chapter concludes by mapping out the thesis structure, guiding readers through subsequent chapters and ensuring a cohesive understanding of the work presented.

1.1 Research Background and Context

Efforts to expand the deployment of clean and sustainable energy have gained urgency due to the adverse impacts of fossil fuel consumption on global warming (Mastrocinque et al., 2022; Akhtar et al., 2019). Governments worldwide have adopted mitigating policies in response (Mastrocinque et al., 2022). A notable example is the European Union's Green Deal, which aims to reach carbon neutrality by 2050 through significant investments in renewable energy (RE) technologies (Aall et al., 2022). Amid these shifts, solar photovoltaics (PV) and wind power have emerged as central mechanisms for reducing carbon emissions. However, their rapid growth presents multifaceted sustainability and supply chain management (SCM) challenges, that involve raw material sourcing, recycling inefficiencies, and logistical complexities (Deberdt and Billon, 2021, Mason-Jones et al., 2022).

The renewable energy sector (RES) involves extensive and intricate supply chains with diverse stakeholders, creating transparency and traceability concerns (Deberdt and Billon, 2021). By 2050, global PV module waste may match the annual volume of new installations, approaching 78 million metric tonnes (Duran et al., 2022). Such large-scale waste streams heighten environmental challenges, particularly since materials like lithium and cobalt are often extracted in environmentally detrimental ways (Kramarz et al., 2021; Rufino et al., 2022). This generates an infrastructure gap, characterized by inadequate recycling facilities, high decommissioning costs, and weak end-of-life management for wind turbines and solar panels (Watari et al., 2020; Ali et al., 2022a; Winkler, Kilic and Veldman, 2022).

Moreover, industry-wide expansion raises ethical and labour concerns, such as cobalt mining's reliance on child labour (Rachidi et al., 2021). Downstream complexities also persist, with many firms struggling to manage large-scale decommissioning that can amount to 60–70% of initial installation costs (Winkler, Kilic and Veldman, 2022). Traceability remains a persistent issue, as some companies cannot verify their raw material origins (Deberdt and Billon, 2021). If the RES is to meet decarbonization targets sustainably, addressing these obstacles is crucial (Darda et al., 2019).

In response to these enduring challenges, scholars propose integrating Green Supply Chain Management (GSCM) practices (i.e., eco-design, reverse logistics, and recycling) across procurement, operations, logistics, and manufacturing (Huber and Steininger, 2022; Birasnav et al., 2022; Yu et al., 2022). Embedding sustainable practices at each supply chain stage can reduce environmental footprints, close resource loops, and optimize efficiency (Nureen et al., 2022; Mendoza et al., 2022). Parallelly, Industry 4.0 technologies like blockchain, the Internet of Things (IoT), and Big Data Analytics (BDA) offer tools for enhanced transparency and coordination (Amjad et al., 2020, Almutairi et al., 2023, Shahzad et al., 2022). Blockchain supports real-time provenance monitoring, IoT enables predictive maintenance and data collection, and BDA aids informed decisions on green operations (Pandey et al., 2023, Sahoo and Jakhar, 2023). By uniting Industry 4.0 with GSCM, RE firms could overcome traceability and resource inefficiencies, thus expediting the sector's shift toward sustained environmental stewardship.

1.2 Research Motivation and Rationale

The potential for combining GSCM practices with Industry 4.0 technologies in the renewable energy supply chains (RESCs) remains underexamined, especially in developing economies. Although GSCM practices can improve sustainability outcomes, their success often depends on complementary digital solutions to enhance transparency and efficiency (Lerman et al., 2022; Putu Artama Wiguna et al., 2021). Comprehensive frameworks that integrate these approaches are scarce, leaving gaps in understanding how African RE firms might tackle end-of-life management, material traceability, and operational inefficiencies.

Developing regions, including Africa, frequently face infrastructural and financial barriers that hamper advanced technological adoption (Ogunlela, 2018; Tumpa et al., 2019). High initial costs for GSCM and Industry 4.0 tools can deter investment, complicating the balance between sustainability goals and profitability (Esfahbodi et al., 2023). Weak regulatory support and limited access to technology exacerbate these challenges (Nkrumah et al., 2021). Additionally, firm-specific capabilities such as technological readiness, leadership commitment, and financial capacity remain insufficiently explored within African contexts, further constraining the transition to sustainable SCM (Younis et al., 2020; Pinto, 2020).

Moreover, the RES is often overlooked in broader sustainability discussions, which typically focus on automotive and manufacturing industries (Bhatia and Gangwani, 2021). Consequently, critical African RESCs issues like raw material sourcing for batteries and efficient solar panel recycling receive minimal attention, despite many African nations actively striving to achieve international sustainability targets, for instance, the Sustainable Development Goals (SDGs). Thus, this study addresses a vital gap by examining how GSCM and Industry 4.0 integration could advance sustainability in African RESCs. The research seeks to present a roadmap accounting for firm capabilities and regional constraints, offering practical strategies for ethical sourcing, circular economy principles, and operational efficiency gains.

Ultimately, this work aims to foster meaningful contributions toward decarbonization and environmental stewardship. By emphasizing both the theoretical underpinnings and practical realities of GSCM and Industry 4.0 in African contexts, the study aspires to provide insights into corporate practices and policies that promote sustainable growth in African RESCs, aligning with initiatives like the European Green Deal and the United Nations SDGs.

Against this backdrop, Africa is deliberately adopted as the empirical context of this study. The continent represents a setting in which RE deployment is expanding rapidly, yet supply chains operate under conditions of infrastructural constraints, institutional fragmentation, and limited digital maturity. These characteristics make African RESCs a theoretically informative context for examining whether and how Industry 4.0 technologies and GSCM practices jointly contribute to sustainability performance. Situating the study in Africa therefore allows the research to extend existing theory beyond the stable and resource-abundant environments in which it has predominantly been tested, while generating context-sensitive insights into sustainable supply chain transformation.

1.3 Problem Statement

The rapid expansion of RE technologies has intensified supply chain management (SCM) and sustainability challenges, including heavy reliance on scarce raw materials, elevated decommissioning costs, and insufficient end-of-life strategies (Winkler et al., 2022; Mason-Jones et al., 2022). Decommissioning wind turbines and solar panels can incur substantial costs, while limited recycling infrastructure exacerbates resource depletion and environmental risks (Rufino et al., 2022). Dependence on critical minerals from geopolitically unstable regions further compounds these vulnerabilities, exposing supply chains to price volatility and supply disruptions (Duran et al., 2022).

In many African contexts, these challenges are magnified by infrastructural limitations and underdeveloped regulatory frameworks (Aliyu et al., 2018). Firms encounter insufficient financing and weak enforcement mechanisms, hindering effective disposal and recycling of solar and wind components (Adenle, 2020). Existing frameworks lack the transparency necessary to trace materials, supervise ethical sourcing, and manage large-scale recycling efforts (Deberdt and Billon, 2021). However, empirical studies often disregard contexts outside the realms of developed and advance regions, particularly disregarding contexts where digital infrastructure is underdeveloped or fragmented. Empirical studies that examined how Industry 4.0 and GSCM interact to influence sustainability performance in African renewable energy supply chains (RESCs) are scarce. Moreover, while both Industry 4.0 and GSCM have been studied independently, there is limited empirical research examining whether GSCM acts as a crucial medium through which digital technologies influence sustainability outcomes particularly within African RESCs. This mediating relationship remains underexplored and represents a crucial aspect of this study.

Existing frameworks such as the Resource-Based View (RBV) and Natural Resource-Based View (NRBV) often assume stable institutional conditions and well-developed infrastructure. African RESCs, characterized by institutional voids, regulatory fragmentation, and digital underdevelopment (Aliyu et al., 2018, Labaran and Masood, 2025), present a compelling setting to test whether digital capabilities yield sustainability gains under constraint. By examining how firms operate within these limitations highlighted in extant literature, this study offers nuanced insights on the generalizability of dominant theories and provides context-specific implications for digital sustainability transitions in the Africa.

Furthermore, while GSCM provides foundational strategies such as green procurement and reverse logistics (Asif et al., 2020b, Panpatil et al., 2023), these alone have not resolved challenges like inadequate end-of-life management and resource depletion. Scholars increasingly argue that Industry 4.0 technologies, which include blockchain and artificial intelligence (AI), may offer traceability, transparency, and real-time oversight needed to strengthen RESCs (Trujillo-Gallego et al., 2022a). Industry 4.0 technologies are therefore adopted by organisations to improve supply chain activities through the enhancement of operational visibility and responsiveness (Masood and Sonntag, 2020, Lerman et al., 2022).

The extant literature often views industry 4.0 as having a direct effect on sustainability, implicitly suggesting that digital transformation automatically yields environmental benefits (Bag et al., 2021a, Chiappetta Jabbour et al., 2020, Dev et al., 2020). This view, with grounds in traditional RBV interpretations, which postulates that digital capabilities function as “valuable, rare, inimitable, and non-substitutable (VRIN) resources” which enhance firm performance (Barney and Clark, 2007). However, prior research findings suggest that this relationship is more nuanced. While some studies (Bag et al., 2021b, Beltrami et al., 2021, Chauhan et al., 2023) support the view that industry 4.0 enhances sustainability performance, others argue that such outcomes are often mediated by organisational capabilities such as GSCM (Trujillo-Gallego et al., 2022b, Sun et al., 2022, Kumar et al., 2021). This contradiction underscores empirical gap in extant literature.

This study attempted to address two underexplored issues. First, it examined the prevalent empirical claim that industry 4.0 technologies inherently yield sustainability gains and explores whether such outcomes are dependent upon their integration with sustainable practices like GSCM practices instead. Second, the study builds on the NRBV by situating its empirical analysis within resource-constrained environments, where institutional and infrastructural challenges are well documented (Peter et al., 2023, Adenle, 2020) yet empirical research relating to digital-sustainability nexus remains underexplored. Although these constraints are not directly operationalized in the model, the study draws contextual insights from this setting to discuss the boundary conditions under which digital capabilities may or may not lead to sustainability gains.

To empirically examine this unresolved theoretical relationship, the role of GSCM practices as mediator in the industry 4.0 - sustainability performance interplay was examined. This study tests whether these technologies directly enhance sustainability or whether their impact is contingent on complementary environmental capabilities, such as GSCM. This argument was tested through PLS-SEM, where the survey data gathered among mid- and senior-level managers within African RES was closely examined.

1.4 Research Aim and Questions

The RESCs face notable sustainability hurdles, including SCM inefficiencies, critical raw material dependence, and suboptimal end-of-life management for wind turbines and solar panels. Tackling these challenges will benefit from innovative solutions that integrate Industry 4.0 technologies with GSCM practices. This study examined the possibility of such integration to improve sustainability performance (economic, environmental, and social).

Research Aim:

To examine the integration of GSCM practices and Industry 4.0 technologies in enhancing sustainability performance in African RESCs.

Research Objectives:

1. To identify and analyse key sustainability and SCM challenges confronting African RE firms.
2. To examine how Industry 4.0 technologies influence the adoption of GSCM practices in African contexts.
3. To evaluate the impact of GSCM and Industry 4.0 integration on sustainability performance across economic, environmental, and social dimensions.

Research Questions:

1. **Primary Research Question**:
    - How does the integration of GSCM practices and Industry 4.0 technologies affect sustainability performance in African RESCs?
2. **Sub-Questions**:
    - What sustainability and SCM challenges do African RE firms face?
    - How do Industry 4.0 technologies facilitate the adoption of GSCM practices in African RE firms?
    - What is the combined effect of industry 4.0 technologies and GSCM practices on sustainability performance in Africa's RESCs?

These questions target the core gap identified in the literature: how digital technologies influence GSCM efforts to address SCM and sustainability issues. By focusing on Africa and adopting GSCM as a mediating factor, this research clarifies how organisational practices, and technological innovations coalesce to advance sustainability performance. Figure 1-1 depict the connection among the major constructs in this study.

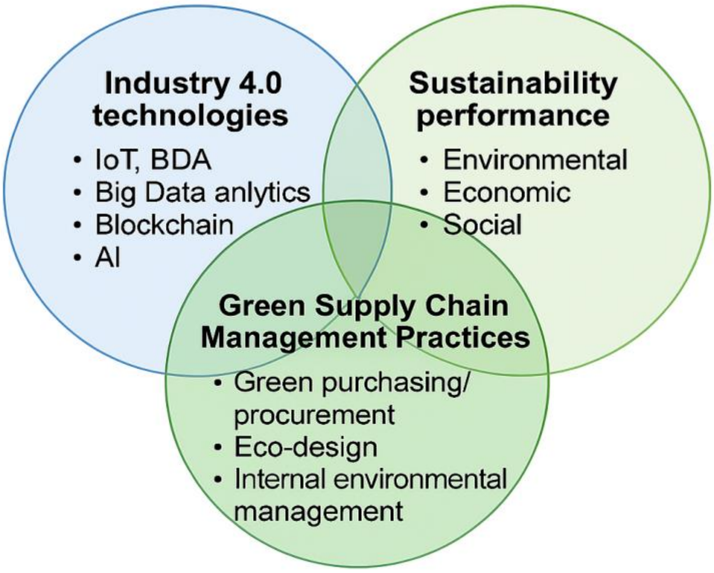

Figure 1-1 Relationship between main constructs

1.5 Methodological overview

In this study, a mixed-methods research technique was adopted to examine the integration of Industry 4.0 technologies and GSCM practices in improving sustainability performance within RESCs in Africa. Given the complexity of the relationships under investigation, a sequential exploratory design was employed, beginning with qualitative insights to inform the development of a conceptual model, followed by quantitative validation through structural equation modelling (SEM).

To provide a strong foundation for this study's mixed-methods design and to ensure contextual and theoretical alignment, two distinct systematic literature reviews were conducted. The first review, presented in Chapter 2, examined over 200 peer-reviewed studies to map current practices and gaps at the intersection of GSCM and Industry 4.0 technologies across various sectors. In line with research questions two and three, this review was instrumental in identifying key digital tools (e.g., IoT, blockchain, AI) and their roles in enhancing GSCM practices such as green procurement, eco-design, and green logistics so that a solid foundation is laid regarding understanding the relationship among the constructs of this study. This review also highlighted sector-specific sustainability challenges in the RESCs, thus guiding the formulation of the study's conceptual framework and research questions.

The second review, covered in Chapter 3, adopted a more context-specific lens focused on RESCs. It systematically analysed over 100 high-quality sources to uncover prevailing sustainability and SCM challenges within the RES, including end-of-life management, logistical inefficiencies, and infrastructure gaps. This review further assessed existing GSCM and Industry 4.0-based interventions reported in the African context and highlighted the absence of integrative strategies tailored for emerging economies. The rationale for conducting two separate systematic literature reviews stems from the need to balance global theoretical constructs with grounded empirical understanding of Africa's RES landscape. By integrating findings from both global and regional perspectives, the study ensured a robust, relevant, and context-sensitive foundation for the qualitative and quantitative phases that followed.

The qualitative phase involved semi-structured interviews with industry experts and professionals in RES, providing contextual insights into the key sustainability and SCM challenges, Industry 4.0 adoption patterns, and the role of GSCM in Africa's RES. The findings from this phase guided the development of the survey instrument and refined the conceptual framework, ensuring alignment with practical industry realities.

The quantitative phase employed an online survey administered through Qualtrics, targeting mid- and senior-level managers in supply chain, procurement, operations, and sustainability roles across various African countries. The minimum required sample size was determined through a power analysis using *G*Power*, a statistical tool commonly used to estimate the minimum required sample size for hypothesis testing (Faul et al., 2009). Rigorous data cleaning procedures were implemented to enhance the reliability of responses. SEM using SmartPLS 4 was conducted to test the proposed hypotheses. The direct impact of Industry 4.0 technologies upon sustainability performance was examined as well as the mediating role of GSCM practices in the relationship.

To assess the reliability and validity of the measurement model, a confirmatory factor analysis (CFA), reliability tests, and discriminant validity assessments (including Fornell-Larcker and HTMT criteria) were conducted. Additionally, common method bias (CMB) was measured using Harman's single-factor test, confirming that CMB was not of a significant concern. These methodological steps ensured that the study produced statistically robust and practically relevant findings, providing valuable contributions to both academia and industry stakeholders in the RES. Figure 1-2 represents a flow diagram of the methodological design.

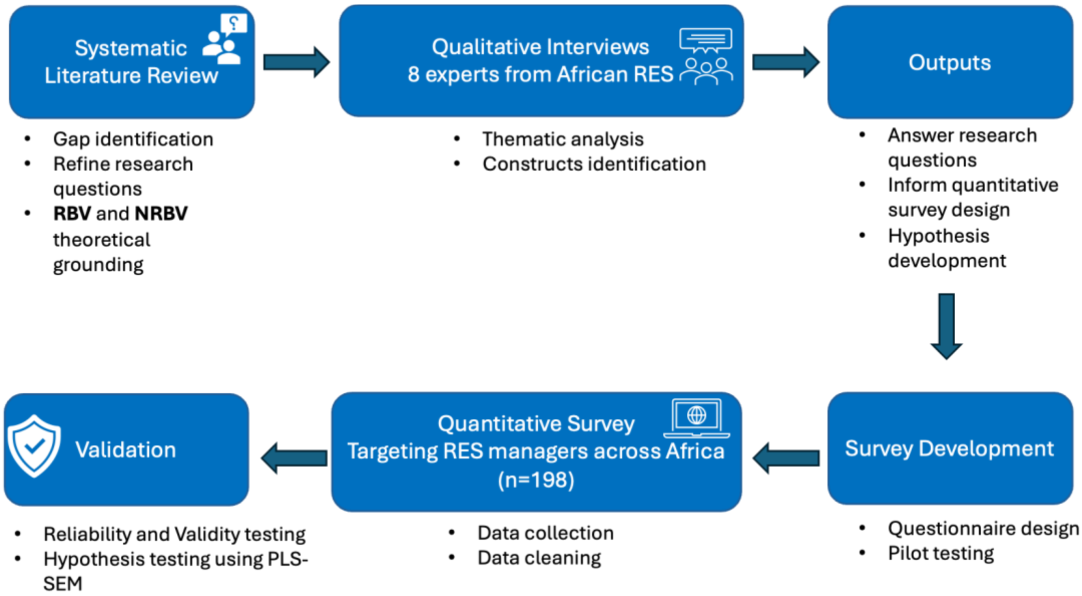

Figure 1-2 Methodological overview

1.6 Overview of Research Findings

The qualitative component of this study provided a foundational understanding of the contextual challenges, barriers, and enablers affecting the adoption of green and digital supply chain practices. Through in-depth interviews with key stakeholders including supply chain managers, policy actors, and industry experts, rich thematic insights were extracted. The thematic analysis revealed six major categories of SCM challenges affecting RESCs in the African context: importation-related constraints, logistics inefficiencies, knowledge and skill gaps, economic and financial barriers, regulatory shortcomings, and corruption-related issues. In addition to these operational bottlenecks, respondents identified sustainability-specific concerns such as poor end-of-life management for RE assets, weak enforcement of environmental regulations, and low awareness of circular practices. Notably, the qualitative findings also identified promising solutions, including structured GSCM strategies, targeted Industry 4.0 technological interventions, and comprehensive policy reforms.

Building on these qualitative insights, the quantitative results revealed that while Industry 4.0 technologies have potential to enhance sustainability outcomes, they do not exert a significant direct effect unless mediated by well-structured GSCM practices. Specifically, the mediating role of green procurement, eco-design, and internal environmental management was found to be critical for realising improvements across economic, environmental, and social dimensions of performance.

Together, the findings present a layered understanding of how digital transformation and environmental practices interact within RESCs. The study contributes novel empirical evidence highlighting that the effectiveness of Industry 4.0 technologies is not automatic but context-dependent, shaped by institutional, infrastructural, and human capital variables. The qualitative phase not only enriches the interpretation of the quantitative findings but also deepens theoretical insights by capturing how stakeholders perceive, implement, and struggle with sustainability and digital transitions in resource-constrained environments.

1.7 Research Novelty and Contribution

This study offers significant theoretical and practical contributions by examining the relationship between GSCM practices and Industry 4.0 technologies in RESCs across several African countries. Addressing the pressing sustainability and SCM challenges facing RE firms in resource-constrained contexts, the study employed a rigorous mixed-methods design comprising systematic literature reviews, qualitative insights from expert interviews from the African RES, and a quantitative survey of 101 RE experts across 17 African countries to uncover how GSCM and Industry 4.0 technologies jointly shape sustainability performance.

The empirical results revealed that while Industry 4.0 technologies are often assumed in extant literature to directly enhance sustainability outcomes (Akkad et al., 2022, Karmaker et al., 2023a), their value in African RESCs is largely indirect and contingent, mediated through strategically aligned GSCM practices. The study also suggests a nuanced context-sensitive theoretical refinement and extension to RBV and NRBV, challenging several common assumptions embedded in these frameworks.

Theoretical Contributions

1. **Refining RBV and NRBV for constrained environments**

   This study extends the RBV and NRBV by demonstrating that I4.0 technologies, though typically classified as VRIN resources (AlNuaimi et al., 2021, Barney and Clark, 2007), do not exert a direct impact on sustainability performance in African RESCs. Rather, their effectiveness depends on alignment with structured environmental capabilities such as GSCM. This finding reframes the RBV logic: technological resources alone are insufficient to generate sustainability outcomes unless embedded within firm-specific environmental capabilities. Furthermore, by introducing institutional voids, regulatory weaknesses, and digital infrastructure gaps as contextual boundary conditions, the research enhances the explanatory reach of both RBV and NRBV in underexplored, resource-constrained economies.

2. **Empirical demonstration of GSCM as a full mediator**

   Using PLS-SEM, the study empirically confirmed that GSCM fully mediates the relationship between Industry 4.0 technologies and sustainability performance. The direct relationship between Industry 4.0 and sustainability performance was not statistically significant, indicating that digital transformation does not yield sustainability gains in isolation. This insight contributes empirical clarity to a fragmented literature, where prior studies have yielded inconsistent findings on the direct efficacy of Industry 4.0 technologies in enhancing sustainability performance (Bag et al., 2021a; Kumar et al., 2021; Trujillo-Gallego et al., 2022). It also affirms recent theoretical discourse that positions capability integration, not technology adoption alone, as the primary mechanism through which sustainability outcomes emerge.

3. **Contextualising digital-sustainability discourse for African RESCs**

   Most empirical applications of RBV/NRBV frameworks are situated in developed economies, where firms operate with institutional stability and mature digital infrastructure. This study expands the geographic and theoretical boundaries by focusing on African RESCs where firms are burdened by import dependency, skill gaps, weak policy enforcement, and economic volatility. Qualitative insights revealed that sustainability is further impeded by unsustainable disposal practices, lack of end-of-life strategies, and minimal environmental consciousness. By foregrounding these contextual realities, the study challenges the universality of VRIN assumptions, suggesting that even “strategic” resources fail to generate competitive or sustainability value when key enabling conditions are absent.

Practical Contributions

In addition to its theoretical implications, this study provides practical guidance for firms, supply chain managers, and policymakers aiming to enhance sustainability performance within African RESCs. The findings underscore that the adoption of Industry 4.0 technologies alone does not automatically lead to improved sustainability outcomes. Rather, their benefits materialize when these technologies are embedded within structured GSCM practices.

Several key practical insights emerge:

1. **Integration of digital tools with environmental processes**: Technologies such as IoT, blockchain, and AI only support sustainability performance when aligned with GSCM routines such as green procurement, lifecycle management, carbon footprint tracking, and end-of-life planning as suggested by this study.
2. **GSCM capability development is path-dependent**: Organisational factors such as environmental awareness, digital maturity, supplier engagement, and certification readiness (e.g., ISO 9001) critically shape the successful implementation of GSCM. In low-capacity settings, practices like recycling partnerships and vendor vetting become essential enablers.
3. **Structural constraints dilute digital transformation efforts**: Weak digital infrastructure, fragmented regulations, and limited human capital continue to hinder the transformative potential of Industry 4.0 technologies in emerging economies. These barriers could be addressed to unlock sustainability value.
4. **Strategic alignment is more critical than technological acquisition**: Simply deploying digital tools without a broader sustainability-oriented strategy yields minimal impact. A deliberate alignment of Industry 4.0 adoption with GSCM and sustainability objectives is essential for achieving meaningful outcomes.

To overcome these challenges, coordinated action is required:

1. **Policy reform and workforce development** are central to enabling digital–green transitions. Governments can accelerate this shift through standardized regulations, targeted tax incentives, and supportive procurement frameworks.
2. **Capacity building and digital upskilling** at the firm level including training in sustainability analytics, digital monitoring, and circular economy principles are valuable to operationalising digital tools effectively.

3. **Public–private collaboration** and **strategic financing mechanisms** (e.g., supply chain financing, subsidies, and de-risking initiatives) are also vital to support technology adoption and GSCM capability development.

Together, these measures provide a roadmap for improving environmental, economic, and social outcomes in African RESCs through the integrated deployment of digital technologies and sustainability-driven management paradigms.

Broader Impact

The study aligns with global sustainability agendas, including the United Nations SDGs, by tackling critical challenges in RESCs. It contributes to the broader discourse on sustainable energy transition by presenting a unified approach coalescing technological innovation, green supply chain strategies, and policy interventions under resource-constrained conditions. By embedding RBV's focus on strategic resource optimization with NRBV's emphasis on environmental stewardship, the study provides a holistic perspective on how African RESCs can contribute to global decarbonization efforts while enhancing local economic resilience.

Overall, this research not only enriches academic literature but also serves as a practical guide for policymakers, industry practitioners, and sustainability advocates. By emphasizing the synergy between GSCM and Industry 4.0 technologies, the study offers a sustainable, and digitally enabled approach to strengthening Africa's RES, reinforcing the continent's role in global climate action and sustainable development.

1.8 Thesis Structure

This thesis is structured into eight chapters, with each chapter contributing to a broad examination of how Industry 4.0 technologies and GSCM practices influence sustainability performance in RESCs within the African context. The chapters are systematically arranged to guide the reader through the research background, literature review, theoretical framework, methodology, findings, discussion, and conclusions.

Chapter 1 (Introduction) offers an overview of this study, which encapsulates the research background, motivation, problem statement, research questions, and contributions. It also presents a methodological overview, outlining the research approach employed, and concludes with a summary of the thesis structure.

Chapter 2 (GSCM Practices and Industry 4.0 Technologies) reviews existing literature on GSCM and Industry 4.0 technologies, particularly focusing on their role in improving supply chain sustainability. This chapter follows a systematic literature review approach, synthesizing key themes such as green procurement, eco-design, supply chain collaboration, drivers, barriers, and the combined impact of Industry 4.0 and GSCM in RES.

Chapter 3 (Sustainability and SCM Challenges in RES) extends the literature review by identifying major sustainability and SCM challenges. It discusses how GSCM and Industry 4.0 technologies have been proposed as solutions to these challenges and highlights the research gaps that inform the study's conceptual framework.

Chapter 4 (Theoretical Framework) introduces the RBV and the NRBV as the guiding theoretical perspectives. The chapter justifies the integration of these theories in studying the interplay among Industry 4.0, GSCM, and sustainability performance, providing the theoretical foundation for the research hypotheses.

Chapter 5 (Research Methodology) details the philosophical underpinnings, research design, and data collection methods used in the study. It outlines the mixed-methods approach, incorporating semi-structured interviews for qualitative insights and a survey-based quantitative analysis. The data collection, sample selection, questionnaire development, and ethical considerations are also discussed.

Chapter 6 (Qualitative Findings – Thematic Analysis) presents the results from semi-structured interviews, identifying key SCM and sustainability challenges in African RESCs, as well as solutions emerging from Industry 4.0 adoption and GSCM. This thematic analysis provides context for the subsequent quantitative validation.

Chapter 7 (Quantitative Results and Interpretation) reports the findings of the Partial Least Squares Structural Equation Modelling (PLS-SEM) analysis, assessing the relationships among Industry 4.0 technologies, GSCM practices, and sustainability performance. It includes assessments of the measurement model, structural model, and hypothesis testing results, offering empirical validation of the conceptual framework.

Chapter 8 (Discussion) synthesizes the research findings, comparing them with existing literature to highlight key contributions, theoretical advancements, and practical implications. It critically examines the study's theoretical contributions to RBV and NRBV, practical contributions to firms and policymakers, and limitations, before concluding with future research directions and the overall thesis conclusion.

The thesis concludes with references and appendices, including consent forms, interview questions, survey items, and supplementary PLS-SEM results, ensuring transparency and reproducibility of the research.

Chapter 9 (Conclusion) synthesizes the study's findings. It highlights the study's theoretical contributions to RBV and NRBV, practical implications for managers and policymakers, and the contextual insights for African RESCs. The chapter also outlines key limitations and proposes future research directions, including comparative, longitudinal, and policy-focused studies.

2 GSCM Practices and Industry 4.0 Technologies

2.1 Chapter Introduction

This chapter provides a structured, systematic review of the literature on GSCM, Industry 4.0, and sustainability issues in the RES. Building on the broader research context introduced in Chapter 1, this review outlines key GSCM practices across diverse industries and highlights the transformative potential of Industry 4.0 technologies related to enhancing those practices. In doing so, the chapter centres on the extent to which these approaches can be integrated to address pressing SCM and sustainability challenges within RESCs, particularly in developing economies.

The chapter is organized to first clarify its review methodology and explain how relevant literature sources were identified and synthesized. 206 studies (both review and empirical), gathered from ScienceDirect, Web of Science and Scopus, form the basis for categorizing GSCM practices according to their positioning across value chain segments, including procurement, manufacturing, and logistics. It then examines the role of Industry 4.0 technologies in driving GSCM implementation, with emphasis on how these technologies can streamline operations, reduce environmental footprints, and improve traceability. Particular attention is given to the unique sustainability and SCM problems affecting the RES, these include risks associated with sourcing raw material, inadequate end-of-life management practices, and logistical inefficiencies.

This discussion culminates in an overview of how GSCM, enhanced by Industry 4.0, can serve as a roadmap for mitigating sustainability challenges and achieving operational resilience in RESCs. By highlighting gaps in the existing literature especially in sectors beyond automotive and manufacturing, the chapter establishes a foundation for subsequent empirical investigation into the African renewable energy context. Ultimately, these findings set the stage for developing a holistic framework in which GSCM practices and digital innovations synergize to support environmentally responsible supply chains, aligning with the thesis's overall objective of guiding RE firms toward more sustainable, efficient operations.

2.2 Systematic Literature Review (1) Protocol

The protocol adopted for this review draws on the seven-step approach proposed by Egger and Masood (2020), selected for its rigor and comprehensive filtering of research resources. Figure 2-1 illustrates the overall review process, while the subsequent paragraphs detail the activities performed at each stage.

Step 1: Planning

The initial phase established the constructs of interest for this systematic literature review, focusing on the combined frameworks of GSCM and Industry 4.0. Although GSCM literature has expanded markedly (Choudhary and Sangwan, 2022), limited studies address the intersection of these two domains. Consequently, this review is guided by four research questions:

1. **What are the current state-of-the-art practices in the GSCM literature?**
   This question aims to identify prominent GSCM practices in various industries and contexts.
2. **What role does Industry 4.0 technologies play in the adoption of GSCM practices?**
   Here, the emphasis is on assessing the level and scope of digital technology application in facilitating GSCM.
3. **What sustainability and supply chain-related problems exist in the RES?**
   The objective is to capture the key challenges, as revealed in the reviewed literature, that impede sustainable supply chains in RE.
4. **How can the integration of Industry 4.0-powered GSCM address these challenges in the RES?**
   This final question explores how digital technologies and GSCM practices collectively mitigate sustainability and SCM issues in RES.

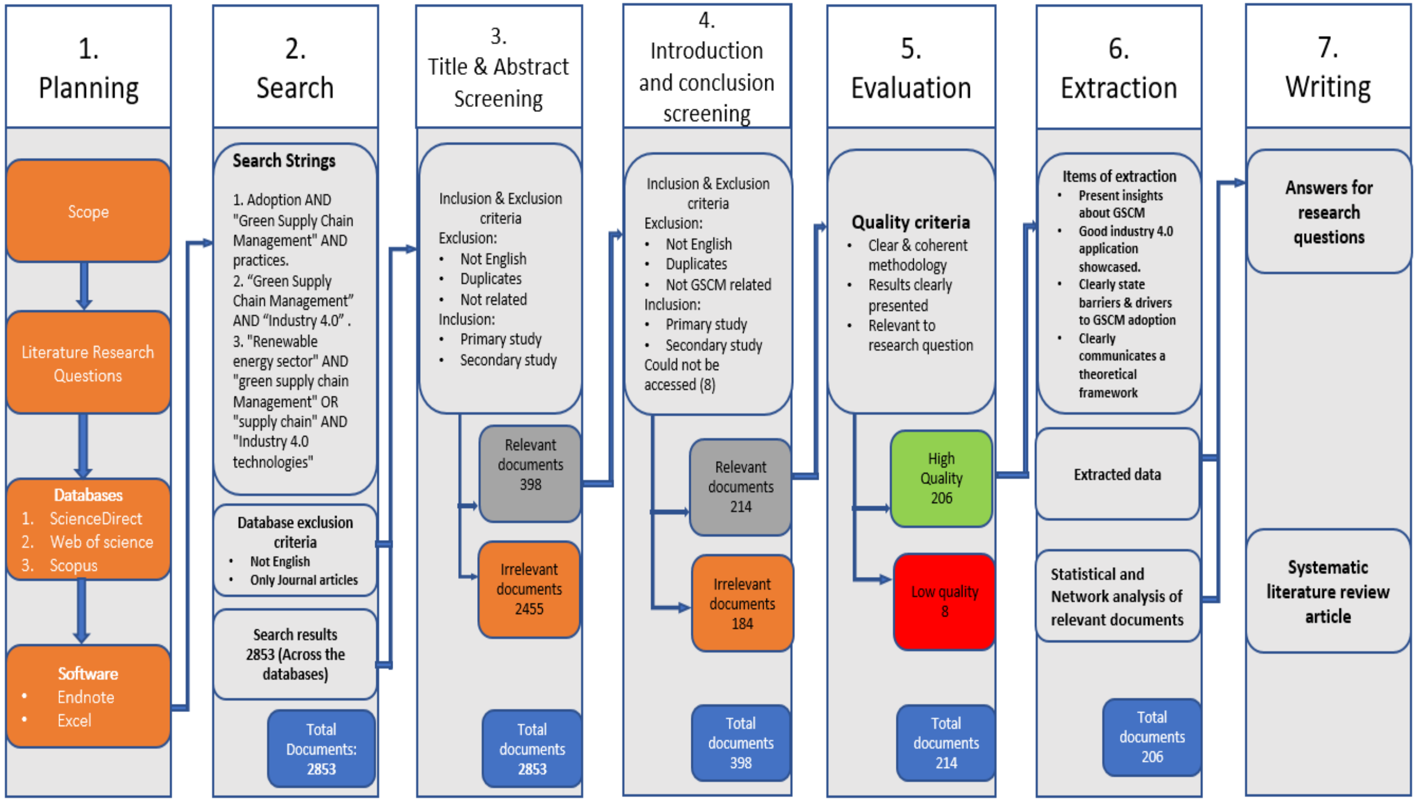

Figure 2-1 Systematic literature review 1 process
(Illustration of the seven-step methodology from Egger and Masood (2020), highlighting the chronological progression from Planning to Extraction.)

To ensure wide coverage, ScienceDirect, Web of Science, and Scopus were selected as the primary databases, given their extensive collection of peer-reviewed journals. Microsoft Excel was used to extract and organize relevant data, while EndNote served as the reference management software due to its versatility and unique functionalities.

Step 2: Search

A set of search strings was developed, informed by an initial scoping exercise and consultations with a senior librarian. These strings, designed to capture fundamental insights about Industry 4.0 technologies and GSCM practices, were each searched independently in the three databases identified above:

1. **Adoption AND "Green Supply Chain Management" AND practices**
2. **“Green Supply Chain Management” AND “Industry 4.0”**
3. **"Renewable energy sector" AND "green supply chain Management" OR "supply chain" AND "Industry 4.0 technologies"**

The searches were conducted on November 9, 2022, March 4, 2023, and December 15, 2025, which focused on identifying relevant titles, abstracts, and keywords. Two main exclusion criteria were applied at this stage: (1) articles not published in English, and (2) non-journal articles.

Step 3: Title and Abstract Screening

All results were imported into EndNote for initial processing. Duplicate records were removed to maintain data integrity. Subsequently, each paper underwent an eligibility check based on its title and abstract, enabling the exclusion of studies that did not align with the review’s scope and research questions.

Step 4: Introduction and Conclusion Screening

Publications passing the initial screening were subjected to more detailed examination, focusing on their introduction and conclusion sections. This deeper reading helped confirm the studies' relevance to GSCM and Industry 4.0 technologies relating to sustainable supply chains context.

Step 5: Evaluation

During this stage, a more rigorous reading and quality assessment determined which studies would be included in the final analysis. Three criteria guided this evaluation:

- **Clarity of methodology**
- **Conciseness in discussing results**
- **Relevance to the review's research questions**

Only papers meeting these benchmarks were incorporated for subsequent data extraction.

Step 6: Extraction

A thorough review of the chosen studies was performed to extract answers to the four guiding research questions. Relevant details ranging from GSCM practices and Industry 4.0 applications to identified challenges and proposed solutions were recorded in a literature matrix in Microsoft Excel. This matrix served as a centralized repository, ensuring consistent data handling and facilitating cross-comparison among studies.

By following this structured protocol, the review offers a robust, transparent approach to mapping and analysing the current state of GSCM research alongside Industry 4.0 literature. The next sections of this chapter present the findings, focusing on key practices, drivers, barriers, and potential synergies as they relate to sustainability challenges in the RES.

2.3 Findings of the review (1)

2.3.1 Industrial Sectors Covered

An analysis of the selected literature reveals that researchers have explored a diverse range of industrial contexts when examining GSCM and Industry 4.0. Specifically, eight sectors emerged as the most frequently addressed. Manufacturing predominates, appearing in 56 studies, followed by multi-sector analyses in 29 papers. Other sectors, including construction (9 papers), electronics (9 papers), and mining (8 papers), also receive attention, while a residual 31 studies did not clearly identify a single industry focus. Figure 2-2 demonstrates the number of times individual sectors appear in the reviewed literature.

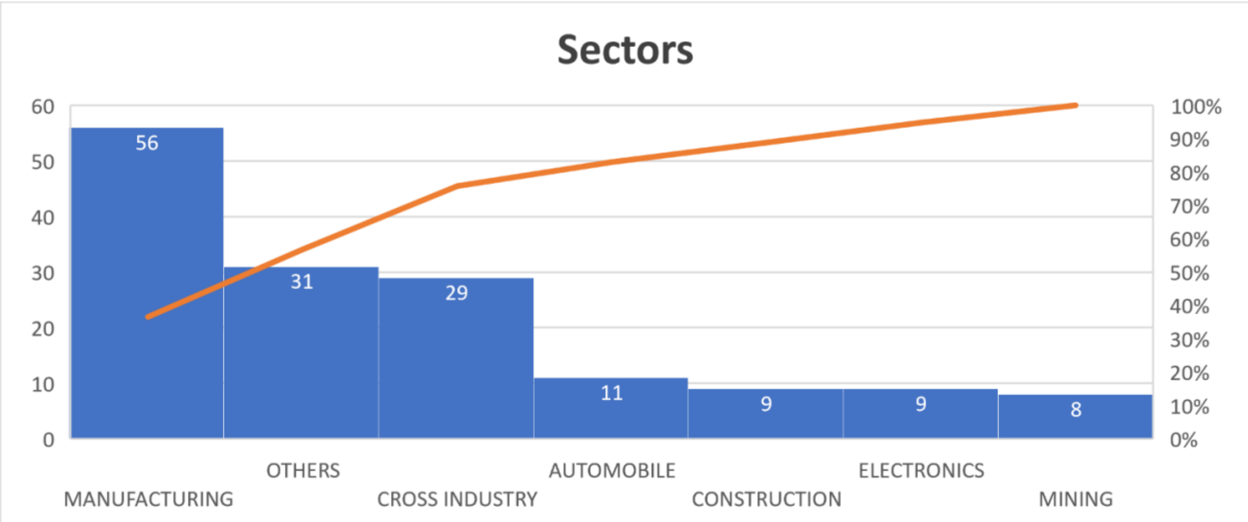

Figure 2-2 Industry sectors covered

Number of times industries are covered by researchers (The line in this pareto graph represents the cumulative percentage of the total frequencies of the industries studies focused on with the most significant appearing first. This line is drawn on the chart to indicate the point at which 80% of the total frequency of the industries covered has been reached).

Despite the breadth of industries examined, the RES remains notably underrepresented. Researchers generally concentrate on manufacturing and multi-sector explorations, indicating potential gaps for more specialized or nuanced studies in renewables. This emphasis on other industries underscores the need to investigate sustainability and SCM challenges specific to RESCs. Moreover, unique features such as heavy reliance on critical raw materials and high end-of-life management costs distinguish renewables from traditional manufacturing or construction domains. Examining RESCs thus offers an opportunity to address issues insufficiently covered in prior work, including the ethical sourcing of conflict minerals for solar panels and the complex decommissioning of wind turbines.

By situating the RES within this broader landscape of GSCM and Industry 4.0 scholarship, the present research positions itself to fill an important void. Focusing on RES not only extends current theoretical discussions by mapping known concepts to sector-specific challenges but also holds potential to deliver tangible outcomes for industry stakeholders contending with operational inefficiencies, stringent environmental targets, and limited regulatory frameworks. Consequently, directing attention to RESCs becomes a logical step in advancing sustainable supply chain practices under Industry 4.0, thereby contributing both rigor and relevance to this evolving area of study. The next section therefore transitions to a focused examination of GSCM concepts and practices, laying the groundwork for exploring how they may address the specific needs of RESCs.

2.3.2 Green supply chain management practices

There has been a considerable attention in recent years towards environmental concerns from both the academia and Industry (Hashmi and Akram, 2021, Kumar Shetty and Subrahmanya Bhat, 2022, Panpatil and Kant, 2022). These concerns have given birth to pressures emanating from the global competitive markets, while environmental regulations as well as customers are forcing firms worldwide to thoroughly think about the environmental footprints arising from their business operations. Therefore, companies have since embarked on a journey to reduce their environmental impacts through the adoption of newer business and management paradigms instead of their traditional practices (Choudhary and Sangwan, 2022).

In the early 1990s, the concept of GSCM was first introduced (Khan et al., 2022c), although it only got popular around the 2000s as evidenced by surging empirical publications (Agi and Nishant, 2017, Arantes et al., 2014). GSCM is among the numerous concepts of sustainable practices; GSCM encapsulates the entire activities of delivering products and services from raw materials to disposal or end of life (Ghosh et al., 2022). GSCM is a fundamental derivative of SCM which is linked to strategically integrating environmental considerations through the implementation of a set of environmental practices namely; green design, green manufacturing, reverse logistics, waste management, green operations among others, across the SC in an effort to minimize adverse environmental footprints (Jell-Ojobor and Raha, 2022).

GSCM is one of the management paradigms that incorporate “green” philosophy in manufacturing, distribution, procurement and logistics (Birasnav et al., 2022). GSCM involves a set of managerial activities that firms adapt to reduce pollution and energy consumption to attain sustainability. Arguably, competitive advantage is achieved due to the implementation of these practices (Nureen et al., 2022). In other words, GSCM buttresses on the integration of environmental aspects into different facets of SCM (Wang and Zhang, 2022).

GSCM practices are the activities or actions that lead to the implementation of GSCM, which are characterized by reduction of environmental deterioration and pollution while improving performance that leads to customer and stakeholder satisfaction (Panpatil and Kant, 2022). Through a critical review of the literature, Choudhary and Sangwan (2022) have found internal environmental management, investment recovery, green procurement, cooperation with customers, reverse logistics, eco-design, and design of packaging as the most important GSCM practices mentioned by researchers.

It has been asserted by Birasnav et al. (2022) that GSCM arguably enhances environmental performance and sustainability of firms. According to El-Garaihy et al. (2022a), GSCM increases companies’ competitive advantage and economic performance. They added that enhanced reputation, efficiency, effectiveness and revenue growth can also be achieved because of successful GSCM implementation. This assertion by El-Garaihy et al. (2022) holds an overly positivist view towards GSCM while Esfahbodi et al. (2023) refute what they call the fallacy of profitable GSCM and added that GSCM might present a trade-off when it comes to the nexus between economic performance and GSCM.

The extensive literature review conducted revealed a wide range of GSCM practices found by researchers in various industries and sectors. For this thesis, a categorization of these practices was done based on where they fall in any given value chain. This categorization is believed to be more robust and succinct than the one presented by Assumpção et al. (2022) and the simplistic internal and external to organisation categorization of practices presented by Stekelorum et al. (2021b) because in this thesis, product or service value chain as well as the most important corporate functions are put into consideration. Figure 2-3 depicts the ten most repeatedly mentioned GSCM practices by researchers.

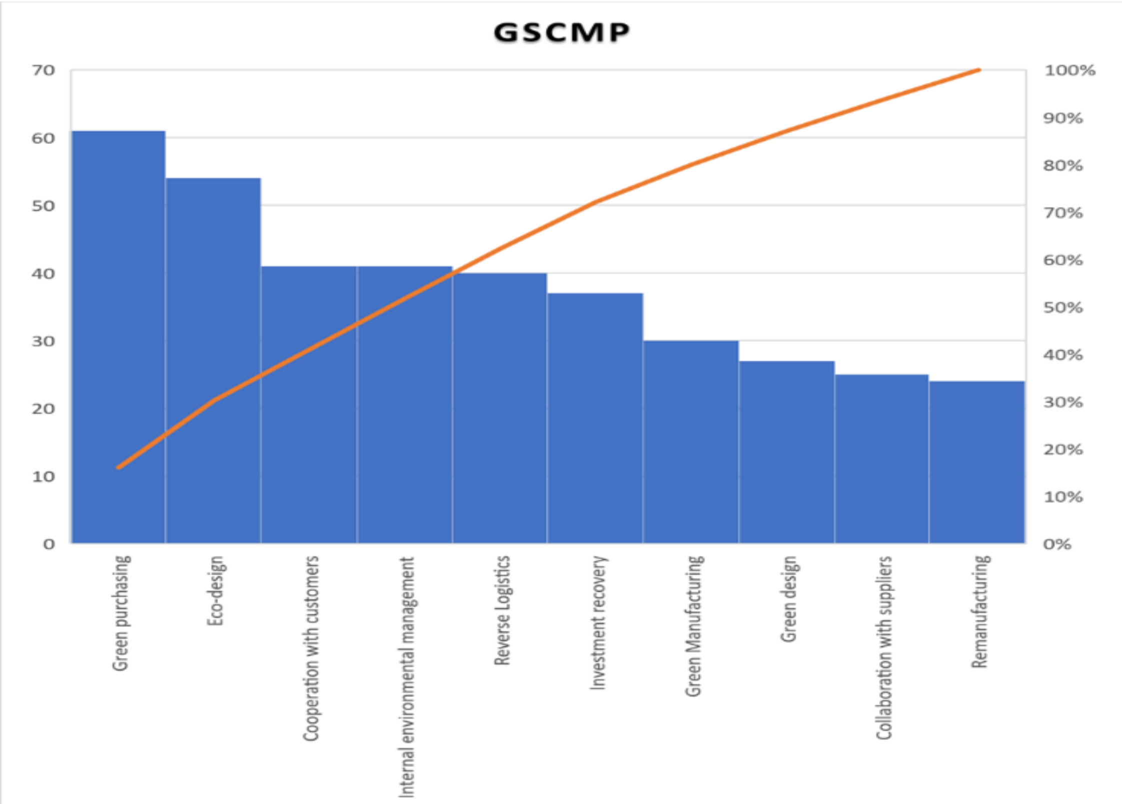

Figure 2-3 Ten most repeatedly mentioned GSCM practices

The line in this pareto graph represents the cumulative percentage of the total frequencies of the individual GSCMP with the most significant appearing first. This line is drawn on the chart to indicate the point at which 80% of the total frequency of the GSCM practices as they are mentioned by authors. Figure 2-3 highlights the most frequently cited GSCM practices in the literature, providing empirical justification for the selection of green procurement, eco-design, and internal environmental management as core dimensions examined in this study.

Procurement and Sourcing related GSCM practices

Procurement and sourcing–related GSCM practices involve selecting and evaluating suppliers based on environmental performance, material sourcing standards, and stakeholder collaboration. Green purchasing consistently emerges as one of the most frequently cited practices (Esfahbodi et al., 2023, Umar et al., 2022b, Trujillo-Gallego et al., 2021), Panpatil and Kant (2022), Khan et al. (2022a), Zhou et al. (2019), Vanalle et al. (2017), Lee et al. (2014), this practice appeared in at least sixty papers out of the papers reviewed.

Green purchasing

As the name implies, green purchasing involves the incorporation of environmental considerations by a firm when choosing suppliers and raw materials that meet ethical and legal standards (Asif et al., 2020a). To achieve green purchasing, there are many other practices cited by researchers that have to do with effective management of corporate relationship. It is imminent that achievement of green purchasing cannot thrive without other green practices like supplier selection based on environmental criteria. Even that is not obtainable without environmental disclosure among partners and Information sharing regarding environmental regulations. The latter is also best achieved when digital technologies like Industry 4.0's blockchain which brings about traceability and transparency in information sharing are embedded. Table 2-1 lists the GSCM practices related to procurement and sourcing.

Table 2-1 Procurement and Sourcing related GSCM practices

GSCMP	Country focus	Sector	Authors
Green purchasing	UK, Pakistan, Columbia, Brazil, Malaysia.	Automobile, Manufacturing, Garment	(Esfahbodi et al. (2023), Umar et al. (2022a), Trujillo-Gallego et al. (2022a), Panpatil and Kant (2022), Khan et al. (2022a), Zhou et al. (2019), Vanalle et al. (2017), Lee et al. (2014)

Green procurement	Multi-regional	Hospitality	(Migdadi (2022), Ghosh et al. (2022), Sajjad et al. (2020))
Green sourcing	Australia	Manufacturing	(Fayezi et al., 2020)
Green outsourcing	Saudi Arabia	Manufacturing	(El-Garaihy et al., 2022a)
Sustainable sourcing	India	Manufacturing	(Sahoo and Vijayvargy, 2021)

Product design related GSCM practices

Product design–related GSCM practices centre on reducing environmental footprints early on at product design stage. Eco-design or "green design" appears repeatedly in the literature. Eco-design Esfahbodi et al. (2023), El-Garaihy et al. (2022a), Alghababsheh et al. (2022), Alcaraz et al. (2022), Stekelorum et al. (2021b), Choudhary and Sangwan (2018), Jabbour et al. (2013), Zhu and Sarkis (2006), Zhu and Sarkis (2004) is the most repeatedly mentioned GSCM practice in this category

Eco-design or Green design

Eco-design, otherwise called Green design, is a green philosophy that juxtaposes environmental thinking and economic logic to innovatively design new products or enhance existing ones in an effort to replace less environmentally friendly ones (Panpatil and Kant, 2022). Scholars have stressed the need for product design to be eco-friendly for an organisation to adopt GSCM. Eco-design has been found across multiple countries and sectors, indicating broad relevance for manufacturing and beyond. Table 2-2 lists the GSCM practices obtained in different sectors and countries which are related to product design.

Table 2-2 Product design related GSCM practices

GSCMP	**Country focus**	**Sector**	**Authors**
Eco-design	UK, Saudi Arabia, Jordan, Mexico, India, Brazil, China	Automobile, Manufacturing, Ceramics, High-tech, Multi-Industry.	(Esfahbodi et al. (2023), El-Garaihy et al. (2022a), Alghababsheh et al. (2022), Alcaraz et al. (2022), Stekelorum et al. (2021b), Choudhary and Sangwan (2018), Jabbour et al. (2013), Zhu and Sarkis (2006), Zhu and Sarkis (2004))

Green design	Not country specific	Not sector specific	(Tseng et al., 2019)
Green Product design	Pakistan	Manufacturing	(Saeed et al., 2018)
Environmental product design	India	Automobile	(Tyagi et al., 2015)

Corporate relationship related GSCM practices

These practices address a firm's collaborations with suppliers, customers, and stakeholders, focusing on environmental data exchange and joint sustainability initiatives. The most frequently mentioned practice in this category is "cooperation with customers" Stekelorum et al. (2021b), Sahoo and Vijayvargy (2021), Nkrumah et al. (2021), Micheli et al. (2020), Kalyar et al. (2020)) and collaboration with suppliers (Ghosh et al., 2022).

Collaboration with Suppliers

It is imminent that for a firm to achieve successful greening of its supply chain a lot of practices need to be adopted with regards to how the relationship of that firm is managed especially with suppliers, customers and other stakeholders. Collaboration with suppliers to achieve environmental objectives has been found to be important in the implementation of GSCM practices but to get suppliers that uphold greening of the supply chain, supplier selection must be conducted on the basis of green compliance.

Cooperation with customers

Increased environmental cooperation and monitoring is often brought about by increased interaction of a firm with its customers on green issues and this has been found to positively enhance a firm's environmental performance, agility and quality (Maditati et al., 2018). This GSCMP has been mentioned by about 40 researchers, and this is due to the importance of the end user's green ideology towards green consumerism which generally aids organisations to comply by GSCM in the conduct of their businesses. Table 2-3 outlines corporate relationship related GSCM practice.

Table 2-3 Corporate relationship related GSCM practices

GSCMP	Country focus	Sector	Authors
Cooperation with customers	India, Ghana, Italy and Pakistan	Manufacturing, Textile	(Stekelorum et al. (2021b), Sahoo and Vijayvargy (2021), Nkrumah et al. (2021), Micheli et al. (2020), Kalyar et al. (2020))
Environmental Data disclosure and transparency	China	Multi-Industry	(Elbaz and Iddik, 2020) (Chen et al., 2022)
Supplier/customer environmental cooperation	Spain, China	Aerospace, Manufacturing	(Ruiz-Benitez et al., 2017), (Govindan et al., 2015), (Liu et al., 2020)
Information sharing regarding environmental regulations	India	Automobile	(Tyagi et al., 2015)
Environmental engagement and responsiveness	China	Multi-Industry	(Chen et al., 2022)
Environmental disclosure	Not country specific	Not sector specific	(Elbaz and Iddik, 2020)
Collaboration with suppliers	India, Vietnam, Brazil, Bangladesh	SMEs, Footwear, Textile	(Ghosh et al., 2022) (Ta et al., 2020), (Sellitto et al., 2019) (Habib et al., 2021)
Supplier selection in the context of sustainable sourcing and environmental criteria	Portugal	Manufacturing	(Elbaz and Iddik, 2020), (Panpatil and Kant, 2022), (Pinto, 2020)
Supplier education, coaching and mentoring of suppliers	Spain	Aerospace	(Ruiz-Benitez et al., 2017)
Supplier evaluation	Malaysia	Manufacturing	(Foo et al., 2018)
Supplier environmental management systems requirement	Spain	Aerospace	(Ruiz-Benitez et al., 2017)
Environmental monitoring upon suppliers	Spain	Aerospace	(Ruiz-Benitez et al., 2017)
Collaboration with partners within the supply chain	Brazil	Automobile	(Lopes and Pires, 2020), (Tseng et al., 2019)
Environmental co-operation	United Arab Emirates	Manufacturing	(Younis et al., 2020),
Green supply process management	Portugal	Manufacturing	(Pinto, 2020)

Organisational structure/strategy related GSCM practices

Practices under this category relate to organizational culture, strategic positioning, and internal environmental management. Under this category, there are a lot of practices mentioned by researchers. The most frequently mentioned by researchers is internal environmental management which involves setting environmental goals, implementing ISO 14001, and fostering a sustainability-focused culture Loaiza-Ramírez et al. (2022), Alghababsheh et al. (2022), Pinto (2020) and Investment recovery (Micheli et al., 2020).

Investment Recovery

This is an important GSCM practice mentioned by researchers which refers to the sale of assets that aren't longer valuable to a firm in an effort to maximally recoup its investment, this also include the sale of returned stock used equipment, in other words, selling or repurposing unneeded assets, thus reducing waste and extending product lifecycles (Assumpção et al., 2022). Although this sounds more business inclined, but researchers consider it as a GSCM practice because it minimizes a firm's waste generation and positively helps in the lifecycle extension of equipment.

Internal environmental management

Internal environmental management encompasses a firm's strategic positioning and commitment to environmental sustainability through well-defined policies and targets (Khan et al., 2022a). This practice plays a pivotal role in GSCM as it aligns closely with an organization's structure and strategic orientation, as illustrated in Table 2-4. Numerous related GSCM practices identified in this study reinforce the importance of internal environmental management. Key examples include the implementation of environmental management systems such as ISO 14001 certification and the integration of green ideology and corporate environmentalism across organizational levels. Since the success of GSCM initiatives heavily relies on human engagement, practices such as Green Human Resource Management which includes green training programs and top management commitment are frequently highlighted in the literature as critical enablers. Table 2-4 further elaborates on other organizational structure and strategy-related GSCM practices.

Table 2-4 Organisational structure/strategy related GSCM practices

GSCMP	Country focus	Sector	Authors
Internal environmental management	Columbia, Jordan, Portugal	Manufacturing	(Loaiza-Ramírez et al. (2022), Alghababsheh et al. (2022), Pinto (2020))
Environmental management systems	Mexico	Manufacturing	(Alcaraz et al., 2022)
Adoption of EMS (ISO 14001)	Not country specific	Not sector specific	(Govindan et al. (2015), Panpatil and Kant (2022)) (Tseng et al., 2019)
Environmental technology	Brazil	Footwear	(Sellitto et al., 2019), (Tseng et al., 2019)

Investment recovery	Italy	Manufacturing	(Micheli et al., 2020)
Green marketing	Bahrain	Shipping and Automobile	(Jassim et al., 2020)
Green training	China	Multi-Industry	(Kuei et al., 2015)
Green human resource management	Not country specific	Not sector specific	(Panpatil and Kant, 2022)
Internal management support	India	SME	(Govindan et al., 2015), (Ghosh et al., 2022)
Total quality management	Vietnam, India	Automobile, SME	(Wu et al., 2015) (Ghosh et al., 2022)
Green policy, performance and environmental strategy	Jordan, Pakistan	Manufacturing, Retail	(Alghababsheh et al., 2022), (Panpatil and Kant, 2022), (Shahzad et al., 2022)
Firm Environmental proactivity (carbon index disclosure score)	Not country specific	Not sector specific	(Elbaz and Iddik, 2020)
Corporate sustainability strategy and environmentalism			
Carbon management	Not country specific	Not sector specific	(Tseng et al., 2019)
Lifecycle assessment	Brazil	Home appliance	(Scur and Barbosa, 2017)
Green supply process management and finance	Columbia, Portugal	Manufacturing	(Loaiza-Ramírez et al., 2022), (Birasnav et al., 2022) (Pinto, 2020)
Green Construction	Indonesia	Construction	(Putu Artama Wiguna et al., 2021)
End-of-life management	India	Construction	(Mojumder and Singh, 2021a)
Use of energy from renewable sources	India	SME	(Ghosh et al., 2022)
Information sharing regarding environmental regulations	India	Automobile	(Tyagi et al., 2015)
Data disclosure and transparency	China	Multi-Industry	(Chen et al., 2022)

Compliance with legal environmental requirements and auditing programs	Brazil	Electronics, Manufacturing	(Kannan et al., 2014), (Assumpção et al., 2022)
External environmental management requirements	Mexico	Manufacturing	(Alcaraz et al., 2022)

Logistics and transportation related GSCM practices

This category is termed as such because the practices mentioned aim to make inbound, outbound, and reverse logistics more sustainable, reducing carbon footprints and operational costs. The most important GSCM practice under this category is Reverse Logistics which involves product returns, recycling, remanufacturing, and source reduction El-Garaihy et al. (2022a), Assumpção et al. (2022), Malviya and Kant (2020).

Reverse Logistics

Reverse logistics is a GSCM practice that involves product returns, material substitution, remanufacturing, source reduction and recycling (Trujillo-Gallego et al., 2022a). The successful implementation of reverse logistics requires high level coordination among supply chain partners, and this is so, because products can easier be tracked back to the point of fault. It is for this reason that researchers mentioned a lot of GSCM practices that have to do with corporate relationship like environmental information sharing among supply chain partners. Table 2-5 contains some logistics and transportation related GSCM practices obtained in this review.

Table 2-5 Logistics and transportation related GSCM practices

GSCMP	Country focus	Sector	Authors
Green logistics and distribution	United Kingdom, Columbia and Thailand.	Automobile, Manufacturing and Electronics	(Esfahbodi et al. (2023), Trujillo-Gallego et al. (2022a), Tippayawong et al. (2015)) (Stekelorum et al., 2021b)
Green transportation	India	Agro	(Sharma et al., 2017)
Greening inbound and outbound	Portugal	Manufacturing	(Pinto, 2020)
Sustainable transportation	Europe	Logistics and Shipping	(Jazairy and von Haartman, 2020)
Green-Deliver	Not country specific	Not sector specific	(Maditati et al., 2018)

Reverse logistics	Saudi Arabia, Brazil and India	Manufacturing (2) and Automobile	(El-Garaihy et al. (2022a), Assumpção et al. (2022), Malviya and Kant (2020))
Green warehousing and green building	Not country specific	Not sector specific	(Panpatil and Kant, 2022), (Stekelorum et al., 2021b)
Optimization of transportation	Malaysia	SMEs	(Lin et al., 2020)
Operations and Logistics Integration	Ghana	Mining	(Kusi-Sarpong et al., 2015)

Waste and pollution management related GSCM practices

This category is termed as such because the practices mentioned under it relate to pollution and waste management processes of implementing systems for minimizing waste, handling wastewater, and dealing with toxic substances (Ghosh et al., 2022, Tyagi et al., 2015). In other words, these activities aim to curb or eliminate pollution, manage waste responsibly, and mitigate environmental harm. Table 2-6 contains a list of practices obtained under this category.

Table 2-6 Waste and pollution management related GSCM practices

GSCMP	**Country focus**	**Sector**	**Authors**
Waste management System for waste minimization Waste water treatment Solid waste management system	India	SME	(Ghosh et al., 2022)
Emission control system Waste minimization	India	Automobile	(Tyagi et al., 2015)
Toxic substance management	Malaysia	SMEs	(Lin et al., 2020)
Superior waste management	UK	Manufacturing	(Cousins et al., 2019)
Reduction of pollutants	Taiwan	Shipping	(Yang, 2018)
Pollution prevention and mitigation Final Waste Destination	Brazil	Footwear	(Sellitto et al., 2019)
Environment-friendly disposal	Oman	Manufacturing	(Al-Sheyadi et al., 2019)

Manufacturing related GSCM practices

Manufacturing related GSCM practices emphasize cleaner production, energy conservation, and resource-efficient operations. Green manufacturing Mojumder and

Singh (2021a), Liu et al. (2020), Asif et al. (2020a), Sharma (2014) is the most important practice mentioned under this category.

Green Manufacturing and Remanufacturing

Green manufacturing is a GSCMP that involves environmentally conscious manufacturing practice that is energy efficient, uses quick and dependable equipment which raises productivity and decreases wastage (El-Garaihy et al., 2022a). A lot of scholars have mentioned practices that augment green manufacturing linking sustainable raw materials handling and processing, so also reduced use of hazardous materials and the blacklisting of some raw materials. Others link it to green and RE utilization like the use of energy from renewable sources as proposed by Ghosh et al., (2022). Scholars like Jassim et al., (2022) link green manufacturing to green or eco-friendly packaging. To stress the fact that green manufacturing is the incorporation of environmentalism in the end-to-end process of manufacturing, authors like Tyadi et al., (2015) mentioned some pollution and waste management GSCM practices alongside end-of-life practices like toxic substance management and superior waste management. Table 2-7 outlines the GSCM practices that are found to be related to manufacturing practices.

Table 2-7 Manufacturing related GSCM practices

GSCMP	Country focus	Sector	Authors
Green manufacturing	India	Construction, Agro	(Mojumder and Singh (2021a), Liu et al. (2020), Asif et al. (2020a), Sharma (2014)
Green/Eco-innovation	Ghana	Mining	(Panpatil and Kant, 2022) (Kusi-Sarpong et al., 2015)
Environmental quality controlling	China	Multi-Industry	(Kuei et al., 2015)
Sustainable manufacturing practices	Not country specific	Not sector specific	(Elbaz and Iddik, 2020)
Product recovery	India	Automobile	(Perotti et al., 2015)
Green production, green operations and green process	Portugal	Manufacturing	(Pinto, 2020)
Cleaner production	India	Multi-Industry	(Singh et al., 2020)

Green service	Not country specific	Not sector specific	(Panpatil and Kant, 2022)
Operational performance and Internal process improvement	India	Ceramic	(Choudhary and Sangwan, 2018)
Reduced use of hazardous materials	United Arab Emirates	Manufacturing	(Younis et al., 2020)
Green materials and design	Germany, Austria and Switzerland	Manufacturing	(Kim et al., 2021)
Blacklist of raw materials	Multi-regional	Multi-Industry	(Wang et al., 2018)
Use of energy from renewable sources	India	SMEs	(Ghosh et al., 2022)
Source reduction	Mexico	Manufacturing	(Alcaraz et al., 2022)
Energy saving	India	Automobile	(Tyagi et al., 2015)
System for waste minimization and Wastewater treatment	India	SMEs	(Ghosh et al., 2022)
Solid waste management system	India	SMEs	(Ghosh et al., 2022)
Reduction of pollutants	Taiwan	Shipping	(Yang, 2018)
Environment-friendly disposal	Oman	Manufacturing	(Al-Sheyadi et al., 2019)
Products' end of life management	India	Construction	(Mojumder and Singh, 2021a)
Emission control system	India	SMEs	(Ghosh et al., 2022)
Eco-friendly, green or Environmental packaging	Bahrain, India	Shipping, SMEs and Automobile	(Jassim et al., 2020), (Elbaz and Iddik, 2020), (Ghosh et al., 2022)
Reuse and recycle	India, UK	SMEs, Manufacturing	(Ghosh et al., 2022), (Cousins et al., 2019)
Remanufacturing	Oman	Manufacturing	(Al-Sheyadi et al., 2019)
Green recycling and upcycling	Multi-regional	Hospitality, Construction	(Migdadi, 2022), (Ali et al., 2020)
Use of less expensive recycled raw materials	United Kingdom	Manufacturing	(Cousins et al., 2019)

2.3.2.1 Concluding Perspectives on GSCM Practices

Collectively, the GSCM practices outlined ranging from procurement and product design to logistics, waste management, and manufacturing illustrate the breadth of strategies firms may adopt to mitigate environmental impacts and potentially achieve competitive advantage (Nureen et al., 2022, El-Garaihy et al., 2022). However, scholars such as Esfahbodi et al. (2023) caution that these practices are not uniformly cost-neutral. In some cases, high initial investments or operational complexities can impede short-term profitability, reflecting the broader debate on balancing sustainability and financial viability.

Nonetheless, the literature converges on GSCM's multifaceted potential for sustainability performance. Many researchers emphasize the role of digital innovations particularly real-time data tools that enhance traceability and foster stakeholder collaboration to address persistent hurdles in implementing GSCM. By embedding these technological solutions, firms may resolve issues such as transparency deficits, suboptimal supplier relationships, or misaligned incentives in end-of-life management processes.

Altogether, these practices provide a robust framework for integrating sustainability into diverse corporate functions. Yet, they also require organizational commitment, supportive policies, and resource allocation. This tension between ecological ideals and practical constraints lies at the heart of GSCM adoption. As the next logical step, the following section explores the drivers of GSCM adoption, examining how internal and external factors like stakeholder pressure, regulatory requirements, and leadership initiatives motivate firms to implement green practices. Understanding these drivers is critical not only for comprehensively assessing GSCM adoption but also for appreciating how Industry 4.0 technologies can expedite and streamline such efforts, particularly in the RES.

2.3.3 Drivers of GSCM adoption

The drivers encouraging firms to adopt GSCM are extensive. In this study, these motivations are categorized into seven main groups: Customer, Stakeholder, Finance, Human Resource, Regulations, Reputation, and Competitiveness. Each category represents a distinct impetus for embracing green initiatives, reflecting the complexity of implementing GSCM across different organizational contexts.

1. **Customer**

This group concerns the influence of customers on environmental practices. Customer awareness levels and reactions (Al-Refaie and Momani, 2018) are consistently identified as significant drivers for GSCM implementation. Customer demands (Asif et al., 2020a), expectations (Ogunlela, 2018), and pressures (Kim et al., 2021) all positively influence green practices adoption, as do specific customer requirements (Laari et al., 2016, Caniels et al., 2016, Mathiyazhagan et al., 2015). Heightened environmental awareness and a focus on meeting customers' ecological preferences (Tseng et al., 2019) further push organizations to integrate sustainability into their operations.

The emphasis on customer-centric drivers underlines the fundamental role that market preferences and awareness play in shaping a firm's commitment to GSCM. As consumers become more environmentally conscious, they actively seek out products and services with minimal ecological footprints (Al-Refaie and Momani, 2018, Tseng et al., 2019). Meeting these demands requires organizations to scrutinize their supply chains, from raw material sourcing to product disposal, to ensure greener operations (Asif et al., 2020, Ogunlela, 2018). In a broader sense, customer-driven pressures serve as a powerful feedback mechanism for continuous environmental improvement, spurring companies to adopt sustainable practices not merely to comply with regulations, but also to align with evolving consumer values. This heightened alignment can, in turn, reinforce the firm's competitive position and reputation within increasingly eco-conscious markets.

2. **Stakeholder**

Stakeholders ranging from supply chain partners and NGOs to society at large create pressure for firms to implement GSCM. Examples include stakeholder capabilities and willingness (Gera et al., 2022), requirements from supply chain partners regarding EMS standards (Tseng et al., 2019), and institutional or stakeholder pressures (Bhatia and Gangwani, 2021). Scholars additionally cite pressure from multiple channels (Gandhi et al., 2015), supply chain stakeholders (Handayani et al., 2021), and non-governmental organizations (Mathiyazhagan et al., 2015). Societal forces (Somsuk and Laosirihongthong, 2017) and internal or external stakeholder requirements (Ogunlela, 2018) also influence GSCM adoption.

Drivers linked to stakeholders extend beyond immediate customer demands and reflect the influence of a broader network, including supply chain partners, local communities, NGOs, and various advocacy groups. These actors collectively shape organizational priorities by imposing or encouraging environmental standards (Bhatia and Gangwani, 2021, Mathiyazhagan et al., 2015). Stakeholder-induced pressures can range from formal requirements such as compliance with EMS guidelines or specific green certifications to more informal expectations around transparency and social responsibility (Tseng et al., 2019, Handayani et al., 2021). Consequently, organizations are prompted to deepen environmental engagement not just to secure a stable market position, but also to cultivate trust and legitimacy across their entire operational ecosystem. Such trust and legitimacy become particularly crucial as firms strive to integrate GSCM practices comprehensively, often coordinating with multiple tiers of suppliers and aligning diverse stakeholder interests within a cohesive sustainability framework.

3. **Finance**

The financial incentives driving GSCM revolve around cost reduction and profitability concerns. Researchers point to cost savings (Meager et al., 2020, Younis et al., 2020), economic constraints or gains (Nkrumah et al., 2021, Susanty et al., 2019), and reduced overall costs (Tumpa et al., 2019) as motivating firms to embrace green practices. Economic benefits include returns on investment (Scur and Barbosa, 2017, Gandhi et al., 2015) and resource efficiency from mitigating waste, water use, and energy consumption (Tseng et al., 2019).

Financial considerations act as a powerful catalyst for integrating green practices into SCM (Meager et al., 2020, Nkrumah et al., 2021, Susanty et al., 2019). By targeting cost reduction in areas like energy consumption, materials procurement, and waste disposal, companies often discover a dual benefit of lowering operational expenses and demonstrating environmental responsibility (Scur and Barbosa, 2017, Gandhi et al., 2015). This pursuit of financial gains through GSCM can extend beyond immediate efficiencies; for instance, long-term payoffs may arise from enhanced brand positioning, lower risk of regulatory penalties, or stable access to eco-conscious markets (Tumpa et al., 2019, Younis et al., 2020). As such, finance-focused drivers encourage firms to view GSCM not merely as a response to environmental pressures but as an avenue for sustained economic and competitive advantage (Tseng et al., 2019).

4. **Human Resource**

Motivational drivers tied to human resource factors underscore the role of personnel attitudes, leadership, and organizational culture. These drivers encompass top management commitment, environmental training, green recruitment, and broader corporate culture (Abdellatif, 2021, Ta et al., 2020, Kuei et al., 2015). Additional elements include employee ambivalence and managerial mindset (Meager et al., 2020), employee empowerment and engagement (Muduli et al., 2013, Sharma, 2014, Taghavi et al., 2021), or the need for specialized technical expertise (Gandhi et al., 2015, Jazairy and von Haartman, 2020). Efforts to embed a green ethos, whether through training, collaboration, or strategic planning (Tumpa et al., 2019, Nkrumah et al., 2021, Lin et al., 2020), further strengthen GSCM adoption.

Human resource–related drivers emphasize that GSCM adoption is not solely a technological or procedural endeavour, but also a human-centric one (Meager et al., 2020, Abdellatif, 2021). Successful green initiatives require robust leadership commitment, adequate training, and a supportive corporate culture factors that determine whether new sustainability protocols are embraced or resisted by employees (Gandhi et al., 2015, Muduli et al., 2013). Moreover, strategic recruitment of eco-aware staff and the cultivation of environmental champions within the organization can foster creativity and collaboration, ensuring that sustainable practices resonate across different departments (Tumpa et al., 2019, Nkrumah et al., 2021). In this light, human resource considerations serve as critical levers for entrenching a “green” mindset at all operational levels, thereby reinforcing and sustaining GSCM integration.

5. **Regulations**

Regulatory drivers capture pressures linked to legal mandates and policy frameworks. These include adapting to regulations, mitigating environmental risks, or meeting environmental certification requirements (Gandhi et al., 2015, Tseng et al., 2019). Scholars highlight supportive government policies, regulatory enforcement (Somsuk and Laosirihongthong, 2017, Xu et al., 2013, Handayani et al., 2021), and broader international agreements or standards (Susanty et al., 2019, He et al., 2018) as catalysts for firms to align their operations with green principles. Compliance with ISO 14000 and similar requirements likewise compels businesses to adopt GSCM (Maditati et al., 2018, Caniels et al., 2016).

Regulatory drivers underscore the role of formal rules, legal mandates, and policy frameworks in compelling businesses to adopt green initiatives (Gandhi et al., 2015, Tseng et al., 2019). These may include local environmental laws, international agreements, or specific green certifications (Nkrumah et al., 2021, Susanty et al., 2019) and often manifest through governmental intervention or standardized audits (Handayani et al., 2021, Caniels et al., 2016). By enforcing compliance, regulations not only minimize ecological harm but also create a level playing field for all market participants, supporting broader sustainability goals (Xu et al., 2013, He et al., 2018). Consequently, organizations that proactively align with such frameworks may benefit from reduced risk of penalties and enhanced public trust two factors that synergize effectively with the other drivers of GSCM adoption, ensuring that environmentally responsible practices become ingrained in daily operations rather than mere afterthoughts.

6. **Reputation**

Motivations under this category focus on corporate image and brand positioning. Enhancing brand reputation (Gandhi et al., 2015), creating a green corporate image (Tseng et al., 2019), and promoting environmental responsibility (Scur and Barbosa, 2017) all drive organizations toward GSCM. Companies also factor in corporate social responsibility obligations and demands from environmental groups or NGOs (Mojumder and Singh, 2021a, Tumpa et al., 2019), using GSCM to cultivate a positive public image (Asif et al., 2020, Ogunlela, 2018).

Reputation-based drivers highlight how a firm's image and perceived responsibility can significantly influence its willingness to adopt sustainable practices (Gandhi et al., 2015, Tseng et al., 2019). In an era of increased public scrutiny and instant communication, companies that position themselves as environmentally conscious often gain loyalty from customers, attract partnerships with like-minded stakeholders, and enhance their market appeal (Scur and Barbosa, 2017, Mojumder and Singh, 2021). Likewise, proactive management of a green reputation can mitigate risks related to negative publicity or activist pressure, thereby complementing other motivational factors such as cost savings and regulatory compliance. When integrated into a broader GSCM strategy, reputation-driven efforts encourage firms to demonstrate authenticity in their environmental commitments, fostering long-term trust among consumers, investors, and community groups alike.

7. **Competitiveness**

Finally, certain drivers reflect the competitive dynamics prompting firms to adopt green strategies. Competitive advantage, supplier performance (Asif et al., 2020), environmental forces, and supply chain pressure (Nkrumah et al., 2021, Al-Refaie and Momani, 2018) fall under this category. Studies also cite competition, globalization, and product differentiation as factors motivating

GSCM adoption (Ogunlela, 2018, Mathiyazhagan et al., 2015, Gandhi et al., 2015). Perceived relative advantage (Lin et al., 2020) and collaboration opportunities (Jazairy and von Haartman, 2020) similarly encourage organisations to integrate sustainable practices to outperform rivals.

Competitiveness as a driver of GSCM adoption emphasises the strategic significance of sustainability in maintaining or improving an organisation's position within global and highly dynamic markets (Ogunlela, 2018, Mathiyazhagan et al., 2015, Gandhi et al., 2015). Whether through product differentiation, process innovation, or leaner operations, companies recognize that "going green" can provide unique value propositions to customers and stakeholders, thereby outmanoeuvring rivals (Nkrumah et al., 2021, Tseng et al., 2019). Indeed, pressures stemming from external competition such as the drive for faster marketability and broader supply chain integration often compel organizations to accelerate GSCM initiatives (Lin et al., 2020, Jazairy and von Haartman, 2020). In the broader context, these competitive motivations converge with other drivers (e.g., cost savings, customer expectations) to create a robust impetus for adopting sustainable practices, illustrating how environmental stewardship can evolve into a core component of a firm's competitive edge.

Taken together, these seven categories reveal how multidimensional and interdependent the motivations for GSCM adoption can be. Customer and stakeholder pressures often serve as the immediate impetus for change, prompting companies to consider more sustainable sourcing and production methods. Meanwhile, financial factors, human resource considerations, and regulatory frameworks significantly influence both the feasibility of initiating such practices and the likelihood that they will endure. Drivers associated with reputation and competitiveness further highlight the strategic advantages of adopting GSCM, encouraging firms to capitalize on enhanced brand image and market positioning.

Nonetheless, even the strongest motivations may falter in the face of significant challenges. Organizational inertia, resource limitations, and high initial costs can undermine otherwise sound initiatives, while resistance from partners or employees may erode the momentum gained from external pressures. Accordingly, the broader literature notes an uneven landscape of GSCM adoption, where robust drivers do not always translate into uniform implementation. To better understand this discrepancy, the upcoming section examines the barriers to GSCM adoption, outlining the key obstacles that persist despite compelling incentives.

2.3.4 Barriers to GSCM adoption

Despite numerous drivers encouraging organizations to adopt GSCM, a variety of obstacles can impede the effective integration of sustainable practices. These challenges may emerge from internal organizational constraints as well as broader external conditions. To better comprehend these obstacles, this section classifies the barriers into seven main groups: (1) Cost-Related Barriers, (2) Human Resource–Related Barriers, (3) Strategy-Related Barriers, (4) Supplier-Related Barriers, (5) Resource-Related Barriers, (6) Change Management–Related Barriers, and (7) Government/Regulation–Related Barriers.

1. **Cost-Related Barriers**

   Many organizations encounter substantial financial burdens when transitioning to eco-friendly operations (Tumpa et al., 2019, Tseng et al., 2019, Ta et al., 2020, Meager et al., 2020, Scur and Barbosa, 2017, Agyemang et al., 2018, Kumar Shetty and Subrahmanya Bhat, 2022). Additional expenses arise from the adoption of green materials, specialized packaging, or newly installed systems that require ongoing maintenance (Kaur et al., 2019). Small and medium-sized enterprises (SMEs) are predominantly constrained due to their limited access to capital and difficulties achieving economies of scale (Perotti et al., 2015). Furthermore, inadequate research and development (R&D) capabilities hamper innovation in green processes (de Oliveira et al., 2018), while uncertainties regarding return on investment (ROI) and the financial implications of eco-design frequently dissuade firms from pursuing more ambitious GSCM initiatives (Tumpa et al., 2019).

From a broader perspective, these cost-oriented hurdles highlight the inherent tension between immediate economic pressures and the longer-term benefits of sustainable initiatives. Firms already operating under tight profit margins may struggle to absorb initial green investments, even if such measures promise eventual gains in market reputation or regulatory compliance. Consequently, cost-related barriers not only slow the adoption of GSCM but can also create disparities in competitiveness, where resource-rich organizations leap ahead, leaving more constrained companies lagging in implementing comprehensive green programs.

2. **Human Resource-Related Barriers**

Human resources significantly influence the success of GSCM, yet various issues can impede progress (Mojumder and Singh, 2021a, Kaur et al., 2019, Kumar Shetty and Subrahmanya Bhat, 2022). Lack of environmental knowledge, insufficient training, and open resistance to new processes or technologies often undermine the internal momentum required for sustainability (El Baz and Iddik, 2022). Organizations may also suffer from inadequate top management commitment (Meager et al., 2020, De Sousa Jabbour and De Souza, 2015, de Oliveira et al., 2018, Tumpa et al., 2019, Tseng et al., 2019, Ta et al., 2020) and weak inter-departmental collaboration (Al-Refaie et al., 2020), exacerbating employee scepticism and halting progress toward an eco-centric corporate culture (Nkrumah et al., 2021).

These human-centred challenges underscore how deeply organizational buy-in and staff capabilities affect GSCM outcomes. Even when senior executives show interest in going green, the absence of specialized training programs or a supportive culture can cause employees to remain unconvinced of GSCM's strategic importance (Perotti et al., 2015, Ghosh et al., 2022). Thus, the interplay of limited skill sets and lukewarm leadership fails to convert sustainability ideals into operational practices, ultimately constraining the firm's ability to make meaningful, lasting environmental improvements (Kumar Shetty and Subrahmanya Bhat, 2022, Agyemang et al., 2018).

3. **Strategy-Related Barriers**

   Strategic hurdles typically arise from fragmented or insufficiently articulated environmental frameworks within organizations (Kaur et al., 2019). In many cases, environmental missions or corporate social responsibility (CSR) strategies are only superficially defined, resulting in sporadic and poorly aligned GSCM activities (Pinto, 2020). Restrictive internal policies can further deter product or process changes, while the complexity of measuring sustainability performance limits the feedback loops essential for strategic refinement (Lerman et al., 2022). Additionally, a lack of integrated data or traceability systems compounds these difficulties by obscuring supply chain visibility (Agyemang et al., 2018).

   The broader implication of weak or absent green strategies is a constrained organizational capacity to commit to transformative sustainability goals. Without clear guidance or accountability mechanisms, companies risk viewing environmental initiatives as peripheral rather than central to their competitive strategy. As a result, even if individuals within the firm acknowledge the value of GSCM, the absence of a cohesive strategic framework undermines comprehensive adoption, leaving businesses ill-prepared to respond effectively to customer or regulatory demands for greener practices (Mojumder and Singh, 2021a).

4. **Supplier-Related Barriers**

   Collaboration with suppliers is integral to the success of GSCM, yet many firms confront barriers tied to supplier engagement. A general shortage of environmentally committed suppliers, coupled with limited willingness or capacity to adopt green practices, disrupts the broader supply chain's environmental ambitions (Bhatia and Gangwani, 2021). Some suppliers lack awareness of sustainability requirements, while others resist sharing the operational data needed to align with a buyer's environmental objectives (Kaur et al., 2019, Mojumder and Singh, 2021a, Tumpa et al., 2019). Inadequate training and minimal incentives further reduce any inclination these partners might have to modify established routines (Perotti et al., 2015, Handayani et al., 2021).

Viewed through a wider lens, these supplier-specific issues underscore the interconnected nature of modern supply chains. Even if a lead firm embraces GSCM, a reluctant or ill-equipped supplier base can erode the aggregate impact of green initiatives (Kim et al., 2021, de Oliveira et al., 2018). This misalignment can also raise transaction costs and complexity, as companies struggle to coordinate consistent standards across multi-tier networks. In sum, supplier barriers reflect how external interdependencies can either amplify or constrain an organization's ability to embed sustainability throughout its value chain.

5. **Resource-Related Barriers**

Resource constraints, especially in developing regions, substantially inhibit GSCM adoption. Organizations may encounter an absence of RE infrastructure, advanced eco-friendly technologies, or specialized materials (Mojumder and Singh, 2021a). Moreover, limited financial liquidity and inadequate outsourcing capabilities confine the range of green innovations a firm can pursue (Sharma et al., 2017, De Sousa Jabbour and De Souza, 2015, Ghosh et al., 2022). These challenges stretch beyond mere capital outlays, encompassing broader infrastructural gaps from dependable power supplies to robust logistics networks fundamental to consistent environmental management (Ta et al., 2020).

These resource limitations, when placed within a broader context, demonstrate how structural deficiencies hamper even the most environmentally motivated enterprises. Without reliable access to key assets, the firm's willingness to invest in greener alternatives often hits a bottleneck. Consequently, companies operating in resource-scarce settings remain in a defensive posture, focusing on immediate cost feasibility rather than exploring more proactive sustainability measures that could strengthen their long-term competitive edge (Kaur et al., 2019).

6. **Change Management-Related Barriers**

   Resistance to internal change remains another salient obstacle to GSCM. Organizations frequently hesitate to abandon traditional processes due to perceived operational risks, long adoption timelines, or scepticism surrounding new technologies (Liu et al., 2020). Negative past experiences such as suboptimal trials with green material scan entrench a culture that views eco-innovation as too uncertain (Kramarz et al., 2021). Under these conditions, entrenched habits dominate, blocking the system-wide reforms necessary for sustained environmental gains.

   In broader terms, these change management issues illustrate how cultural inertia and risk aversion can undermine even the most promising green frameworks. A lack of trust in novel strategies or reluctance to invest time in building new competencies can stall an organization's green momentum at an early stage. Consequently, the firm fails to capitalize on potential synergies between operational efficiency and environmental performance, leaving it vulnerable to external pressures or shifting consumer expectations that favour eco-responsible businesses (de Oliveira et al., 2018, Perotti et al., 2015).

7. **Government/Regulation-Related Barriers**

   Government policies and regulatory environments also complicate GSCM adoption. Inconsistent or insufficiently enforced legislation often provides limited clarity on compliance, leaving firms uncertain about best practices and potential penalties (Tumpa et al., 2019). Corruption or unequal distribution of subsidies in certain developing regions can further deter sustainable investments, while the lack of infrastructure for waste management imposes additional logistical and cost burdens (Watari et al., 2020, health and Billon, 2021). Under such unpredictable policy frameworks, organizations may remain hesitant to devote significant resources to long-term green projects.

   From a broader perspective, inadequate regulatory support underscores the interplay between public governance and private environmental initiatives

(Kumar Shetty and Subrahmanya Bhat, 2022). Even when organizations are driven to adopt GSCM for competitive or reputational reasons, they often rely on stable, consistent regulations to guide investment and manage risk. A poorly developed policy context thus increases uncertainty and weakens the collective momentum for greening entire industries, leading to fragmented or superficial environmental progress.

The collective view of these seven categories underscores the complexity of obstacles that can derail or delay the adoption of GSCM. Many of these barriers, such as cost pressures and organizational culture, arise predominantly from internal organizational dynamics, whereas supplier compliance and regulatory unpredictability highlight external factors. This interplay between internal and external challenges illustrates why even highly motivated firms may struggle to institute robust green practices: achieving meaningful sustainability typically depends not only on the firm's internal capabilities but also on coordinated efforts across suppliers, policymakers, and communities. Without a balanced approach that tackles both inward-facing reforms like strategic planning and leadership development and outward-facing collaborations such as supplier training programs and constructive policy engagement firms risk implementing piecemeal solutions that fail to generate significant, long-term environmental impact.

Addressing these barriers thus requires a multifaceted framework that integrates financial planning, workforce readiness, and supportive governance structures with technological innovations that streamline operations and improve transparency. In recent years, Industry 4.0 technologies have gained traction for their potential to reduce operational inefficiencies, enhance data backed decision-making, and improve collaboration in the supply chain (Akkad et al., 2022). Such technologies can help firms overcome persistent hurdles by lowering transaction costs, fostering real-time monitoring, and clarifying responsibilities among stakeholders (Alvarez-Aros and Bernal-Torres, 2021). The next section explores these Industry 4.0 solutions and examines how they might bolster GSCM adoption, offering fresh opportunities for organizations to transform existing supply chain configurations into more sustainable, resilient networks.

2.3.5 Role of Industry 4.0 technologies in GSCM adoption

Industry 4.0 represents the fourth industrial revolution, characterized by transformative technological advancements that seamlessly integrate digital processes with physical operations (Egger and Masood, 2020, De Giovanni and Cariola, 2021). These technologies are pivotal in optimizing supply chain processes, minimizing waste, and fostering collaboration key elements for achieving the environmental and operational goals of GSCM. The following subsections detail the fundamental technologies underpinning Industry 4.0 technologies as well as their significant contributions to GSCM practices:

Internet of things (IoT): IoT is referred to as a network of physical objects which are interconnected through various embedded technologies such as sensors to produce data, process and exchange it (Rad et al., 2022). In other words, IoT makes it possible for various smart devices to be connected and monitored, so also allows the devices to communicate among themselves (Sun et al., 2022). In business sense, IoT facilitates the secure exchange of materials, goods and services related information in global supply chains and since the advent of this technology, businesses have been transformed into advanced and smart entities (Yu et al., 2022).

Blockchain: As a decentralized peer-to-peer network, blockchain provides a secure means to track data changes over time for example along a global supply chain (Sun et al., 2022). Depending on the use case, some firms use blockchain to develop a system to track and trace emission data while others use the technology to bring about transparency and visibility in the conduct of their business (Kunkel et al., 2022). With regards to supply chains, blockchain technology enables a real-time flow of data which could easily be processed to ramp up predictive capacity of possible disruptions and bottlenecks (Enrique et al., 2022).

Artificial intelligence (AI): AI is one of the industry 4.0 technologies that are considered to be the elementary units of Industry 4.0 and the basic tools at the forefront of industrial digitalization (Demir et al., 2022). AI is referred to as the computer applications and systems that need human intelligence in performing tasks which through data and algorithms gains the ability to learn and improve on thinking and perception (Sun et al., 2022). AI brings about numerous benefits such as distributed and localized production based upon smart business models, as well as giving customer benefits through more responsive and flexible manufacturing practice with overall fewer delays and defects thereby achieving faster delivery (Mastrocinque et al., 2022).

Big data analytics (BDA): BDA refers to the analytical capability to process a huge amount of data with high complexity, velocity and variety (Sun et al., 2022). In the aviation sector for instance, commercial aircrafts use BDA and other cloud services to promote informed inflight decisions and flight route planning so that fuel consumption is minimized (Ghobakhloo and Fathi, 2021). Shao et al., (2021) added that BDA through intelligent tracking systems, energy efficiency management, predictive maintenance and material assessment enables companies to be more competitive.

Augmented reality (AR): AR is referred to as the overlaying of digital information like texts, effects and images generated by a computer in the real world which interact with users giving real time instructions in a way that is user friendly (Sun et al., 2022). AR enhances end user experience and minimizes workflow disruptions particularly on the shop floor (Shao et al., 2021). Furthermore, AR is found to be impactful in terms of employee productivity, training efficiency, error reduction and better equipment maintenance (Ghobakhloo et al., 2021).

Virtual technologies and simulation: These are powerful tools that are capable of evaluating, optimizing, controlling and mimicking a system or real-world entity by digitally representing it under a cost-efficient environment that is risk-free (Sun et al., 2021). Additionally, these tools provide an immersive environment which enhances productive interaction with information (Kamble et al., 2022).

Cybersecurity: This refers to the practice of protecting and defending critical data, computers, servers, software and other IT infrastructure from malicious activities and cyber-attacks (Calabrese et al., 2023). Cybersecurity involves use of different processes and technologies to ensure the integrity, confidentiality and availability of information systems (Sun et al., 2021).

Cyber-physical systems (CPS): CPS refer to the integration of virtual and physical processes of interconnected machines to obtain real-time information that positively impacts the decision-making for maintenance and production processes alongside improving efficiency, control of production capacity and operational transparency (Morella et al., 2020). Sun et al., (2021) added that CPS which enables effective interactions between humans and systems leveraging computational intelligence and physical elements, is aimed at achieving high level of intelligence, connectivity and automation through the integration of both physical and cyber components.

Cloud computing (CC): CC technologies represent a central platform for the integration and storage of configurable information technology resources which make accessing data and resources from decentralised locations feasible (Sun et al., 2021). With regards to buyer-supplier relationship, CC technologies can facilitate more collaborative buyer-supplier relationships (Patrucco et al., 2021).

Additive manufacturing (AM): AM is an alternative production strategy which is different from traditional manufacturing process and can be referred to as the process of joining different materials to make objects out of 3D model data, usually layer upon layer contrary to subtractive manufacturing methodologies (Rinaldi et al., 2021). Furthermore, AM, otherwise known as 3D printing, is considered as generative manufacturing or layer-wised production through the addition of materials in a layered form to achieve effective production of items at required shape and size without any waste (Sun et al., 2021).

Autonomous robots: These are highly intelligent robots with the ability to self-organise, self-evaluate and independent decision-making to execute numerous tasks without human instructions (Sun et al., 2021). In the RES, there has been the robotisation of the process of maintenance for example, robots being deployed to clean PV panels or inspect wind turbines (Franki et al., 2023).

Based on the literature reviewed, a handful of research papers covered the combined construct of GSCM and Industry 4.0. Umar et al., (2022b) in empirical research studied

Industry 4.0 and GSCM practices in Pakistan. They found that GSCM practices mediate the effect of Industry 4.0 on environmental and economic performances. Also, their results indicated that GSCM practices are affected positively by Industry 4.0. They showed that companies in Pakistan's manufacturing Industry found the industry 4.0 technologies helpful in the adoption of eco-friendly practices through the monitoring and evaluation of GSCM practices and their impacts on economic performance as well as environmental performance.

Another empirical research conducted by Ghadge et al. (2022) studied the link between GSCM and Industry 4.0. Their research focused on the automotive Industry in Europe and the UK. Their study provides robust empirical evidence on how the integration of Industry 4.0 technologies in the automotive supply chains corroborate with the initiation of GSCM practices and their respective impact on the improvement of GSCM performance measures in terms of operational, environmental and economic performances. The researchers recommended that future GSCM research should focus on linking technologies like IoT, Blockchain, CPS to drive the effective implementation of GSCM practices.

De Giovanni and Cariola (2021) empirically studied process innovation enhanced through Industry 4.0 technologies, GSCM and Lean manufacturing in a cross section of industries in Europe. They have found that organizations could gain higher performance by investing in Industry 4.0 technologies. Sutawijaya and Nawangsari (2020) investigated the relationship between GSCM and Industry 4.0 in event management companies in Indonesia. They have found a significant impact of Industry 4.0 on the implementation of GSCM.

Zhang et al., (2022) conducted empirical research in Italy focusing on the food Industry. The authors have examined the role of big data analytics in linking GSCM practices with competitiveness during Covid-19. The findings of their study promote the notion that the incorporation of GSCM, environmental management, environmental visibility and a combination of BDA and AI could enhance market competitiveness during periods of crises like Covid-19.

Trujillo-Gallego et al., (2022b) in another empirical research, built and tested a set of hypotheses that suggested positive effects of digital technologies (Industry 4.0) and green human resource management on GSCM operational practices, so also environmental and economic performances. The researchers carried out their study on manufacturing companies in Colombia. They found a strong support for their assumptions suggesting that the effects of green human resource management and digital technologies on environmental and economic performances become higher when mediated by GSCM operational practices.

Shahzad et al., (2022) in their own part studied the moderating role of BDA on institutional pressures and GSCM to achieve organisational performance in retail points and superstores in Pakistan. The findings of their empirical research showed that the moderating effect of BDA strengthened the impact of GSCM on organisational performance positively.

De Giovanni and Cariola (2021) examined a cross-section of industries in Europe, their study focused on Industry 4.0 powered process innovation strategy implemented by firms on green supply chains and lean practices. The authors found that with investment in Industry 4.0 technologies, firms can achieve higher organisational performance.

Although the cited empirical studies primarily examined the intersection of GSCM and Industry 4.0 in regions like Pakistan, Europe, Indonesia, and Colombia, their findings strongly indicate that integrating digital technologies can substantively elevate sustainability performance outcomes. In the African context where concerns such as infrastructural gaps, underdeveloped regulatory frameworks, and limited resource availability are often especially pronounced this evidence points to a crucial research gap. Indeed, the lack of Africa-specific analyses underscores the need to verify whether the positive correlations observed elsewhere hold equally true for African firms. By focusing on Africa's RESCs, the current research aims to determine how Industry 4.0 might help local organizations surmount known barriers, such as high operational costs and insufficient supplier engagement, and thereby realize the potential benefits of GSCM. This regional emphasis not only addresses a recognized shortcoming in the literature but also contributes practical insights into how digital transformation can foster both sustainability and economic development in African markets.

2.3.6 GSCM-Industry 4.0 combined approach to supply chain problems in the RES

Many researchers have studied the fusion of SCM with different aspects of digital angles and in that process, already terminologies have been developed (Lerman et al., 2022). For instance, the term Smart GSCM was used by Lerman et al., (2022), the fourth industrial revolution of supply chains or supply chain 4.0 (Barata, 2021), Srhir et al. (2022), digitally-enabled sustainable supply chains (Chiappetta Jabbour et al., 2020), Industry 4.0-enabled sustainable supply chain (Mastrocinque et al., 2022), among others. According to Lerman et al., (2022), smart supply chains allow for a real-time sharing of data to achieve faster transactions and decisions and that is made possible by technologies like IoT, BDA, CC, blockchain, AI, among other Industry 4.0 technologies.

Smartness of supply chains and sustainability have been studied disjointedly in recent years and to this end, there is no consensus among scholars with regards to a framework of integrating smart supply chains with sustainability (Demir et al., 2022). Smart SCM or supply chain 4.0 is seen as a process that enables the adoption of Industry 4.0 technologies coupled with environmental and human dimensions to make sustainability at the centre of business development. Indeed, sustainability remains a priority of our time and is expected to remain relevant in smart supply chain agenda Srhir et al. (2022), (Barata, 2021).

Brata (2021) argues that unless their adoption leads to new business models as well as redesigned business services and processes, technologies are pointless. That’s why this research proposes Industry 4.0 powered GSCM to, in a more robust manner, join the efforts made by some researchers to study different aspects like logistics, sustainability and digital transformation in trying to solve some of the managerial challenges and to highlight the need for interdisciplinary approaches to solving business problems by embedding sustainability, digitalisation, resilience and efficiency into supply chain networks (Barata, 2021). It is for this reason that this thesis tries to draw a roadmap for tackling sustainability and SCM related problems in the RES using this multidisciplinary Industry 4.0 powered GSCM approach.

Industry 4.0 enabled GSCM otherwise termed as digitally-enabled GSCM is referred to as Industry 4.0 powered GSCM which operates through new technologies and digital platforms (Chiappetta Jabbour et al., 2020). Embedding Industry 4.0 technologies into GSCM and manufacturing operations can bring about visibility and enable a more efficient tracking of materials especially the so called conflict minerals across supply chains (Ghobakhloo and Fathi, 2021). Additionally, through the digital twinning technology (one of the Industry 4.0 technologies), RE consumers can obtain real-time data and accurate estimation of energy consumption (Mastrocinque et al., 2022).

Furthermore, blockchain is a crucial Industry 4.0 technology that provides transparency and traceability in terms of real-time transactions and product traceability. With the blockchain technology, it is possible for business partners to track and trace the flow of products from manufacturing to consumption stages along the RE supply chains which in turn bring about effectiveness and efficiency along the supply chains (Sahebi et al., 2022).

Chiappetta Jabbour et al., (2020) have found that big data analytics is significantly applicable to sustainable supply chains (i.e. GSCM) in different ways that include encouragement of ethical behaviour by partners allowing high level of traceability and transparency. This may also lead to increased commitment towards green practices, supplier collaboration on implementation of GSCM practices, information sharing enhancement, monitoring of social sustainability issues like child labour, forced labour and slavery.

Finally, the GSCM proposes green practices (as were elaboratively mentioned and categorized in tables 2-1 to 2-7) that are capable of tackling some of the supply chain challenges mentioned in the previous section. GSCM practices like green purchasing represent a model that tackles issues relating to sourcing of minerals. With a blockchain or BDA embedded GSCM green purchasing practice, raw materials or mineral sourcing risks identified in the upstream RESCs can be largely tackled because product traceability and provenance is created along the supply chain.

Another set of supply chain challenges in the RESCs has to do with end-of-life management bottlenecks. GSCM holds a plethora of practices of end-of-life management like remanufacturing and repurposing. Again, Industry 4.0 embedded remanufacturing would work even more efficiently in tackling product end-of-life challenges (Ghobakhloo and Fathi, 2021). From product development stage, GSCM's eco-design or green design encourages a model of design that is environmentally conscious of the product life cycle and end-of-life management to reduce the use of hazardous materials. Industry 4.0 technologies like AI, machine learning and human-robot collaboration would enhance the practice of eco-design (Beltrami et al., 2021). Table 2-8 contains some of the RESC challenges and the respective Industry 4.0-GSCM mix to tackle the issues.

Table 2-8 RESC challenges and industry 4.0-GSCM solutions

Renewable energy supply chain problems	**Industry 4.0-GSCM**	**Reference**
End-of-life management of wind turbines, batteries and solar panels	Industry 4.0 powered eco-design and remanufacturing.	Velenturf (2021) (Al-Sheyadi et al., 2019)
Raw materials and mineral sourcing risks	IoT, BDA and blockchain powered green purchasing.	Velenturf (2021) (Asif et al., 2020a)
Lack of visibility along the supply chain	Industry 4.0 powered collaboration with suppliers, environmental disclosure and green supplier selection	(Mayyas et al., 2019) (Habib et al., 2021)
Wind turbine maintenance issues	Robot powered green operations and maintenance.	Velenturf (2021) (Pinto, 2020) (Chang et al., 2021)
Production planning and scheduling challenge in the renewable hydrogen supply chain	Smart manufacturing powered green manufacturing and green operations.	(Pinto, 2020) (Sgarbossa et al., 2023)

The synergistic relationship between Industry 4.0 technologies and GSCM offers a promising pathway for addressing the RES's persistent supply chain challenges, ranging from upstream raw material risks to downstream end-of-life bottlenecks. As highlighted in Table 2-8, integrating digital tools such as blockchain, IoT, and advanced analytics with green practices can substantially enhance visibility, reduce operational costs, and foster more collaborative, sustainable networks. This digitally enabled approach not only streamlines critical tasks (for instance, maintenance with robots or production planning through smart manufacturing) but also mitigates ethical concerns, such as child labour or environmental violations, by reinforcing traceability and accountability across multiple tiers of the supply chain.

2.3.7 Performance measurement in GSCM literature

Performance measurement has long been recognized as a cornerstone of competitiveness, as firms must continuously evaluate efficiency, effectiveness, and capability to sustain advantage (Sangwa and Sangwan, 2018, Al-Ashaab et al., 2016). Traditionally, in SCM, performance evaluation has focused on operational metrics such as cost reduction, delivery reliability, and customer service (Abdullah et al., 2019). However, the rise of environmental and sustainability imperatives has broadened this scope to include ecological and social indicators, ushering in the paradigm of green supply chain performance measurement (Sangwa and Sangwan, 2018, Mishra et al., 2022). Within the context of GSCM, performance measurement is therefore not only about cost efficiency or customer satisfaction but also about capturing environmental and social externalities associated with supply chain operations. Scholars emphasize that without robust frameworks for assessing these multidimensional outcomes, justifying the adoption of GSCM practices to managers and shareholders becomes difficult (Mishra et al., 2022; Choudhary and Sangwan, 2022).

Over the past two decades, GSCM research has converged on three dominant dimensions of performance: environmental, economic, and operational outcomes (Sahoo and Vijayvargy, 2021). Environmental performance (e.g., reduced emissions, waste minimization) is the most widely studied, but scholars increasingly highlight that it must be complemented by economic performance (both positive and negative) and operational performance (e.g., quality, delivery times, efficiency) to provide a holistic evaluation (Choudhary and Sangwan, 2022, Choudhary et al., 2022).

Some scholars add nuance by disaggregating economic performance into positive economic performance and negative economic performance to account for both gains and losses associated with GSCM adoption (Choudhary and Sangwan, 2022).

1. **Environmental Performance:** Encompasses reduction in emissions, waste minimization, energy efficiency, and compliance with environmental regulations. Numerous studies establish a link between GSCM practices and improved environmental outcomes, often treating this as the primary performance indicator (Acquaye et al., 2018, Zhu et al., 2013, Choi and Hwang, 2015).
2. **Economic Performance:** Positive outcomes include cost savings, revenue growth through green products, and improved market positioning (Choudhary and Sangwan, 2022; Zhu et al., 2013; Choi and Hwang, 2015). Negative outcomes reflect increased short-term costs, high capital requirements, and reduced profitability, particularly during early implementation stages (Luthra et al., 2016, Choudhary et al., 2022).
3. **Operational Performance:** Includes improvements in quality, flexibility, lead times, and supply chain resilience. Although operational outcomes are less studied compared to economic or environmental metrics, they represent an important mechanism linking green practices to competitive advantage (Sahoo and Vijayvargy, 2021; Younis et al., 2020).

However, empirical studies have produced mixed results. Some evidence indicates "win–win" outcomes where GSCM enhances both environmental and economic performance (Zhu et al., 2013; Choi and Hwang, 2015), while other research shows trade-offs, especially in cost-sensitive sectors where initial investments may suppress short-term profitability (Luthra et al., 2014; Liu et al., 2018; Choudhary et al., 2022). Operational performance, though less frequently addressed, has emerged as an important bridging construct, linking green initiatives to competitiveness and supply chain resilience (Sahoo and Vijayvargy, 2021; Aldaas et al., 2022).

GSCM performance measurement is particularly critical because without objective evidence of outcomes across economic, environmental, and operational dimensions, organizations often struggle to justify investments in green initiatives to top management and shareholders (Mishra et al., 2022). Despite the exponential growth of literature on GSCM practices, research explicitly focused on performance assessment frameworks remains comparatively underdeveloped (Choudhary and Sangwan, 2022). This gap is more acute in developing economies, where managerial demand for credible performance metrics is rising but scholarly attention has been limited (Acquaye et al., 2018, Appiah et al., 2022).

Recent works highlight that GSCM performance cannot be divorced from contextual variables such as firm size, strategic orientation, and the role of complementary practices like lean and quality management (Choudhary et al., 2022; Alghababsheh et al., 2022). For instance, lean and quality initiatives were found to enhance environmental and operational performance but reduce economic outcomes in resource-intensive industries (Choudhary et al., 2022). Similarly, the strategic orientation of firms whether cost-leadership or differentiation conditions which GSCM practices translate into measurable financial outcomes (Alghababsheh et al., 2022). This suggests that performance measurement in GSCM is inherently multidimensional, context-contingent, and evolving.

Bibliometric and critical reviews in the extant literature further reinforce that, while the literature on GSCM is growing rapidly, systematic frameworks for evaluating performance remain underdeveloped, particularly in developing economies (Mishra et al., 2017; Choudhary and Sangwan, 2022; Choudhary, 2022). Scholars thus call for integrative models that can simultaneously capture economic, environmental, and social dimensions across diverse industrial contexts.

2.3.8 Sustainability Performance in GSCM literature

Closely related to performance measurement is the construct of sustainability performance, which encompasses the triple bottom line: environmental, economic, and social outcomes (Karmaker et al., 2023a). While sustainability performance has become a central outcome variable in GSCM research (El-Garaihy et al., 2022; Sahoo and Vijayvargy, 2021), there remains little consensus on how it should be operationalized. Many studies emphasize environmental and economic dimensions, but the social pillar of sustainability is frequently neglected (Appiah et al., 2022; Aldaas et al., 2022). This omission is particularly problematic in emerging economy contexts where issues such as labour conditions, community engagement, and energy access are inseparable from sustainable development.

Evidence from cross-sectoral studies suggests that GSCM practices such as eco-design, reverse logistics, and green procurement can contribute to sustainability performance, but their effects vary by context and are mediated by organizational capabilities and external institutional pressures (Trujillo-Gallego et al., 2022; Ghadge et al., 2022). For example, digital technologies and green human resource management practices enhance environmental and economic performance by building environmental capabilities, but their effect depends on complementary resources and dynamic capabilities (Trujillo-Gallego et al., 2022). Similarly, Industry 4.0 tools such as IoT and blockchain are often perceived to directly impact sustainability performance (Ghadge et al., 2022).

Despite these advances, significant gaps remain in sustainability performance measurement. First, empirical studies continue to produce inconsistent findings regarding the link between GSCM and firm-level sustainability performance (Esfahbodi et al., 2023), reflecting variation in contexts, industries, and performance indicators (Alghababsheh et al., 2022; El-Garaihy et al., 2022). Second, most of the evidence comes from developed economies or large industrial sectors (e.g., automotive, electronics, ceramics), with very limited research on RESCs in Africa.

Where studies do exist in African contexts (Appiah et al., 2022), they emphasize environmental outcomes in oil and gas or extractive industries but rarely extend to renewables, leaving a gap in understanding how sustainability performance should be measured in resource-constrained RESCs. Scholars consistently highlight that empirical finding on the GSCM–sustainability performance relationship are inconclusive and contradictory (Alghababsheh et al., 2022). Some studies provide evidence of positive synergies between GSCM adoption and sustainability performance (Fang and Zhang, 2018), while others report insignificant or even negative effects (Green Jr et al., 2012, Abdullah and Yaakub, 2014).

For African RESCs, measuring sustainability performance is particularly critical yet underexplored. Structural challenges such as infrastructure deficits, reliance on imports, and institutional inefficiencies alter how GSCM practices translate into outcomes (Feng et al., 2022). For instance, while eco-design or investment recovery may be effective performance levers in manufacturing, in RESCs the key performance indicators may instead revolve around lifecycle cost of renewable assets, reliability of energy provision, and local employment creation. Current literature does not adequately capture these nuances, underscoring the need for context-specific sustainability performance frameworks tailored to the realities of emerging renewable energy markets.

2.3.9 Conceptual & theoretical gaps (GSCM, I4.0, performance)

This section synthesises the conceptual, theoretical, and empirical gaps emerging from the literature on GSCM practices, Industry 4.0 technologies, and sustainability performance. The focus here is on identifying limitations in existing frameworks, inconsistencies in empirical findings, and underexplored relationships between green and digital supply chain strategies. Contextual and sector-specific gaps relating to RESCs are addressed separately in **Chapter 3**.

Although the literature on GSCM practices has expanded significantly, the domain of performance measurement remains fragmented and underdeveloped (Acquaye et al., 2018). Several key gaps can be highlighted.

1. **Lack of integrative frameworks:** Existing studies often examined environmental, economic, or operational outcomes in isolation rather than through comprehensive frameworks that capture their interdependencies. This has limited the ability to provide a holistic understanding of GSCM's contribution to firm performance (Choudhary and Sangwan, 2019; Choudhary et al., 2022).
2. **Inconsistent empirical evidence:** Research findings on the relationship between GSCM practices and firm performance are contradictory. While some studies report positive synergies, others identify trade-offs or no measurable effects, reflecting inconsistencies in conceptualization, measurement, and context (Green Jr et al., 2012, Ardekani et al., 2023).
3. **Neglect of the social dimension:** Most GSCM performance frameworks focus on environmental and economic outcomes, with limited attention to social indicators such as labour standards, community well-being, and equitable resource distribution. This undermines alignment with the triple bottom line (Appiah et al., 2022).
4. **Contextual underrepresentation:** Most performance-related studies are conducted in developed economies and traditional industrial sectors, while evidence from developing countries, and especially RESCs, is scarce (Mishra et al., 2017; Alghababsheh et al., 2022).
5. **Lack of context-sensitive metrics for African RESCs:** Sector-specific performance indicators for RE such as lifecycle cost efficiency, energy access, or end-of-life management of renewable assets remain underexplored. This gap is particularly pronounced in Africa, where infrastructural constraints and institutional voids shape how performance should be defined and measured (Appiah et al., 2022, Labaran and Masood, 2023, Labaran and Masood, 2025).

Together, these gaps underscore the need for more comprehensive and context-sensitive approaches to performance measurement in GSCM, particularly in RESCs across Africa.

2.4 Summary of Literature Gaps and Link to Research Questions

The preceding review of the literature has examined GSCM practices, Industry 4.0 technologies, and sustainability performance across diverse industrial and supply chain contexts. While this body of research provides valuable insights into the potential of green and digital strategies to improve supply chain outcomes, it also reveals a few conceptual, empirical, and contextual gaps that motivate the present study.

First, the literature on supply chain sustainability and GSCM practices indicates that organisations face persistent environmental and operational challenges that are highly context dependent. Although these challenges have been widely explored in manufacturing and other traditional sectors, relatively limited attention has been paid to the specific sustainability and SCM challenges characterising RESCs. Particularly, issues related to material criticality, end-of-life management, supply chain fragmentation, and long asset lifecycles remain insufficiently examined. This gap provides the basis for **Research Question 1**, which seeks to identify and understand the sustainability and SCM challenges affecting RESCs, with relevance to developing economy contexts.

Second, a growing stream of literature highlights the role of Industry 4.0 technologies in enhancing supply chain transparency, coordination, and efficiency. However, existing studies often examine digital technologies independently of environmental management practices, offering limited insight into how Industry 4.0 technologies support or enable the adoption of GSCM practices. Empirical evidence on the mechanisms through which digital technologies facilitate green supply chain initiatives remains fragmented and sector biased. This limitation motivates **Research**

Question 2, which investigates the role of Industry 4.0 technologies in enabling the adoption of GSCM practices.

Third, although prior research has explored the performance implications of GSCM practices and digital technologies, findings remain inconsistent, and integrated empirical models are scarce. Limited attention has been given to examining the combined effects of Industry 4.0 technologies and GSCM practices on sustainability performance outcomes. Moreover, most existing studies are grounded in developed economy contexts, raising questions about the generalisability of their findings to RESCs in Africa. These gaps underpin **Research Question 3**, which examines how the integration of Industry 4.0 technologies and GSCM practices influences sustainability performance.

Taken together, the gaps identified in the literature underscore the need for a study that simultaneously considers sustainability challenges, digital technologies, and green supply chain practices within the context of RESCs. By addressing these gaps, the present research aims to contribute to a more integrated understanding of how Industry 4.0-enabled GSCM can support sustainable supply chain development, particularly in African contexts.

2.5 Chapter summary

The chapter has provided an encapsulating review of key concepts, practices, and emerging trends associated with GSCM and Industry 4.0 technologies. Beginning with an outline of the review protocol, the chapter clarified how research articles were identified and screened across multiple databases. In doing so, it highlighted the primary industries covered in extant GSCM literature, with an emphasis on the fields most frequently studied (e.g., manufacturing, automotive) and the relative underrepresentation of others, such as RES. A detailed discussion of GSCM practices ranging from procurement and product design to logistics, waste management, and manufacturing then underscored how environmental considerations can be woven into various stages of the supply chain.

Subsequent sections examined drivers of GSCM adoption, such as customer pressure, regulatory demands, and cost savings, as well as barriers that inhibit more widespread implementation, including high financial outlays, limited supplier engagement, and uncertain policy frameworks. Tying into these barriers and drivers, the chapter illustrated how Industry 4.0 technologies offer promising avenues for the enhancement of efficiency, traceability, and decision-making within supply chains. Empirical evidence from multiple contexts revealed that when GSCM and Industry 4.0 approaches are integrated, organizations often achieve not only environmental gains but also operational and economic benefits.

By mapping both the opportunities and persistent obstacles in GSCM, this chapter provides a foundation for understanding the ongoing evolution of green practices in supply chains, especially under conditions where digital transformation is accelerating. However, a recurring theme in extant literature is arguably paucity of research focused on the RES, particularly in developing economies, where infrastructural and policy challenges may diverge significantly from more studied contexts. This gap highlights the need to explore how Industry 4.0–enabled GSCM might tackle sustainability and SCM issues specific to RES, an area poised for rapid expansion yet fraught with structural complexities.

To bridge this gap, the study undertook two complementary systematic literature reviews. The first review (presented in this chapter) synthesised over 200 peer-reviewed studies on GSCM and Industry 4.0 across diverse sectors, revealing that while manufacturing, construction, and traditional energy industries have been extensively analysed, the RES remains significantly underrepresented. Limited studies in this body of literature explicitly focused on RESCs, underscoring the need for deeper sectoral review of the extant literature. The second review (presented in the upcoming Chapter 3) therefore adopted a sector-specific lens, systematically analysing over 100 high-quality sources to map sustainability and SCM challenges in RE contexts, with particular emphasis on African RESCs. Together, these reviews ensured both conceptual breadth (by engaging state-of-the-art theoretical debates) and contextual depth (by grounding the study in the contexts of RESCs and Africa).

With these insights in mind, the next chapter conducts a systematic literature review on sustainability and SCM issues within the RES. Building on the drivers, barriers, and digital solutions outlined here, it delves deeper into sector-specific challenges and the role of policy in shaping green transitions. This sector-focused analysis aims to illuminate how RES supply chains can leverage GSCM and Industry 4.0 to accelerate the shift toward cleaner, more resilient energy systems.

3 Sustainability and SCM challenges in RES

3.1 Chapter Introduction

This chapter investigates the critical sustainability and SCM challenges facing the RES, alongside the potential of integrating GSCM practices with Industry 4.0 technologies to address these issues. Drawing on a systematic literature review encompassing over 100 high-quality sources, the chapter identifies factors such as closed-loop recycling, AM, design for durability, and supply chain diversification as key drivers in overcoming current constraints in the RESCs.

These drivers underscore the necessity of strategically merging GSCM principles with advanced digital solutions to facilitate systemic change in the sector. For instance, blockchain can bolster supply chain transparency, AI can enhance demand forecasting, and the IoT can support predictive maintenance. Taken collectively, these Industry 4.0 tools provide a robust framework for improving operational efficiency, reducing environmental impacts, and fostering collaboration among stakeholders.

Ultimately, this chapter demonstrates how informed, technology-enabled GSCM practices can help the RES substantially advance global decarbonization and sustainability objectives. It emphasizes the importance of coordinated efforts among industry players, policymakers, and technology providers in establishing the supportive conditions essential for sustainable innovation and long-term sectoral resilience.

This chapter builds on the conceptual insights developed in Chapter 2 by focusing specifically on RESCs. While Chapter 2 reviewed the broader literature on GSCM practices, Industry 4.0 technologies, and sustainability performance across diverse sectors, the present chapter narrows the analytical lens to examine the distinctive characteristics and challenges of RESCs. In doing so, the chapter provides the contextual foundation necessary for understanding why generic supply chain and sustainability approaches may be insufficient when applied to the RES.

More specifically, this chapter addresses **Research Question 1** by synthesising the literature on sustainability and SCM challenges associated with RE systems, including issues related to material sourcing, supply chain fragmentation, long asset lifecycles, and end-of-life management. By examining these challenges in both global and developing-economy contexts, the chapter highlights the conditions under which RESCs operate and clarifies the contextual factors that shape sustainability outcomes. This contextual analysis complements the conceptual review presented in Chapter 2 and prepares the ground for subsequent examination of how GSCM practices and Industry 4.0 technologies can be integrated to address these challenges in later chapters.

3.2 Systematic Literature Review 2 Protocol

A systematic literature review was conducted based on the seven-step methodology adopted from Egger and Masood (2020). This was selected due to its robustness and rigour in terms of filtering research resources so also its elaboratively comprehensive nature. Based on the literature, several sustainability and SCM challenges within the RES were gathered, so also Industry 4.0 and GSCM approaches to tackling these issues. Figure 3-1 depicts the steps involved in the literature review procedure.

Step 1 of the review aims to thoroughly examine the RES by exploring sustainability and SCM issues and challenges alongside solutions to these issues particularly Industry 4.0 and GSCM solutions reported by researchers. The following research question was coined to reflect the aim of this study:

"What approaches, combining GSCM practices and Industry 4.0 technologies, can effectively mitigate both sustainability and SCM challenges within the RES?"

Web of Science and Scopus were the databases identified for search purpose, and they were particularly chosen because of their wide coverage of articles. A literature matrix was created using Microsoft excel while Endnote was used as the reference management software because of its versatility and unique features.

Step 2 (Search)

Some search strings representative of the research questions this review is aiming to answer were carefully designed after a prior literature search. Each of the three strings mentioned below were searched independently in each of the two databases identified above.

1. (Renewable energy AND supply chains) OR (renewable energy AND green supply chains)
2. Renewable energy AND supply chain AND (Industry 4.0)
3. (Sustainability) AND (supply chain) AND (issues OR challenges) AND (solar OR wind) AND (digital technologies or Industry 4.0)
4. (Renewable energy AND supply chains) AND (Africa OR "Sub-Saharan Africa")
5. (Renewable energy AND green supply chains) AND (Africa OR "Sub-Saharan Africa")
6. (Sustainability) AND (supply chain) AND (Africa OR "Sub-Saharan Africa") AND (Industry 4.0 OR digital technologies)

In addition to the general search strings designed to capture the global literature on GSCM, Industry 4.0, and RESCs, a supplementary set of search strings incorporating the terms “Africa” and “Sub-Saharan Africa” was applied. This targeted search was introduced to ensure the inclusion of region-specific empirical studies relevant to the contextual focus of the research. By adopting this two-tiered search strategy, the review maintains broad theoretical coverage while systematically capturing evidence that reflects the unique institutional, infrastructural, and sustainability challenges shaping RESCs in African contexts.

The search was conducted on 06/03/2023, 11/10/2023, 21/08/2024 and 18/12/2025. The search was carried out to look for relevant results that contain the elements of the search strings in their titles, abstracts and keywords. The exclusion criteria applied at this stage was:

- Not in English
- Only journal articles

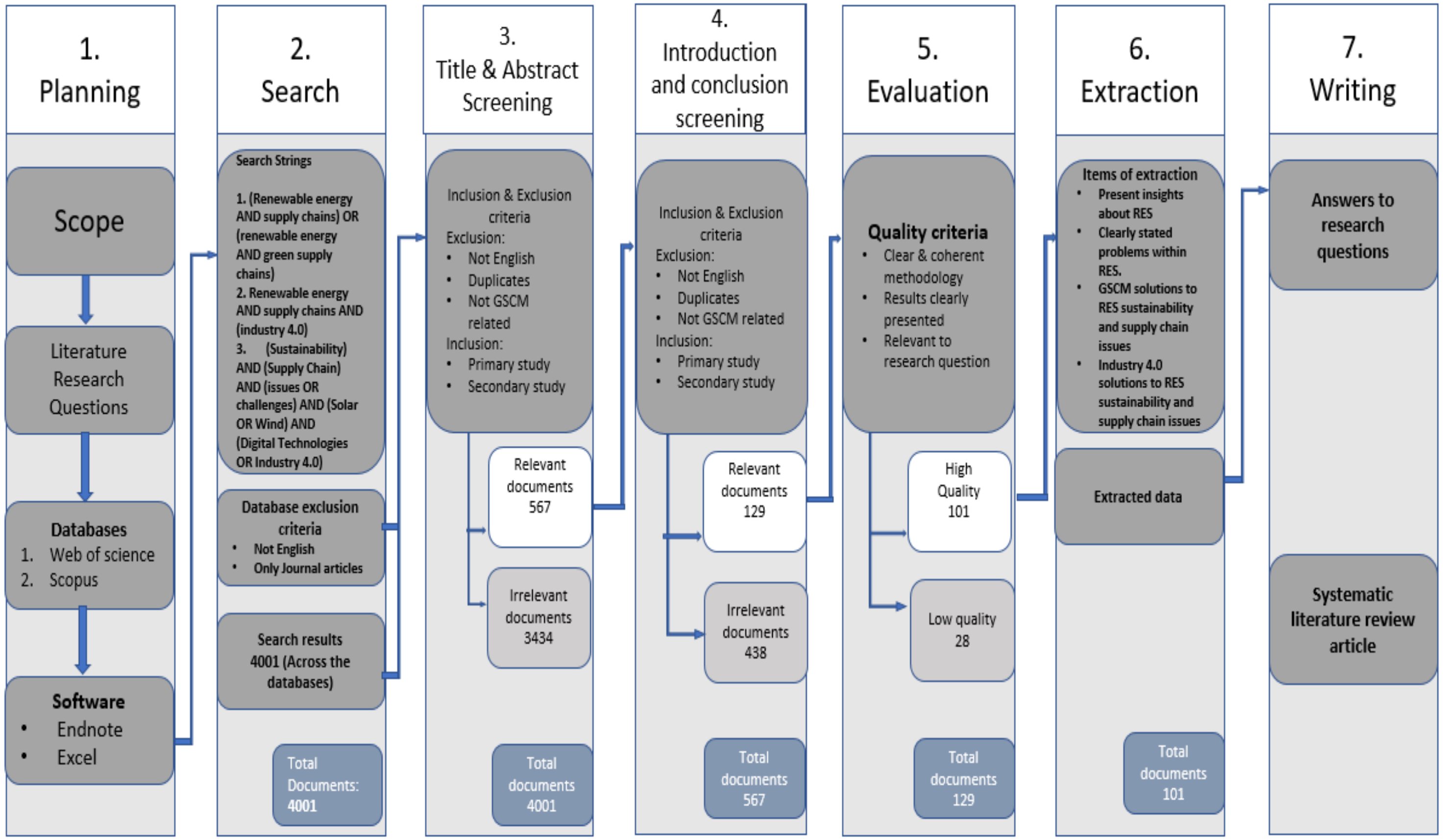

Figure 3-1 Process of systematic literature review 2.

Step 1 (Planning)

Step 3 (Title and abstract screening)

At this stage, the results were imported into the reference management software (Endnote) where duplicates were removed, and the eligibility of papers was decided by screening and glancing through their titles and abstracts. At this stage, inclusion and exclusion criteria were set to include primary and secondary studies and exclude resources not written in English or not GSCM related or duplicates. The relevant articles obtained at this stage amounted to 567 articles while the irrelevant articles that were removed amounted to 3434 articles.

Step 4 (Introduction and conclusion screening)

A more in-depth reading (of introduction and conclusion sections) was done at this stage to reliably decide the suitability of resources for the systematic literature review. Out of the 567 articles screened in this stage, 129 were relevant, while 438 were not, therefore removed. A comprehensive breakdown of duplicates and irrelevant papers is given in Figures 1.

Step 5 (Evaluation)

More rigorous reading was done here to finally decide on the quality of resources to work with. The following quality criteria were set:

-Clarity of methodology

-Results are discussed succinctly

-The resource is relevant to the research question.

Out of the 129 articles examined at this stage, 28 articles were low quality based on the above quality criteria, while 101 were found to be high quality and therefore used for this systematic literature review exercise.

Step 6 (Extraction)

A thorough reading was carried out to extract answers to the identified research questions. Microsoft excel was used to generate a literature matrix that served as the repository of all relevant data extracted from the resources used. Through this process, insights into RES including sustainability and SCM issues in RES, Industry 4.0 and GSCM solutions to these challenges were gathered.

3.3 Findings of the review (2)

3.3.1 SCM and sustainability issues in RES

Sustainability challenges in the RES frequently revolve around resource-intensive production methods, ethical concerns, and insufficient end-of-life infrastructures. Conflict mineral mining for tantalum, tin, tungsten, and gold has been linked to human rights violations and conflict financing (Huber and Steininger, 2022, Rachidi et al., 2021). Additionally, lithium-ion battery production has been cited for aggravating environmental impacts particularly local water depletion and concerns over cobalt, lithium, and graphite depletion (Kramarz et al., 2021, Ren et al., 2021, Rufino et al., 2022). Wind turbine construction, meanwhile, demands large volumes of cement, a substantial contributor to greenhouse gas emissions (Kramarz et al., 2021).

Recycling mineral components remains technically and economically challenging. While in 2018 only 29% of the cobalt and 22% of the tin consumed were recovered (Huber and Steininger, 2022, Ali et al., 2022b), electrical and electronic materials from wind turbines achieve just a 50% recycling rate, and other materials polyvinyl chloride, fiberglass, lubricants, paints, adhesives commonly end up in landfills (Mendoza et al., 2022). Failing to adopt circular economy principles across the lifecycle of RE components jeopardizes the sector's sustainability (Duran et al., 2022). Compounding matters, many RE businesses are both technology- and capital-intensive, which raises entry barriers (Mastrocinque et al., 2022). In some instances, government policies and regulations, while aiming to spur market demand, inadvertently inflate bottlenecks or deter manufacturers wary of uncertain market conditions (Xiong et al., 2022, Mastrocinque et al., 2022).

Within solar energy supply chains, PV glass production exemplifies these challenges due to its sensitivity to impurities (Mirletz et al., 2022). Moreover, RE supply chains rely on globally sourced, often disruption-prone raw materials (Kramarz et al., 2021, Xiong et al., 2022). Researchers also note insufficient information exchange among solar industry actors (Boukhatmi et al., 2023) and the wind turbine sector's capital intensity, rendering installations complex (Keivanpour et al., 2020). Solar PV cells, for instance, require more raw materials per unit energy than other renewable sources such as wind or hydropower (Ali et al., 2022a). As a result, failing to adopt circular principles throughout the entire lifecycle of solar panels and similar components could undermine the long-term viability of RES (Huber and Steininger, 2022).

High costs and limited recycling technologies compound these issues. For example, discarding a solar panel in a landfill may cost as little as $1–2, whereas recycling it can run $20–30 (Duran et al., 2022). The recycling supply chains for minerals, especially cobalt, remain insufficiently regulated and lack transparency. Instances of child labour and hazardous working conditions in battery recycling have been reported in nations such as China, Bangladesh, and India (Huber and Steininger, 2022). Meanwhile, global decarbonization targets intensify the demand for RE installations particularly in large markets like the U.S., where PV capacity expansions could yield up to 97 million metric tonnes of additional raw material demands by 2050, accompanied by an estimated 8 million metric tonnes of lifecycle waste (Mirletz et al., 2022). Balancing these ambitious decarbonization goals with the raw material and waste management burdens underscores the sector's reliance on robust circular economy frameworks (Duran et al., 2022). However, the absence of closed-loop recycling solutions for many PV components and inadequate collaboration among key actors (Winkler et al., 2022) highlight persistent gaps in sustainable RESC governance. Table 3-1 encapsulates SC challenges obtained from the review of literature and the corresponding authors that suggested them.

Table 3-1 SCM issues in RES

Challenge	Author
High entry barriers in PV due to technology and capital needs	(Mastrocinque *et al.,* 2020, Mason-Jones *et al.,* 2022).
Demand surges unmet by manufacturing unwilling to enter renewable supply chains	(Lin *et al.,* 2022).
Imbalance in real-time demand and supply in microgrids	(Mirletz *et al.,* 2022).
PV glass supply chain issues due to purity sensitivity	(Duran *et al.,* 2022).
Increasing PV module waste, projected to reach 78 million metric tonnes by 2050	(Ali *et al.,* 2022b).
Limited recycling infrastructure with higher recycling vs. landfill costs	(Winkler *et al.,* 2022).
High material requirements for green energy infrastructure	(Mirletz et al., 2022)
Collaboration gaps in offshore wind turbine decommissioning	(Deberdt and Billon, 2021).
Traceability challenges in complex mineral supply chains	(Huber and Steininger, 2022).
Dependency on geographically concentrated raw materials, leading to potential disruptions	(Xiong *et al.,* 2022, Mayyas *et al.,* 2019).
Government regulations impacting RE markets and supply chains	(Ren *et al.,* 2021).

Furthermore, there are numerous sustainability issues in the upstream activities of RES, depletion of local water sources in mining locations caused by lithium extraction from brine and mineral deposits, exposure of human populations to an array of health-related issues that include damage to kidneys, thyroid and nervous system (Dallas et al., 2021, Mayyas et al., 2019). Also, some critical metals used in lithium ion battery production are extracted through processes that are highly carbon-intensive (Kramarz et al., 2021). According to Mendoza *et al.*, (2022), by 2028, sustainable waste management of wind turbine blades is projected to be a critical global problem, as composite blade waste generation between 2020 to 2030 is forecast to reach 570 MT in EU alone, while other wind turbine constituents, electronic/electric components get recycled at the rate of only 50%, other materials such as lubricants, fibreglass, paints and adhesives eventually end up at landfills. In solar segment of the RES, PV waste in Europe is projected to grow from fifty thousand tonnes in 2020 to about one and a half million tonnes in 2030 (Boukhatmi et al., 2023).

Importantly, for the enablement of high-quality recycling and component reuse, there is need for sustainable decommissioning solutions, and these are underdeveloped, plans for decommissioning are often vague when it comes to resource management methods and are often lacking in providing evidence that materials could and will be recovered sustainably (Velenturf, 2021). Wind turbine composite materials are difficult to be recycled and that poses a great environmental challenge. By 2050, about 42 million tonnes of rotor blade waste would require to be recycled yearly worldwide (Martinez-Marquez et al., 2022). According to Delaney et al. (2023), currently, there are no sustainable solutions regarding how to manage fibre-reinforced polymer composite of wind blades which are non-biodegradable. Table 3-2 contains sustainability challenges based on the literature that are mostly related to resource/raw material demand and issues with end-of-life management of RE modules.

Table 3-2 Sustainability issues in RES

Challenge	Author
Challenges in sustainable decision-making due to PV supply chain complexity	(Mastrocinque *et al.,* 2020).
Waste treatment concerns in PV and wind sectors	(Rachidi *et al.,* 2021).
Child labour reliance in cobalt mining and e-waste disposal	(Rufino *et al.,* 2022).
Environmental impacts from lithium-ion battery production	(Mirletz *et al.,* 2022, Choudhary and Sangwan, 2022).
Rising PV installations increasing supply chain strain	(Winkler *et al.,* 2022).
Raw material depletion risks, notably cobalt, lithium, and graphite.	(Huber and Steininger, 2022, Ren *et al.,* 2021).
Decommissioning costs for offshore wind turbines projected high	(Kramarz *et al.,* 2021, Maquera *et al.,* 2022).
Conflict mineral sourcing issues tied to human rights abuses	(Boukhatmi *et al.,* 2023, Velenturf, 2021).
Low collection rates and infrastructure for recyclable materials	(Martinez-Marquez *et al.,* 2022, Delaney *et al.,* 2023).
Environmental damage from extraction processes (e.g., lithium mining)	(Mirletz *et al.,* 2022, Duran *et al.,* 2022).

In summary, the RES faces a multifaceted array of sustainability and supply chain challenges. Concerns range from unethical sourcing of conflict minerals and lithium-ion battery impacts to the significant resource demands of wind turbine construction and the inadequate recycling systems that hamper circular economy principles. These dynamics create both operational and ethical dilemmas, as enterprises must balance the immense raw material requirements for global decarbonization with pressing societal and environmental responsibilities. Limited infrastructure, high capital intensity, and an urgent need for supportive policy frameworks further complicate the pathways to sustainable growth in the sector.

Against this backdrop, GSCM emerges as a promising framework for addressing core issues such as raw material sourcing, waste management, and logistical inefficiencies. The next section explores how GSCM principles, spanning eco-design and green purchasing to collaborative strategies with suppliers, can be leveraged to tackle these sustainability and SCM hurdles in the RES. By outlining a broad spectrum of green practices, it illuminates the potential for driving long-term resilience and environmental responsibility throughout RE value chains.

The sustainability and supply chain challenges identified in this section highlight the distinctive operational and environmental pressures characterising RESCs. These challenges, including material sourcing constraints, supply chain fragmentation, long asset lifecycles, and end-of-life management issues, underscore the need for targeted analytical attention beyond generic supply chain models. Accordingly, the insights synthesised here directly inform **Research Question 1**, which seeks to examine the sustainability and SCM challenges affecting RESCs, with relevance to developing-economy contexts.

3.3.2 GSCM approach to tackling sustainability and SCM challenges

Strengthening the durability and extending the lifetime of RE components is pivotal for reducing both waste and resource consumption. For instance, superior blade coatings and the use of lighter materials in wind turbines can diminish cement requirements and associated greenhouse gas emissions (Velenturf, 2021). Moreover, designing for durability fosters reuse, refurbishment, retrofitting, remanufacturing, and repurposing to preserve valuable resources towards end-of-life stage (Maquera et al., 2022). Recycling, effective disassembly, and material recovery, are equally important, ensuring that resource loops within the RE infrastructure remain as closed as possible.

Diversifying RE supply chains to incorporate upstream recycling efforts emerges as a priority (Ali et al., 2022c, Gawusu et al., 2022). For solar PV, prolonging module lifetimes from 25 to 30 years could conserve 6.7–24% of cumulative metals (Ren et al., 2021). Addressing PV waste recycling also demands regulatory action alongside large-scale investments in logistics infrastructure and technological innovation

(Duran et al., 2022). By promoting closed-loop recycling, both material demand and landfill disposal can be minimized (Mirletz et al., 2022).

In the wind turbine context, planning for recycling, remanufacturing, and sustainable disposal is crucial due to the growing volume of wind turbine waste. Blades, for example, can be repurposed for infrastructure applications (Duran et al., 2022). Battery recycling is similarly critical, as it captures valuable components from end-of-life lithium-ion cells, thereby reducing virgin material demand (Rufino et al., 2022). Reusing electric vehicle batteries such as integrating second-life units into charging stations further optimizes resources and mitigates raw material extraction.

Closed-loop strategies, coupled with lifetime extension for components like PV modules, serve as robust mechanisms for diverting waste from landfills and lowering the consumption of new materials (Mirletz et al., 2022). Yet, such initiatives hinge on policy support and substantial investment in recycling infrastructure (Duran et al., 2022), as well as supply chain diversification including upstream collaboration during mining and midstream processing (Ali et al., 2022b). Downstream, supply chain coordination is vital to navigate collective uncertainties, especially for decommissioning complex installations like offshore wind turbines, where no single entity can manage the logistics alone (Winkler et al., 2022).

Within mineral supply chains, adopting ethical sourcing standards and extending regulations beyond the scope of conflict minerals are crucial steps to mitigate both social and environmental harms (Huber and Steininger, 2022). Processes like design for durability, reuse, refurbishment, and efficient disassembly not only close resource loops but also maximize the value extracted from RE components (Mendoza et al., 2022). In the offshore wind subsector, improved blade coatings, lighter materials, and the adoption of alternative resins help reduce negative environmental impacts (Velenturf, 2021). Additionally, finding substitutes for SF_6 in switchgear and reducing reliance on critical raw materials can further address sustainability concerns. Table 3-3 summarizes these GSCM approaches, demonstrating how targeted actions ranging from remanufacturing and battery recycling to collaboration and ethical standards in decommissioning can effectively mitigate SCM and sustainability challenges in the RES.

Table 3-3 GSCM approach to tackling issues in RES

Challenge	Author
Planning for recycling, remanufacturing, and disposal to manage wind turbine waste	(Rufino *et al.,* 2022).
Repurposing wind turbine blades for construction and furniture	(Mirletz *et al.,* 2022, Duran *et al.,* 2022).
Battery recycling to reduce raw material demand	(Ali *et al.,* 2022b, Ren *et al.,* 2021).
Second-life applications for electric vehicle batteries (e.g., charging infrastructure)	(Mendoza *et al.,* 2022, Velenturf, 2021).
Closed-loop recycling and lifespan extension to reduce material demands	(Winkler *et al.,* 2022, Huber and Steininger, 2022).
Investments in logistics and recycling infrastructure for PV panels	(Ren *et al.,* 2021, Mendoza *et al.,* 2022).
Supply chain diversification to include upstream recycling activities	(Winkler *et al.,* 2022, Kramarz *et al.,* 2021).
Extending PV lifetimes to conserve metal resources	(Huber and Steininger, 2022).
Design for durability and reuse, with strategies like retrofitting and repurposing	(Mendoza et al., 2022)
Collaboration and ethical standards in offshore wind decommissioning	(Xiong *et al.,* 2022, Mayyas *et al.,* 2019).

These GSCM-focused strategies underscore the importance of durability, efficient resource loops, and collaborative networks as cornerstones for addressing sustainability and SCM challenges in the RES. By adopting GSCM thinking, firms can reduce their reliance on scarce raw materials and mitigate the environmental impacts associated with large-scale renewable infrastructure expansion. However, such progress hinges on supportive policies, strategic supplier engagement, and substantial infrastructural investments.

Building upon these foundational GSCM practices, Industry 4.0 technologies hold significant promise for streamlining operations, enhancing traceability, and fostering data-driven decision-making within RESCs. The next section delves into how these digital tools can complement and amplify GSCM efforts, offering a pathway for more resilient and transparent supply chains that align with global sustainability targets.

3.3.3 Industry 4.0 Approach to tackling sustainability and SCM challenges

Industry 4.0 technologies increasingly show promise for addressing the complex sustainability and SCM challenges prevalent in the RES. Blockchain, for instance, can track materials in lithium-ion batteries, enabling ethical sourcing and real-time visibility over global mineral supply chains (Rufino et al., 2022, Tripathy et al., 2023). By combining blockchain with geolocation, organizations can further enhance transparency and sustainability in raw material extraction (Deberdt and Billon, 2021). Within energy markets, decentralized trading platforms powered by blockchain facilitate peer-to-peer (prosumer) energy exchanges and local energy flexibility markets (Antal et al., 2021, Lin, 2022). Blockchain-based solutions also improve billing systems and carbon pricing initiatives, helping to optimize demand control through secure, transparent transactions (Rufino et al., 2022). Meanwhile, AI plays a significant role in operational optimization and prediction of system uncertainties in smart grids, offering improved demand-side management, reduced power losses, and better allocation of generation resources (Hua et al., 2022, Wang et al., 2021).

The IoT complements these innovations by offering real-time data on energy generation and consumption, supporting efficient storage solutions and load management across RE infrastructures (Juszczyk and Shahzad, 2022). BDA, in particular, addresses challenges related to demand forecasting, smart-grid optimization, and overall system performance by processing high volumes of consumer, geographical, and weather data (Kava et al., 2021, Ren et al., 2021). These analytical capabilities also promote environmental data sharing, reinforcing stakeholder awareness of greenhouse gas emissions (Ali et al., 2021, Waseem et al., 2023).

Additional Industry 4.0 applications range from machine learning for predictive maintenance (Liu et al., 2023b, Xu et al., 2023) to AM that lessens dependence on certain raw materials (Mendoza et al., 2022, Waseem et al., 2023). Automated tools and robotics likewise foster higher safety standards, enhanced production rates, and reduced downtime (Onifade et al., 2023), while smart mining with IoT and blockchain-based supplier assessment systems can secure ethical sourcing (Onifade et al., 2023, Xu et al., 2023). In logistics, 5G-enabled solutions coupled with cyber-augmented collaboration transform traditional warehousing and distribution networks, further streamlining RESCs (Aravindaraj and Rajan Chinna, 2022). At end of useful life of RE components, smart remanufacturing or digitally enabled remanufacturing which is data-driven remanufacturing system is proposed by Okorie et al. (2020) for enhanced end-of-life management. Additionally, Numerous energy sector applications could be achieved through IoT in the areas of energy supply, RE integration, power generation, load demand management, transmission and distribution, among others (Ahmad and Zhang, 2021). Table 3-4 highlights various Industry 4.0 solutions and the specific SCM or sustainability hurdles they aim to resolve in the RES. By integrating these digital approaches, firms can pursue greater efficiency, transparency, and resilience, ultimately reinforcing their environmental objectives.

Table 3-4 Industry 4.0 approach to tackling issues in RES

Challenge	**Author**
Blockchain for decentralized energy trading and transparency	(Hua *et al.,* 2022, Almutairi *et al.,* 2023).
AI for operational optimization and prediction in smart grids	(Wang *et al.,* 2021, Antal *et al.,* 2021).
Blockchain-supported carbon pricing to incentivize decarbonization	(Zhang *et al.,* 2022).

Peer-to-peer energy trading enabled by blockchain and IoT	(Lin *et al.,* 2022, Wu *et al.,* 2022).
Battery material tracking through blockchain for sustainability	(Rufino *et al.,* 2022, Tripathy *et al.,* 2023)
Real-time transparency and secure transactions in SCs	(Almutairi *et al.,* 2023, Juszczyk and Shahzad, 2022).
BDA for demand-side management and smart-grid optimization	(Ren *et al.,* 2021).
AM to reduce raw material dependency	(Mendoza *et al.,* 2022, Waseem *et al.,* 2023).
Machine learning for predictive maintenance and reduced operational downtime	(Liu *et al.,* 2023, Xu *et al.,* 2023).
IoT for energy management and RE integration	(Okorie *et al.,* 2020).

By tackling issues such as ethical mineral sourcing, power system optimization, and demand forecasting, Industry 4.0 solutions show considerable potential for alleviating many of the barriers previously described in the RESC context. Blockchain-based traceability can mitigate supplier non-compliance, while AI-driven analytics enhance grid resilience and efficiency. Likewise, AM and automation reduce material dependency and operational downtime, reinforcing circular economy aims within RE infrastructures.

3.4 Comparative Perspectives on RESCs: Africa and Other Regions

RESCs have been increasingly examined in developed and emerging economies outside Africa, particularly within contexts characterised by relatively stable institutional environments and established industrial ecosystems. Much of the existing sustainability and supply chain literature has focused on manufacturing-intensive sectors and regions with mature regulatory frameworks, advanced logistics infrastructure, and greater access to technological and financial resources (Bhatia and Gangwani, 2021). In these settings, RESCs tend to benefit from stronger supplier coordination, more developed recycling and decommissioning systems, and clearer regulatory oversight governing environmental and operational performance (Winkler et al., 2022; Mason-Jones et al., 2022).

In contrast, RESCs operating in African contexts exhibit markedly different structural and operational characteristics. Many African RE projects rely heavily on imported components, resulting in extended and fragmented supply chains with limited upstream control and heightened exposure to supply disruptions (Aliyu et al., 2018; Duran et al., 2022). Local manufacturing, recycling, and end-of-life management infrastructure for RE assets remains underdeveloped, increasing lifecycle costs and environmental risks associated with decommissioning activities (Rufino et al., 2022; Adenle, 2020). These challenges are further compounded by infrastructural limitations, weak regulatory enforcement, and constrained access to finance, which collectively shape how supply chain sustainability initiatives are implemented (Ogunlela, 2018; Tumpa et al., 2019).

These contextual differences have important implications for the adoption of GSCM practices and Industry 4.0 technologies. In developed regions, digital technologies are often deployed to optimise already established supply chain processes, enhance operational efficiency, and support compliance with environmental regulations. By contrast, in African RESCs, digital technologies may be required to address more fundamental challenges, such as improving transparency in material sourcing, strengthening traceability across fragmented networks, and compensating for institutional and infrastructural gaps (Deberdt and Billon, 2021; Nkrumah et al., 2021). As a result, the mechanisms through which Industry 4.0 technologies support GSCM practices, and ultimately influence sustainability performance, are likely to differ significantly between African and non-African contexts.

Despite these pronounced differences, much of the empirical literature on RESCs continues to draw predominantly on evidence from developed economies, implicitly assuming that observed relationships between sustainability practices, digital technologies, and performance outcomes are transferable across regions (Bhatia and Gangwani, 2021). This assumption remains largely untested in African RESCs, where contextual constraints fundamentally shape organisational capabilities and strategic choices (Aliyu et al., 2018; Adenle, 2020). By explicitly contrasting African and non-African RESCs, this study positions Africa as a theoretically informative context for examining the boundary conditions under which the integration of GSCM practices and Industry 4.0 technologies contributes to sustainability outcomes.

3.5 Sustainability and SCM challenges in African RES

Africa possesses abundant RE resources that could address the continent's persistent energy shortfalls. Despite this endowment, over 600 million Africans don't have access to electricity in the sub-Saharan Africa, with rural communities disproportionately affected (Bugaje, 2006, Adenle, 2020). This severe energy gap hinders socio-economic progress, compromising growth in education, healthcare, and other critical sectors (Ibrahim et al., 2021). Transitioning to RE solutions can help alleviate these challenges, but existing structural and logistical hurdles must first be resolved.

Fossil fuels still dominate Africa's energy mix at over 80%, contributing minimally to global carbon emissions yet leaving the region vulnerable to climate change impacts, such as desertification and erratic rainfall (Mutezo and Mulopo, 2021). Overcoming the high cost of RE technologies and scarce local expertise remains crucial for scaling up sustainable energy production. An additional barrier is the dependence on imported solar and wind modules, which inflates costs and exposes supply chains to exchange rate volatility and global market shifts (Bugaje, 2006). Inadequate infrastructure and logistical inefficiencies ranging from limited transportation networks to insufficient storage further elevate operational and distribution costs (Ibrahim et al., 2021).

A shortage of skilled labour and underdeveloped institutional frameworks also impede Africa's RES (Maisiri et al., 2021). Many projects face high initial capital demands, compounded by limited access to finance and elevated transaction fees, especially in remote regions (Mutezo and Mulopo, 2021). Weak or inconsistent government policies, combined with lax enforcement, deter private investment and curtail efforts to scale renewable solutions (Ouedraogo, 2019). Similarly, corruption and bureaucratic delays hamper targeted subsidies and support mechanisms, resulting in reduced market impact (Amir and Khan, 2022).

Addressing sustainability and SCM challenges in Africa's RES demands an integrated approach: policymakers should cultivate supportive regulations, while industry and international partners can help fill resource and knowledge gaps. Upgrading local manufacturing capacities, refining infrastructure, and leveraging digital innovations can improve supply chain resilience and efficiency. The next section covers adoption level of GSCM practices and Industry 4.0 technologies in the African RES contexts.

3.6 GSCM and Industry 4.0 technologies adoption in African RES

The merger of GSCM practices and Industry 4.0 technologies holds promise for overcoming the RES's constraints in Africa (Onifade et al., 2023). However, adoption is still limited, stifled by high costs, inadequate infrastructure, and unstable electricity supplies (Ukoba et al., 2023). Many firms lack the requisite technical capabilities, while SMEs which dominate the African RE landscape are particularly challenged in securing financing or governmental backing (Ugwu et al., 2022).

Despite these barriers, emerging success stories illustrate the potential of digital solutions to boost sustainability. Blockchain-based systems, for instance, can validate material sourcing and facilitate peer-to-peer energy trading, enhancing transparency and cutting transaction inefficiencies (Bhagwan and Evans, 2023). Likewise, AI-driven analytics help forecast and optimize energy generation in off-grid or rural settings, reducing waste and improving service reliability (Peter et al., 2023). Governments and private-sector actors must collaborate to provide enabling policies, training, and financial incentives that encourage broader implementation of these technologies (Ukoba et al., 2023).

South Africa's smart grid initiatives exemplify how real-time data and AI can modernize energy infrastructure, while pilot programs in Kenya and Rwanda demonstrate the viability of blockchain for trading and traceability (Bhagwan and Evans, 2022). These precedents suggest that, with adequate support, Industry 4.0–

enabled GSCM can strengthen the competitiveness and sustainability of African RE firms.

Efforts to mainstream GSCM and Industry 4.0 tools in Africa's RESCs hinge on bridging capability gaps and fostering robust public-private partnerships. As demonstrated by nascent projects, even incremental application of these technologies can significantly enhance supply chain transparency, cost-efficiency, and stakeholder trust. Building on these insights, the next section highlights key research gaps covering policy, finance, and technology deployment that must be addressed to ensure scalable, context-specific interventions across African RE markets.

The discussion in this section illustrates how GSCM practices and Industry 4.0 technologies are increasingly positioned as complementary mechanisms for addressing sustainability and supply chain challenges within RESCs. By highlighting the role of digital technologies in enabling green practices and improving coordination, transparency, and performance outcomes, this section provides conceptual grounding for **Research Question 2**, which examines the role of Industry 4.0 technologies in supporting GSCM adoption. Furthermore, the integrated perspective developed here informs **Research Question 3** by emphasising the potential combined effects of Industry 4.0-enabled GSCM practices on sustainability performance, particularly within African RE contexts.

3.7 Contextual Research Gaps (RES, Africa, sectoral issues)

Building on the conceptual and theoretical gaps identified in Chapter 2, this section highlights contextual gaps arising from the distinctive characteristics of RESCs. It focuses on sector-specific and geographical limitations in the literature, including the underrepresentation of RESCs and African contexts. These contextual gaps further refine the motivation for the present study and underscore the need for empirical investigation within African RESCs.

This study identifies several key research gaps that justify the need for further investigation into the relationship between GSCM practices and Industry 4.0 technologies in Africa's RESCs:

1. **Lack of empirical evidence in African context**:

   A major gap in existing literature revolves around empirical evidence for integrating GSCM practices and Industry 4.0 technologies in Africa's RES (Maisiri et al., 2021, Umar et al., 2022b, Nkrumah et al., 2021, Ofori Antwi et al., 2022, Peter et al., 2023). Much of the research focuses on developed regions, leaving questions about how digital solutions and green supply chain principles can adapt to Africa's distinct socio-economic and infrastructural conditions (Bhagwan and Evans, 2022).

2. **Underexplored firm-level capabilities**:

   Firm-specific capabilities remain underexplored, as SMEs often lack both the financial resources and technical acumen needed for effective technology adoption (Peter et al., 2023). The literature insufficiently addresses how firm-specific capabilities or the lack thereof affect sustainability transitions in the RESCs (Peter et al., 2023).

3. **Inadequate policy alignment and enforcement mechanisms**:

   Further research is warranted on policy alignment. While African countries may have RE strategies, these typically overlook GSCM priorities and digitalization objectives, complicating enforcement (Adenle, 2020). Minimal study has examined the real-world effectiveness of these policies or proposed strategies for improving governance and accountability in RE development (Mutezo and Mulopo, 2021).

4. **Limited analysis of socio-economic outcomes**:

   The socio-economic impacts of GSCM and Industry 4.0 in Africa also demand attention; how digital-enabled sustainability practices influence job creation, skill upgrading, and equitable growth remains understudied (Amir and Khan, 2022, Chauhan et al., 2023).

5. **Neglect of circular economy applications in RES:**

   Another noteworthy gap concerns circular economy applications in Africa's RES. Detailed analyses of how principles like recycling and remanufacturing could integrate into local supply chains are crucial for fostering long-term sustainability (Deng et al., 2021). Addressing these multifaceted gaps will guide not only academic discourse but also the practical implementation of GSCM and Industry 4.0 across the continent's diverse markets.

Overall, while Africa's RES offers immense potential, the knowledge void in how to leverage GSCM and Industry 4.0 technologies remains a significant hurdle. By focusing on localized contexts, policy coherence, and capacity-building, future research can carve out impactful strategies tailored for Africa's unique economic realities. These insights will be essential for shaping the subsequent discussions on empirical approaches, policy considerations, and technology frameworks that can bridge these gaps and advance sustainable energy solutions throughout the region. Table 3-5 summarises how the literature reviewed in Chapters 2 and 3 supports the development of the research questions addressed in this study.

Table 3-5 Mapping of Research Questions to Literature Review Chapters

Research Question	**Relevant Sections in Chapter 2**	**Relevant Sections in Chapter 3**
RQ1		3.3.1; 3.4
RQ2	2.3; 2.4	3.5
RQ3	2.3.7; 2.3.8; 2.3.6	3.5

3.8 Chapter Summary

This chapter has examined the intricate sustainability and SCM challenges confronting the RES, focusing on the urgent need for tailored solutions that address raw material sourcing, end-of-life component management, and infrastructural limitations. The review highlighted the potential of GSCM practices and Industry 4.0 technologies to transform current supply chain inefficiencies into resilient, transparent, and environmentally responsible operations. Yet, gaps persist in the literature regarding how best to adapt these strategies to regional contexts, particularly in Africa, where socio-economic constraints and limited infrastructure may substantially differ from more developed settings.

These findings underscore the importance of bridging the theoretical and empirical shortfalls identified. GSCM has proved beneficial in reducing waste, optimizing logistics, and integrating environmental objectives across supply chain stages, while digital innovations facilitate real-time monitoring, data backed decision-making, and system agility enhancement. However, the review consistently points to the scarcity of studies that empirically validate the integration of GSCM and Industry 4.0 in African RESCs underscoring a critical knowledge gap in understanding how both organizational practices and technological tools can jointly advance sustainability performance within resource-constrained environments.

It is precisely this intersection of GSCM, Industry 4.0, and the African RES context that aligns with the Research Aim of the thesis to investigate how GSCM practices and Industry 4.0 solutions can be integrated to elevate sustainability performance in African RESCs. By identifying and analysing core SCM issues, and exploring the role of digital technologies, presenting a roadmap for integrating these components, the thesis directly addresses the literature's gaps.

In particular, the Research Questions target whether Industry 4.0 can bolster GSCM's effect on environmental, economic, and social outcomes, how digital tools influence green practice implementation, and what combined influence they exert on performance metrics in Africa's RES. By approaching these questions systematically, the study provides the framework necessary for answering fundamental concerns about cost barriers, government policies, and local capabilities that hamper the widespread adoption of sustainable solutions.

Looking ahead, subsequent chapters will delve deeper into these findings, proposing empirical methodologies to validate the conceptual arguments and offering strategic recommendations for policymakers and industry leaders. Through comprehensive analysis and localized adaptation of GSCM-Industry 4.0 solutions, the research seeks to empower Africa's RES to overcome existing constraints thus not only addressing immediate sustainability and SCM needs but also contributing significantly to global decarbonization and sustainable development goals.

Finally, based on the insights gotten from the systematic literature review, the next chapter turns to RBV and NRBV theories as foundational lenses for understanding how firms can cultivate and leverage both tangible and intangible assets such as advanced digital capabilities, supply chain partnerships, and environmental expertise to achieve a sustainable competitive advantage. While the previous sections have underscored the importance of technology integration and green practices in RESCs, RBV and NRBV offer a structured framework for examining how these resources and capabilities interact, develop, and confer value in dynamic market conditions. By adopting this theoretical backdrop, this thesis can more systematically assess the significance of Industry 4.0-driven GSCM innovations, especially within the resource-constrained and policy-challenging contexts found in Africa's RES.

4 Theoretical Framework

4.1 Chapter Introduction

The review of the literature presented in Chapters 2 and 3 has identified a set of interrelated conceptual and contextual gaps that necessitate a robust theoretical explanation. Chapter 2 highlighted limitations in existing research concerning the adoption of GSCM practices, the enabling role of Industry 4.0 technologies, and the inconsistent evidence regarding their combined effects on sustainability performance. Chapter 3 further demonstrated that these gaps are amplified within the context of RESCs, particularly in developing economy settings, where sector-specific characteristics and contextual constraints shape sustainability and supply chain outcomes.

The aim of this chapter is therefore to provide a theoretical lens through which the study's investigation of GSCM and Industry 4.0 technologies in the RES can be understood. Theory serves as a structured framework for interpreting complex organisational phenomena and for explaining how firms deploy resources and capabilities to achieve environmental, economic, and social outcomes. Accordingly, this chapter begins by outlining the broader role of theory in sustainability and supply chain research, before reviewing commonly adopted theoretical perspectives in GSCM scholarship. This discussion culminates in the selection of the RBV and its ecological extension, the NRBV, as the foundational theoretical perspectives guiding this study.

By emphasising the strategic and environmental dimensions of resource utilisation, RBV and NRBV together provide a robust platform for analysing how firms can achieve sustainable competitive advantages through the effective deployment of both tangible and intangible resources. These include digital capabilities associated with Industry 4.0 technologies and organisational capabilities underpinning GSCM practices. The chapter subsequently examines key characteristics of RBV and NRBV, including the value, rarity, inimitability, and non-substitutability of resources, alongside the role of ecological imperatives, to demonstrate how these theories illuminate the alignment between Industry 4.0 technologies and GSCM practices. In doing so, the chapter clarifies the relevance of these frameworks for RESCs, where resource constraints and heightened sustainability pressures necessitate integrated and innovation-driven approaches.

4.2 Theory in Research

The concept of theory in research is a subject of considerable debate, with no definitive consensus on its definition or clear demarcation between theories and non-theoretical constructs (Mintzberg, 2017). The absence of a universal standard or strategy for theory selection stems from differing perspectives on whether a theory should be built or adopted to address a specific research problem (Eisenhardt and Graebner, 2007). Abend (2008) underscores the critical importance of theory, defining it as a general lens through which one observes and interprets the world. According to Abend (2008), theories guide researchers in framing their understanding of social reality, determining what is recognizable and worth knowing, and shaping the questions that may be posed. Moreover, theories influence what constitutes valid evidence, how concepts within the social world are interrelated, and what attributes can be ascribed to them.

The theoretical framework, as described by Imenda (2014), represents the application of a theory or a combination of theoretical constructs to explain a specific phenomenon or address a research problem. It serves as the foundation for the entire research process, offering a structured approach to knowledge investigation. In essence, the theoretical framework functions as a blueprint, providing a conceptual structure that aligns the research problem with existing knowledge and guiding the researcher in the pursuit of new insights (Imenda, 2014). Furthermore, it contributes to two critical objectives: to position the research within existing literature and to demonstrate how the study advances the broader academic discourse within its field (Lederman and Lederman, 2015).

A well-articulated theoretical framework synthesizes existing theories and relates them to concepts and empirical findings, thereby forming a robust foundation for the development of new theoretical insights. It does not merely restate existing ideas but serves as a critical analytical tool that positions the research within the broader academic landscape. Abend (2008) emphasizes that a theoretical framework must align with the "ontological and epistemological plurality" inherent in social research, ensuring coherence between the framework's philosophical underpinnings and the research objectives. This alignment enables researchers to construct frameworks that are theoretically rigorous and methodologically sound.

In this context, the theoretical framework also serves as a unit of analysis, providing the structural lens through which the research problem is examined. It integrates conceptual frameworks, analytical tools, and models, ensuring that the study remains grounded in established academic traditions while contributing to theory-building efforts. As such, a theoretical framework is not static; it evolves through the research process, synthesizing empirical findings with theoretical constructs to create a foundation for understanding the conduct and outcomes of the study.

In this research, the theoretical framework provides a baseline for uncovering the dynamics of the research problem and interpreting its results. By synthesizing relevant theories and applying them to the specific context of the study, the framework establishes the foundation for methodological rigor and theoretical innovation. This approach ensures that the research not only offers its contributions to the extant body of knowledge but also advances the academic discourse by offering new perspectives and insights into the field.

4.3 Theoretical Frameworks in GSCM Research

In the reviewed literature, several theories have been identified for hypothesis development and testing. Some researchers have employed these theories as standalone theoretical lenses, including Institutional Theory (Wang and Zhang, 2022, Jazairy and von Haartman, 2020, Akhtar, 2019, Yang, 2018, Jasmi and Fernando, 2018, Ahmed et al., 2018, Hoejmose et al., 2014, Zhu and Geng, 2013), RBV (Khan et al., 2022d, Huma et al., 2022, Muduli et al., 2020, Jell-Ojobor and Raha, 2022, Foo et al., 2018, Chiappetta Jabbour et al., 2017, Kim et al., 2016), and NRBV (Ilyas et al., 2020; Cousins et al., 2019; Migdadi, 2022).

For instance, Institutional Theory has been applied to explain how regulatory pressures, market forces, and stakeholder expectations drive GSCM adoption in diverse contexts such as manufacturing and logistics (Wang and Zhang, 2022; Jazairy and von Haartman, 2020; Akhtar, 2019), while the RBV has been employed to examine how firms leverage internal resources and capabilities such as green technologies and supply chain integration to enhance competitiveness and sustainability outcomes (Khan et al., 2022d; Muduli et al., 2020; Kim et al., 2016). Similarly, the NRBV has been used to analyse how environmentally oriented capabilities (e.g., pollution prevention, product stewardship) contribute to superior performance in resource-intensive and emerging economy contexts (Ilyas et al., 2020; Cousins et al., 2019; Migdadi, 2022).

Additionally, many studies have adopted a multi-theoretical approach, integrating two or more theories to enhance the explanatory power of their hypotheses. Furthermore, Figure 4-1 provides an overview of the different theoretical frameworks used for hypothesis development and testing in the context of GSCM as revealed by the systematic literature review conducted in this study.

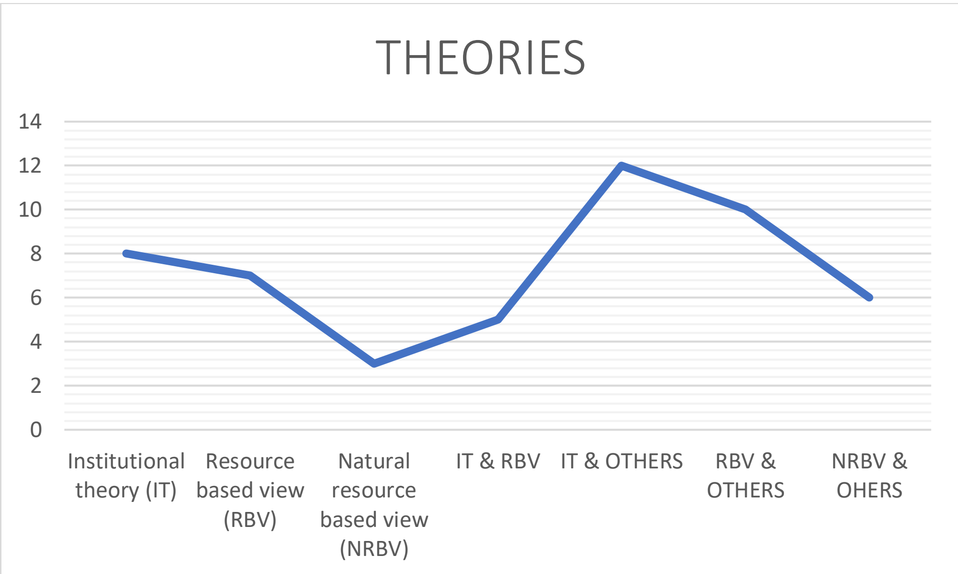

Figure 4-1 Extent of usage of theoretical frameworks

Figure 4-1 demonstrates that RBV and NRBV are among the most frequently employed theoretical lenses in GSCM-related hypothesis development. However, their application remains largely concentrated in manufacturing and developed economy contexts. This pattern highlights both the theoretical relevance of these frameworks and the need to extend their application to underexplored contexts such as RESCs in Africa.

4.4 Resource Based View

The RBV is a widely acknowledged theoretical framework that explains how firms can identify and utilize their resources to gain a competitive edge (Barney, 1991). The RBV focuses on VRIN resources to achieve competitive advantage in a firm (Barney and Clark, 2007). RBV is recognised as a prominent theoretical framework used in examining sustainable performance of firms through resource utilisation to enable firms to achieve sustainable competitive advantage (Karmaker et al., 2023a). RBV has been applied across multiple management domains ranging from human resources management (Aldaas et al., 2022) organisational performance (Appiah et al., 2022) to operations management (Huma et al., 2022)to elucidate the relationships between key organizational variables. At its core, the RBV suggests that resources, whether tangible or intangible, must be effectively integrated to form capabilities that underpin a firm’s survival and competitive advantage (Khan et al., 2022a).

RBV underscores the importance of resource heterogeneity and immobility in explaining why some firms outperform their competitors, even when operating under similar external conditions. Firms that possess unique combinations of resources, such as proprietary technologies or specialized expertise, can differentiate themselves in the market and achieve superior performance (Peteraf, 1993). For example, Mahoney and Pandian (1992) emphasize that resource bundling and leveraging specific capabilities allow firms to create value through innovative supply chain practices.

These resources encompass a broad spectrum, including frameworks, information systems, technology, human and physical capital, as well as a firm’s reputation

(Aldaas et al., 2022, Gonzalez et al., 2022). Importantly, resources alone yield limited value until they are strategically combined (Khan et al., 2022a). By thoughtfully aligning and deploying them, organizations can develop unique competencies that set them apart in the marketplace. Additionally, resources encompass tangible and intangible resources that are possessed by firms which facilitate production and delivery (Bae, 2017). Scholars further note that successful integration of resources depends on robust information networks (Aldaas et al., 2022), effective supply chain coordination mechanisms (Nkrumah et al., 2021), and capable top management teams (Mojumder and Singh, 2021b) to maximize their potential for creating and sustaining competitive advantages.

In the context of sustainability, RBV provides a framework for understanding how firms can leverage their internal strengths to adopt environmentally friendly practices. Firms that invest in advanced environmental management systems, green technologies, and sustainability-focused human resources can achieve both economic and environmental objectives (Hart, 1995, Barney and Arikan, 2005). These practices align with RBV's focus on resource optimization to achieve competitive advantage.

Collaboration is another critical aspect of RBV. Firms that partner with external entities, such as suppliers and technology providers, can enhance their resource base by accessing complementary assets. In supply chain contexts, these partnerships often involve co-developing innovative solutions and sharing best practices, which amplify the impact of GSCM initiatives (Peteraf, 1993). RBV offers a robust framework for analysing how firms optimize their resource configurations to achieve operational and sustainability objectives. By identifying and leveraging their VRIN resources, firms can navigate market complexities, respond to regulatory pressures, and meet evolving customer demands (Barney et al., 2010, Hart, 1995).
The RBV generally offers theoretical models to examine the relationships between Industry 4.0 technologies, GSCM practices, and sustainability performance in organisations (Aldaas et al., 2022). Therefore, the RBV underpins this study to

conceptualise the combined influence of industry 4.0 technologies and GSCM practices as resources that bring about sustainability performance in organisations. In terms of achieving exceptional competitive edges that are difficult to be imitated by competitors, Industry 4.0 technologies can help (De Sousa Jabbour and De Souza, 2015). GSCM practices comprise of important organisational competences that yield competitive advantage and environmental benefits, the practices include green purchasing, and collaboration among others (Yu and Huo, 2019, El-Garaihy et al., 2022b). Consequently, based upon the RBV and NRBV, the research framework is developed.

4.5 Natural Resource Based View

Hart (1995) introduced the NRBV to extend the RBV. The NRBV emphasizes that sustainable strategic initiatives such as sustainable development, pollution prevention, and product stewardship serve as tacit resources that competitors find challenging to replicate (Hart, 1995). This difficulty arises from dynamic capabilities or institutional constraints, ultimately enabling firms to acquire as well as maintain a sustainable competitive advantage (Huma et al., 2022). In other words, aligning a firm’s valuable resources and competencies with expectations of both society and the environment has led to NRBV from the RBV (Jell-Ojobor and Raha, 2022). While the RBV primarily emphasizes business-centric aspects, the NRBV considers a firm’s resources and environmental implications from its operations (Appiah et al., 2022).

NRBV comprises three interconnected strategic capabilities (1. pollution prevention, 2. product stewardship, and 3. sustainable development) (Migdadi, 2022, Samad et al., 2021). Under pollution prevention, a firm proactively avoids emissions and waste rather than addressing them after they occur. Pollution prevention focuses on minimizing waste and emissions through operational efficiency improvements. Firms that adopt this strategy can reduce costs and regulatory risks while enhancing their environmental performance. For example, companies implementing energy-efficient production processes or waste minimization programs often realize significant cost savings alongside reduced environmental impact (Hart, 1995).

Product stewardship extends this focus by encompassing the entire value chain and full product lifecycle, embedding the perspectives of stakeholders into the design of products (Appiah et al., 2022). Product stewardship lengthens this focus to the entirety of product lifecycle, integrating sustainability considerations from design to disposal. This strategy aligns with GSCM practices such as eco-design, enabling organisations to meet consumer demand for sustainable products while minimizing their ecological footprint (Jell-Ojobor and Raha, 2022).

Sustainable development goes even further, aiming not only to address environmental challenges but also to secure the long-term well-being of future generations by integrating economic and social considerations alongside environmental concerns (Migdadi, 2022). Sustainable development entails long-term strategies that balance economic growth with ecological preservation. Firms adopting this pathway invest in RE technologies, circular economy models, and other innovations that align their operations with environmental sustainability (Barney and Arikan, 2005). These initiatives often require significant organizational commitment and resource investment.

According to the NRBV, firms enhance their competitiveness by effectively managing their interactions with the natural environment. A company's ability to tackle environmental challenges fosters the creation of unique and difficult-to-replicate resources and capabilities that yield competitive advantages (Stekelorum et al., 2021a). Pollution prevention, focuses on minimizing waste within internal processes, aligning closely with GSCM practices capable of yielding enhanced operational and financial performance. While product stewardship, expands environmental efforts beyond the firm's own boundaries, typically requiring collaborative efforts guided by trust among supply chain partners, thereby delivering competitive advantage (Sarkis et al., 2011).

While the RBV emphasizes leveraging firm's internal resources to gain competitive edge, the NRBV posits that achieving a competitive advantage also requires considering the external natural environment, given that organizations face both internal and external environmental factors (Huma et al., 2022). Hart (1995) introduced the NRBV to bridge this gap, facilitating an understanding of how strategic resources intersect with environmental imperatives. In this context, the current study examined how organisations adopt GSCM practices alongside industry 4.0 technologies to outperform competitors. According to NRBV theory, firms must address the environmental implications of their operations by allocating appropriate resources and capabilities, thereby converting potential environmental threats into a sustained competitive advantage (Sarkis et al., 2011).

Within this perspective, GSCM emerges as a firm's strategic implementation of environmentally responsible practices, ultimately enabling the company to maintain a competitive advantage and achieve profitability (Huma et al., 2022). By integrating the NRBV into strategic management, juxtaposing organisational unique resources and GSCM practices amplifies the complexity of such sustainable initiatives (Jell-Ojobor and Raha, 2022). Consequently, a firm's complementary strategy in terms of environmental management, which fully integrates GSCM practices into its operations and organisational structure, can mediate the valuable prospect of GSCM practices, with the latter providing an enduring competitive advantage.

4.6 RBV and NRBV in GSCM and Industry 4.0 Research

The integration of RBV and NRBV into Industry 4.0 and GSCM research provides a robust framework for exploring how firms can align their internal resources with sustainability and digital transformation goals. The literature reveals that these theoretical lenses are widely utilized to explain how firm-specific resources and environmental strategies contribute to sustainable competitive advantage and operational efficiency.

Numerous studies have applied RBV to understand how firms leverage internal resources to implement GSCM practices effectively. Khan et al. (2022) employed RBV to analyse how advanced environmental management systems (EMS) and green procurement processes contribute to superior operational and sustainability performance. Their findings emphasize that firms with VRIN resources, such as skilled personnel and proprietary green technologies, are better positioned to meet environmental regulations and stakeholder expectations.

Li et al. (2019) focus on the role of RBV in the adoption of Industry 4.0 technologies within supply chains. They argue that these technologies act as enablers that amplify the value of existing resources by improving transparency, traceability, and operational efficiency. For example, IoT sensors allow monitoring of resource usage in real-time, enhancing decision-making and aligning operational goals with sustainability targets.

RBV also provides insights into how firms overcome barriers to implementing GSCM and Industry 4.0 technologies. For example, Muduli et al. (2020) highlight that firms with strong leadership commitment and a culture of innovation are more likely to succeed in integrating green practices and digital tools. These intangible resources, embedded in organizational culture, create a foundation for sustainable supply chain transformation.

The NRBV framework extends RBV by incorporating ecological considerations into resource analysis. Hart (1995) maintains that "pollution prevention, product stewardship, and sustainable development" are strategic pathways through which firms can achieve environmental and economic goals. In the GSCM context, NRBV has been used to study how firms integrate sustainability into their supply chain operations.

Jell-Ojobor and Raha (2022) employed NRBV to examine how firms achieve lifecycle sustainability through green product design and reverse logistics. Their research highlights that product stewardship, a key principle of NRBV, is central to reducing environmental impacts while enhancing customer satisfaction. These strategies align with NRBV's emphasis on aligning firm resources with ecological imperatives.

Industry 4.0 technologies, when analysed through the NRBV lens, are seen as critical tools for enhancing environmental performance. For example, Khan et al. (2022)

emphasized that blockchain technology ensures compliance with green procurement standards, while IoT facilitates efficient resource utilization. NRBV underscores how these technologies contribute to pollution prevention by enabling firms to monitor and optimize energy consumption in real time.

The literature increasingly combines RBV and NRBV to offer adequate comprehension of Industry 4.0 and GSCM adoption. For example, Aldaas et al. (2022) highlight that while RBV focuses on leveraging VRIN resources to achieve operational efficiency, NRBV complements this perspective by emphasizing the ecological sustainability of these practices. Their study demonstrated that firms with strong green innovation capabilities achieve superior sustainability outcomes by integrating advanced technologies and environmentally friendly practices.

Barney and Clark (2007) emphasize that the integration of RBV and NRBV offers a dual advantage: achieving competitive differentiation through resource optimization and aligning operational goals with long-term ecological sustainability. This dual perspective is particularly relevant in industries such as RE, where both economic and environmental imperatives drive decision-making.

The integration of RBV and NRBV into GSCM and Industry 4.0 research provides valuable insights into how firms can align internal resources with sustainability and technological advancement goals. By leveraging their unique capabilities, firms can achieve competitive differentiation and ecological sustainability. The literature demonstrates the complementary nature of these frameworks, offering a robust theoretical foundation for addressing the challenges of supply chain sustainability and digital transformation.

4.7 Justification for Choice of RBV and NRBV

The decision to ground this study in RBV and NRBV stems from two core considerations:

1. Alignment with Research Objectives and Context

- Previous chapters underscored the complex interplay between sustainability imperatives, supply chain processes, and digital transformation in the RES, particularly in emerging markets like Africa. The RBV's emphasis on identifying and leveraging firm-specific resources directly corresponds to the ways organizations can optimize GSCM practices and adopt Industry 4.0 solutions to achieve competitive differentiation.
- Meanwhile, the NRBV extends this analysis by highlighting ecological responsibilities and stakeholder pressures essential to sustainable development. As RESCs grapple with raw material sourcing, end-of-life management, and eco-design, NRBV provides a specialized lens for evaluating how environmental performance can become an integral strategic resource.

2. Complementary Strengths in Addressing both Economic and Environmental Dimensions
    - The RBV framework explains how VRIN resources such as proprietary technologies, skilled personnel, and robust data infrastructures can deliver a sustained market advantage. By applying RBV to the study of Industry 4.0 and GSCM, it becomes possible to assess how digital capabilities enhance organizational processes, reduce operational risks, and elevate firms' market standing.
    - The NRBV lens incorporates an ecological dimension, spotlighting pollution prevention, product stewardship, and sustainable development as strategic pathways (Hart, 1995). This perspective aligns firmly with the essential tasks in RESCs: minimizing waste, designing environmentally friendly products, and ensuring holistic sustainability across the life cycle. NRBV thus captures how environmental imperatives can serve as catalysts for innovation and unique resource configurations that competitors cannot easily replicate.

By merging RBV's business-centric viewpoint with NRBV's ecological concerns, the combined framework offers a dual vantage point: it supports the study's objective of evaluating how Industry 4.0–driven GSCM practices not only enhance operational and cost efficiencies but also fulfil long-term ecological and societal obligations. This complementary nature is particularly pertinent to the RES, where digital innovation and sustainable supply chain practices are inextricably linked to achieving both firm-level competitiveness and broader environmental resilience.

4.8 Hypothetical research model

As earlier discussed in Chapter 4, both RBV and NRBV are adopted in this study as the theoretical lenses. The RBV emphasizes that by leveraging the deployment of resources that are VRIN, firms can achieve competitive advantage (Barney and Clark, 2007). It is a widely recognized framework used to examine how a firm's resource base influences its ability to sustain competitive advantage (Karmaker et al., 2023b). Resources are subsequently transformed into organizational capabilities, which enable firms to enhance cost efficiency and achieve stronger financial outcomes. As argued by Grant (1991), firms generate capabilities by strategically combining and applying their resources in coordinated ways. However, resources themselves cannot provide firms any value until they are logically combined (Sirmon et al., 2008).

The RBV primarily explains how firms develop and sustain competitive advantage through the strategic deployment of internal resources and capabilities (Barney, 1991). In contrast, the NRBV extends this logic by arguing that such advantage must also be ecologically sustainable, focusing on how environmental concerns are integrated into a firm's strategic resource configuration (Hart, 1995). These resources may take various forms, including human capital, physical assets, and organizational infrastructure (Barney, 1991). Furthermore, resources can also be categorized into intangible (for example, organisational knowledge base) and tangible resources (for example, digital infrastructure) that facilitate production and service delivery (Bae, 2017). Capabilities refer to organisational resource utilization and deployment alongside firm's routines (practices) and processes (Karmaker et al., 2023b).

However, RBV does not fully account for environmental constraints and ecological responsibilities, limitation that is addressed by the NRBV (Hart, 1995). The NRBV extends RBV by incorporating environmental sustainability as a key strategic component, emphasizing that firms not only leverage resources for competitive advantage but also align their strategies with ecological imperatives to achieve long-term sustainability (Ilyas et al., 2020, Cousins et al., 2019). NRBV presents three strategic paths that include “product stewardship, pollution prevention, and sustainable development” (Hart, 1995), which are indispensable for organisations engaging in GSCM and Industry 4.0 adoption.

This study applies both RBV and NRBV to conceptualize GSCM practices and Industry 4.0 being an important set of organisational resources that enhance sustainability performance. It is also important to distinguish between organizational practices and capabilities. Practices (such as GSCM) refer to observable routines or processes that firms implement (Abdullah et al., 2019, Agyemang et al., 2018). Capabilities, by contrast, denote the underlying capacity to orchestrate and deploy resources systematically and effectively over time (AlNuaimi et al., 2021). Industry 4.0 technologies equip firms with exceptional capabilities that are difficult to replicate (De Sousa Jabbour and De Souza, 2015). This study treats GSCM as a dynamic capability because it reflects a firm's ability to coordinate environmental practices and integrate them strategically across the supply chain.

GSCM practices encapsulate key organisational routines like green procurement, and eco-design that foster both competitive advantage and environmental benefits (Yu and Huo, 2019). When these practices are embedded within a firm’s broader environmental management strategy and internal structures, they can mediate the value-generating potential of sustainability initiatives positioning GSCM as a source of enduring competitive advantage (Barney, 2001, Barney and Clark, 2007, Jell-Ojobor and Raha, 2022). Proactive GSCM practices, like internal environmental management (IEM), integrate resources like organizational learning and stakeholder engagement to minimize life-cycle environmental costs (Khan et al., 2022a). Unlike reactive compliance-based practices, these proactive strategies are harder to replicate and constitute firm-specific environmental capabilities aligned with the NRBV (Hart and Dowell, 2011, Jell-Ojobor and Raha, 2022).

Although GSCM practices may appear widespread, their effective integration and strategic alignment with firm-wide operations remain relatively rare and difficult to replicate (Abdellatif, 2021, Agarwal et al., 2018). As emphasized in NRBV literature, the value-generating potential of GSCM depends on a firm's superior ability to combine underlying resources and execute practices proactively, not merely as regulatory compliance (Sharma and Vredenburg, 1998, Russo and Fouts, 1997). This rarity arises from differences in organizational culture, digital maturity, supplier coordination, and environmental knowledge base factors that make GSCM a VRIN-based capability when fully institutionalized and technologically supported (Ahmadi-Gh and Bello-Pintado, 2022, Khan et al., 2022a). With the integration of NRBV, this study acknowledges that beside gaining competitive advantage, firms should prioritize sustainability as a central driver when making strategic decisions in their digital-green supply chain transformations.

To strengthen theoretical alignment, the study positions Industry 4.0 technologies as firm resources that align with the RBV's VRIN criteria and support NRBV's pollution prevention and sustainable development imperatives. GSCM practices are treated as organizational capabilities that represent the firm's ability to deploy resources effectively toward environmental goals, especially through NRBV's product stewardship lens. Sustainability performance is the outcome variable reflecting both economic and ecological success, consistent with the dual logic of RBV and NRBV. Grounded in this theoretical framing, the subsequent sections develop hypotheses that examine how Industry 4.0 technologies influence GSCM practices and, in turn, shape sustainability performance.

4.8.1 Industry 4.0 Technologies and Sustainability Performance (H1)

Industry 4.0 technologies are increasingly recognized as strategic assets that transform how firms manage operations and compete in complex supply chains (Akkad et al., 2022, Bag et al., 2021b). From the lens of the RBV, these technologies qualify as VRIN resources (Barney and Clark, 2007), offering firms a sustainable competitive advantage through enhanced efficiency, and responsiveness (Ahmed et al., 2020, Agrawal et al., 2023).

However, RBV alone provides an incomplete picture when sustainability is a central concern. The NRBV extends RBV by embedding ecological priorities into strategic considerations. It argues that firms must not only possess unique resources, but also align them with “pollution prevention, product stewardship, and sustainable development” with the aim of achieving long-term environmental and competitive benefits (Cousins et al., 2019, Hart, 1995). In this integrated view, Industry 4.0 capabilities are not merely tools for optimization; they are enablers of strategic environmental transformation (Chiappetta Jabbour et al., 2020, Bag et al., 2021a).

Technologies like IoT and AI empower firms to continuously monitor energy consumption, track emissions, and improve resource efficiency in real time directly supporting NRBV’s pollution prevention pathway (Ghobakhloo and Fathi, 2021). For example, AI-driven analytics can pre-empt waste in production cycles, while IoT devices provide granular environmental data that informs green decision-making (Dev et al., 2020). These capabilities transform sustainability from a compliance function into a proactive, strategy-driven process.

Moreover, blockchain enhances transparency alongside traceability in supply chains, enabling firms to enforce responsible sourcing and ethical standards (Khan et al., 2022a). Additive manufacturing and cloud computing promote circular economy practices through waste minimization and product lifecycle extension (Karmaker et al., 2023a). Such applications reflect the NRBV's emphasis on sustainable development and holistic environmental accountability (Hart, 1995).

From an economic standpoint, these technologies also deliver performance benefits that reinforce their strategic value. Automation and data integration reduce lead times, boost agility, and optimize supply chain operations, translating into cost savings and resilience (Naseem and Yang, 2021, Umar et al., 2022b). Yet, as NRBV highlights, these outcomes must be tied to ecological objectives to constitute true strategic sustainability.

Taken together, the integration of RBV and NRBV allows us to view Industry 4.0 not only as a set of operational assets but as environmentally enabling capabilities. The synergy between technological advancement and ecological alignment positions these digital tools as dual-purpose resources central to both performance and sustainability goals.

Hence, integrating RBV and NRBV, it is hypothesized that:

H1. *Industry 4.0 technologies positively enhance a firm's sustainability performance.*

4.8.2 Industry 4.0 technologies and GSCM Practices (H2)

The incorporation of environmental consciousness in key supply chain functions such as procurement, manufacturing, logistics, and distribution is what GSCM represents (Birasnav et al., 2022). It represents a strategic orientation in which firms proactively reduce pollution, minimize energy consumption, and promote material efficiency throughout their value chains (Nureen et al., 2022, Birasnav et al., 2022). From the RBV perspective, GSCM practices constitute valuable and rare capabilities distinct routines and processes that can yield sustained competitive advantage by differentiating a firm's operations on environmental performance (Wang and Zhang, 2022).

However, since the RBV doesn't fully capture the strategic necessity of environmental sustainability in the face of rising ecological pressures, the NRBV addresses this limitation by positioning GSCM not merely as a differentiating capability but as a required organizational response to ecological imperatives (Hart, 1995). NRBV's product stewardship pathway emphasizes the importance of embedding sustainability throughout the supply chain, from product design to supplier relationships, to ensure long-term ecological and organizational viability.

It is pertinent to argue that Industry 4.0 technologies serve as critical players when it comes to operationalising GSCM practices. These tools increase transparency in supply chains, automate compliance checks, while facilitating collaboration among green partners. For instance, blockchain ensures traceability and verification of raw materials, allowing firms to validate the environmental credentials of their suppliers

(Khan et al., 2022a). AI-powered analytics enhance decision-making in supplier selection and forecasting, enabling real-time adjustments to reduce waste and optimize green sourcing strategies (Hua et al., 2022). IoT sensors track environmental information (like carbon emissions data), making it easier for corporate entities to monitor sustainability impacts across distributed networks (Umar et al., 2022b).

By enabling real-time data visibility, automating green compliance, and fostering collaborative environmental practices (Ghadge et al., 2022), Industry 4.0 technologies do more than just bringing about improvements in operational efficiency, they make execution of GSCM feasible, scalable, and auditable. This digital foundation allows firms to actualize the strategic potential of GSCM, particularly in complex or globally distributed supply chains.

Furthermore, integrating RBV and NRBV offers a more complete understanding of this relationship. While RBV explains why firms benefit from developing GSCM as a unique capability, NRBV emphasizes why such a capability is imperative for long-term sustainability. Industry 4.0 acts as the bridge that connects the theoretical value of GSCM with its practical execution.

However, it is important to recognize that of Industry 4.0’s efficacy in enabling GSCM practices may depend on contextual factors such as digital infrastructure, institutional support, and supply chain maturity. In regions with limited digital penetration or weak regulatory enforcement, the realization of GSCM through digital means may be constrained.

Therefore, integrating RBV and NRBV, It is hypothesized that:

H2. ***Industry 4.0 technologies positively enhance GSCM practices in firms.***

4.8.3 GSCM Practices and Sustainability Performance (H3)

GSCM practices are increasingly recognized not only as tools for regulatory compliance but as strategic enablers of sustainability performance. These practices allow firms to embed sustainability considerations into various stages in a given value chain (Maditati et al., 2018, El-Garaihy et al., 2022a). Their impact extends beyond reduced emissions and waste; they also drive resource efficiency, enhance stakeholder trust, and open access to environmentally conscious markets.

Based on RBV, GSCM practices can be viewed as complex organisational capabilities (VRIN) which are difficult to be imitated, i.e. capabilities that help firms achieve superior positioning through environmentally differentiated operations (Wang and Zhang, 2022). For example, a firm that consistently sources from certified green suppliers or designs products for circular reuse gains a reputational and operational edge that rivals may struggle to replicate.

The NRBV extends RBV's framework by emphasizing that firms must go beyond traditional notions of competitiveness and embed ecological responsibility into their operational logic (Hart, 1995). NRBV's product stewardship principle underscores the importance of integrating environmental objectives into sourcing, production, and distribution to ensure both ecological and strategic viability.

The integration of RBV and NRBV provides a comprehensive rationale for GSCM's contribution to sustainability. While RBV highlights the firm-level benefits and uniqueness of GSCM capabilities, NRBV stresses that adopting these practices is not just optional, it is essential for firms responding to ecological degradation and stakeholder pressure. In this dual framework, GSCM emerges as both a performance-enhancing resource and a strategic necessity.

Mechanistically, GSCM practices contribute to sustainability performance by establishing upstream controls, reducing life-cycle impacts, and promoting closed-loop systems (Santoso et al., 2022). Eco-design minimizes waste generation from the product development stage; green procurement enforces environmental criteria during supplier selection; and collaborative sustainability efforts with supply chain partners help drive compliance and innovation. Together, these mechanisms create a systemic improvement in environmental outcomes.

It is important to recognize that the extent to which GSCM translates into sustainability performance may be shaped by contextual factors, such as supplier capacity, enforcement mechanisms, and the maturity of institutional infrastructure particularly in emerging economies where green supply chain integration is nascent. Thus, the following hypothesis is proposed:

H3. ***GSCM practices positively influence a firm's sustainability performance.***

4.8.4 GSCM Practices as a Mediator (H4)

While Industry 4.0 technologies provide firms with enhanced digital capabilities such as supply chain monitoring in real-time, and traceability, these technologies alone do not guarantee improved sustainability performance. From the RBV perspective, these digital tools represent strategic assets that can offer competitive advantages if deployed effectively (Barney and Clark, 2007). However, the benefits of these technologies depend not just on their existence, but on how they are leveraged through organizational processes.

The NRBV provides a complementary perspective by emphasizing that resources must be directed toward ecological ends to generate sustainability gains (Hart, 1995). In this context, GSCM practices serve as the operational mechanisms that translate digital capabilities into environmental outcomes (Esmaeilian et al., 2020). They ensure that data generated by Industry 4.0 tools leads to actionable, sustainability-oriented decisions across the supply chain.

This mediating role is especially evident when examining how specific technologies interact with green practices. Blockchain, for instance, is capable of tracking materials' origins and certify their ethical sourcing, but unless firms enforce procurement policies through GSCM, such data remains underutilized (Sahebi et al., 2022). Similarly, BDA enables supplier performance monitoring and predictive modelling, but its sustainability impact hinges on whether the firm integrates these insights into green supplier collaboration and lifecycle management (Chiappetta Jabbour et al., 2020).

The Industry 4.0-GSCM interaction enables firms to implement circular economy models, reduce lifecycle emissions, and enhance environmental compliance (Ghobakhloo and Fathi, 2021). From a theoretical standpoint, this implies that these technologies offer a promising addition to environmental sustainability, but GSCM practices realize that potential by embedding environmental responsibility into daily supply chain operations.

This relationship is principally salient in developing regions, where the mere adoption of digital technologies may not suffice where structured, green-oriented supply chain practices are absent. The mediating role of GSCM becomes a critical link that operationalizes technological potential within constrained institutional and infrastructural contexts.

Thus, it is hypothesized that:

H4. ***The positive and significant impact of Industry 4.0 technologies on sustainability performance in firms is mediated by GSCM practices.***

To illustrate these relationships, the proposed research model is presented in figure 4-2 below, depicting the linkages among constructs.

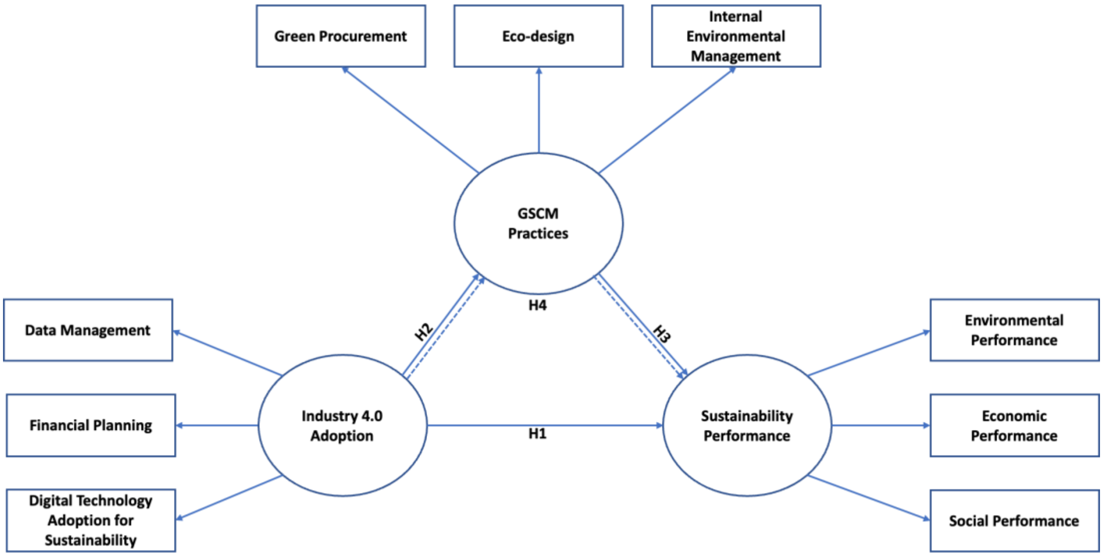

Figure 4-2 Research Model

Figure 4-2 illustrates the theoretically grounded research model developed from the RBV and NRBV. Industry 4.0 technologies are conceptualised as strategic digital resources, while GSCM practices represent organisational environmental capabilities through which these resources are deployed. Sustainability performance is modelled as the outcome variable capturing environmental, economic, and social dimensions. The model explicitly tests both the direct effect of Industry 4.0 technologies on sustainability performance and the indirect effect mediated through GSCM practices, reflecting the study's core theoretical proposition.

4.9 Chapter summary

In sum, this chapter has established a robust theoretical grounding for investigating the interplay between GSCM and Industry 4.0 solutions within the RES. By aligning RBV concepts of VRIN resources with NRBV imperatives of pollution prevention, product stewardship, and sustainable development, the chapter highlights how organizations can simultaneously pursue economic and environmental objectives. These perspectives are particularly vital for understanding how African RE firms, often hampered by infrastructural and market constraints, might capitalize on advanced digital tools to create distinct resource configurations that offer both competitive advantages and ecological benefits.

Moving forward, this theoretical framework will guide the empirical and analytical phases of the research, shaping the study's approach to methodology, data collection, hypothesis formulation, and interpretation of findings. In the next chapter, the focus turns to the methodological steps adopted to investigate whether, and how, Industry 4.0–enabled GSCM practices can enhance sustainability performance in Africa's RESCs. By integrating theoretical insights from RBV and NRBV into the study's research design, the project ensures that each stage from sampling to data analysis remains grounded in a strategic vision of how organizational resources and environmental stewardship coalesce to drive long-term success in the evolving landscape of RE.

5 Research Methodology

5.1 Chapter Introduction

This chapter provides a detailed explanation of the research methodology employed in this study to investigate the integration of Industry 4.0 technologies with GSCM practices within the RES in Africa. The chapter serves as the backbone of the research process, detailing the philosophical underpinnings, research design, data collection techniques, and analytical methods adopted to ensure rigor, validity, and reliability of the findings. The research methodology integrates a mixed-method approach, blending qualitative and quantitative techniques. This hybrid approach allows for an in-depth exploration of the contextual complexities of African RESCs and the validation of hypothesized relationships between industry 4.0 technologies, GSCM practices, and sustainability outcomes.

The chapter also outlines how ethical considerations influenced the research design, ensuring that the methods align with the study's objectives and real-world applicability. Furthermore, this chapter highlights the theoretical lens of the RBV and the NRBV as the guiding frameworks. By leveraging these theories, the research not only examined the role of unique resources and environmental capabilities but also addresses their implications in fostering sustainable competitive advantage through advanced digital technologies.

5.2 Research Philosophy

A research philosophy encompasses the foundational assumptions and beliefs governing how researchers perceive knowledge, reality, and evidence (Saunders, 2009). In the field of management and business, these assumptions profoundly influence both the design and execution of an inquiry. By selecting a particular philosophical standpoint, the researcher defines not only what counts as valid data but also the methods of collecting, interpreting, and applying that data (Jackson et al., 2015).

Given that this thesis explores the integration of Industry 4.0 technologies with GSCM practices to enhance sustainability performance within Africa's RESCs, a single paradigm may be insufficient to capture the multidimensional nature of this inquiry. The endeavour involves quantifiable phenomena, such as operational outputs, and performance metrics as well as context-specific human factors, including managerial perceptions, policy environments, and cultural considerations. This chapter clarifies the philosophical underpinnings of the study, justifying a mixed-method (positivist-interpretivist) stance that aligns with the research objectives and research questions.

5.2.1 Ontological and Epistemological Underpinnings

Ontology concerns the nature of reality whether social and physical worlds exist independently of human perceptions (Bell et al., 2022)while epistemology addresses the means by which knowledge is acquired (Mingers, 2006). In management science, two predominant ontological and epistemological traditions have long been recognized: **positivism** and **interpretivism** (Jackson et al., 2015). Positivism posits that reality can be observed objectively, enabling researchers to formulate causal laws through empirical observation and statistical measurement (Mingers, 2006). By contrast, interpretivism contends that reality is socially constructed, emphasizing context-specific insights and multiple subjective perspectives (Bhaskar, 2013).

Given the multifaceted nature of African RESCs, which involve both measurable operational variables and context-dependent human aspects, this study adopts a mixed-method approach. This approach draws on positivist assumptions for collecting and analysing quantitative data while integrating interpretivist elements to capture in-depth qualitative insights.

5.2.2 Positivist Paradigm

Rooted in natural science, positivism posits that reality exists independently of human perceptions and can be measured objectively (Mingers, 2006). Positivists maintain that causal relationships and universal laws can be derived from empirically verifiable data. Thus, researchers adopting a positivist stance typically use structured surveys, statistical modelling, and experiments to test hypotheses against a broader population (Saunders, 2009, Jackson et al., 2015). In the historical context, American journals in fields like operations management and information systems have predominantly leaned towards positivist traditions, emphasizing generalizability and empirical rigor (Orlikowski and Baroudi, 1991, Walsham, 1995).

In the context of this thesis, the positivist approach is particularly valuable for addressing parts of Objectives 2 and 3 and for validating relationships outlined in the Primary Research Question (*"How does the integration of GSCM practices and Industry 4.0 technologies affect sustainability performance in African RESCs?"*). For instance, quantitative instruments such as large-scale surveys can gather data on adoption rates, performance improvements, or cost savings associated with GSCM and Industry 4.0 initiatives across multiple African RE firms, thus enabling statistical testing of hypothesized benefits.

5.2.3 Interpretivist Paradigm

Emerging from critiques of positivism's narrow focus on observable phenomena, interpretivism contends that social reality is deeply influenced by human interpretation, context, and meaning (Bell et al., 2022). Researchers adopting an interpretive stance typically acknowledge that people's beliefs, cultural norms, and contextual experiences shape their understanding of organizational processes. Interpretivism is, therefore, well-suited for investigating the nuanced, subjective aspects of organizational decision-making, stakeholder collaboration, and policy influences topics integral to Objective 1 and the Sub-Questions exploring how managerial behaviours influence technology adoption and sustainability outcomes.

Given Africa's diverse socio-economic environments and infrastructural inconsistencies, purely objective measurements often fall short of capturing qualitative nuances. By engaging semi-structured interviews, the interpretivist dimension allows a deeper exploration of why certain strategies succeed or fail in specific organizational contexts. This approach is indispensable for explaining complexities around raw material sourcing, cultural barriers, or policy enforcement challenges, which may not be neatly quantifiable yet critically impact the integration of GSCM and Industry 4.0.

5.2.4 Rationale for a Mixed-Method Approach

Mixed-method research combines the systematic, hypothesis-testing strengths of positivism with the in-depth, context-sensitive insights of interpretivism. This hybrid paradigm is pivotal for addressing the research objectives and questions in a holistic manner:

1. Rich and Triangulated Data
    - The integration of quantitative data (survey-based performance measures) and qualitative data (interviews with managers) provides triangulation, enhancing the robustness and credibility of the findings (Bell et al., 2022).
2. Alignment with Research Objectives
    - Objective 1 (identifying key SCM challenges) benefit from empirical qualitative richness to account for stakeholder perceptions, cultural dynamics, and policy environments.
    - Objective 2 and 3 (examining how digital tools facilitate GSCM in local contexts) demands verification of hypothesized relationships via quantitative methods.
3. Addressing the Primary Research Question
    - By quantifying the impact of Industry 4.0 technologies under GSCM mediation, improvements in environmental, economic, and social performance can be measured. Meanwhile, interpretive insights clarify the organizational and contextual mechanisms underlying these improvements, thus satisfying both explanation (causality) and understanding (social context).

In short, combining positivist and interpretivist elements ensures a more comprehensive exploration of how digital innovation and environmental sustainability interweave within Africa's RES. This synergy is especially pertinent in resource-constrained settings, where objective metrics alone cannot capture the full complexity of social and logistical realities.

5.2.5 Relevance of Epistemic Relativism and Pragmatism

While positivism and interpretivism are framed as distinct paradigms, some scholars advocate pragmatism or critical realism, philosophical stances acknowledging that multiple layers of reality may coexist, and researchers must be flexible in selecting methods that best suit the research questions (Mingers, 2011, Bhaskar, 2013). Under a pragmatic lens, knowledge is judged by its practical utility for solving real-world issues, a guiding principle well-aligned with the practical aims of improving sustainability performance in Africa's RESCs.

Although this study primarily weaves together positivist and interpretivist techniques, it implicitly embraces the pragmatic notion that methodological choices are governed by research objectives, i.e. to explain broad patterns while also understanding the complexities behind them. This results in a multi-layered approach conducive to capturing both the quantitative scale and qualitative depth necessary to formulate actionable recommendations for industry stakeholders.

This thesis adopts a mixed-method stance that integrates positivist and interpretivist paradigms, a choice that resonates with the research objectives and questions aimed at evaluating how Industry 4.0–enabled GSCM practices enhance sustainability within African RESCs. On one hand, positivism provides empirical rigor for quantifying adoption rates, measuring performance outcomes, and statistically validating hypothesized relationships. On the other, interpretivism delivers critical insights into the social, cultural, and organizational factors influencing how these digital and green initiatives are carried out in practice.

By harnessing the strengths of both paradigms, this thesis attempts to address the nuanced, context-specific challenges that define African RESCs while systematically testing and generalizing key findings. This cohesive philosophical framework ensures that each stage of the research design remains consistent with a multifaceted view of how and why digital and environmental strategies can produce meaningful, sustainable transformations in the RES.

5.3 Research Design

A research design is the overall blueprint for how a study intends to collect, analyse, and interpret data in order to answer its research questions (Saunders, 2009). It serves as the guiding framework that ensures repeatability and rigor in research execution (Creswell, 2021). For this thesis, which aims to *“examine the integration of GSCM practices and Industry 4.0 technologies in enhancing sustainability performance in African RESCs.”* a carefully structured design is necessary to capture both breadth and depth.

5.3.1 Rationale for a Mixed-Method Approach

Mixed-method research combines quantitative and qualitative approaches to capitalize on their respective strengths (Morgan, 1998, Creswell, 2021). It is particularly useful when the research objectives demand a holistic understanding of complex phenomena, involving both measurable operational metrics and context-dependent stakeholder insights (Onwuegbuzie and Leech, 2006). In this study:

1. Quantitative Inquiry is suited to answer questions about frequency, extent, and relationships for instance, measuring how widespread specific GSCM practices and Industry 4.0 tools are within RE firms, and how they correlate with sustainability performance indicators.
2. Qualitative Inquiry provides contextual and exploratory insight into why and how such practices are adopted, illuminating managerial, cultural, or policy-driven factors that may not be captured by purely numerical data.

Given the primary research question on leveraging digital and green supply chain practices for enhanced sustainability in the African context, a single data source would prove insufficient. The inherent complexity ranging from policy and infrastructural constraints to organizational culture necessitates multiple forms of evidence. Hence, a sequential mixed-method design is adopted, in line with established recommendations that a single paradigm is rarely adequate for fully addressing multifaceted research problems (Creswell, 2021, Tashakkori and Teddlie, 2003).

5.3.2 Priority-Sequence Model and Sequential Exploratory Design

Morgan (1998) introduces the Priority-Sequence Model as a framework for mixing qualitative and quantitative methods, stipulating that one method should serve as the principal method, with the other as a complementary phase. This study follows the model by first conducting a preliminary qualitative phase followed by a larger, quantitative phase design often referred to as Sequential Exploratory Design (Creswell et al., 2011).

1. **Preliminary Qualitative Phase**:
    - Objective: Gain exploratory insights into unique challenges and contextual factors in the African RES.
    - Method**:** Semi-structured interviews with experts from mini-grid companies, regulatory bodies, and financial institutions funding RE projects.
    - Outcome: A deeper understanding of the key variables, barriers, and contextual conditions that shape the adoption of GSCM and Industry 4.0 solutions, guiding the construction of the subsequent quantitative instrument.
2. **Main Quantitative Phase**:
    - Objective**:** Generalize findings, test hypotheses, and measure prevalence or extent of specific practices and outcomes across a wider population of African RE firms.
    - Method**:** Survey-based data collection to assess the relationship between Industry 4.0 adoption, GSCM practices implementation, and sustainability performance.

    - Outcome: Statistically validated insights into how significantly and in what ways digital tools and GSCM practices influence environmental, economic, and social dimensions of sustainability.

5.3.3 Aligning Research Design with Thesis Objectives

This two-phase approach aligns closely with the research objectives and questions:

- **Objective 1** (*Identify and analyse key sustainability and SCM challenges*): The qualitative phase uncovers sector-specific challenges by engaging with individuals who directly confront these issues, providing a rich contextual basis for the quantitative survey.
- **Objective 2 and 3** (*Examine how Industry 4.0 tools can facilitate GSCM in African contexts to achieve sustainability performance*): The quantitative analysis measures the extent and impact of digital tool adoption, while the qualitative insights explain *why* certain practices succeed, or fail, in certain organizational or infrastructural settings.

Although this study employed a Sequential Exploratory mixed-method structure leveraging positivist and interpretivist techniques, it is fundamentally pragmatic (Onwuegbuzie and Leech, 2006). In other words, methodological decisions are driven by the practical demands of answering research questions and achieving research objectives, rather than strict allegiance to a single paradigm. This approach encourages the use of both structured surveys for empirical validation and open-ended interviews for contextual exploration, acknowledging that neither method alone suffices to capture the full range of phenomenon under study (Creswell et al., 2011). Figure 5-1 illustrates the mixed method research design.

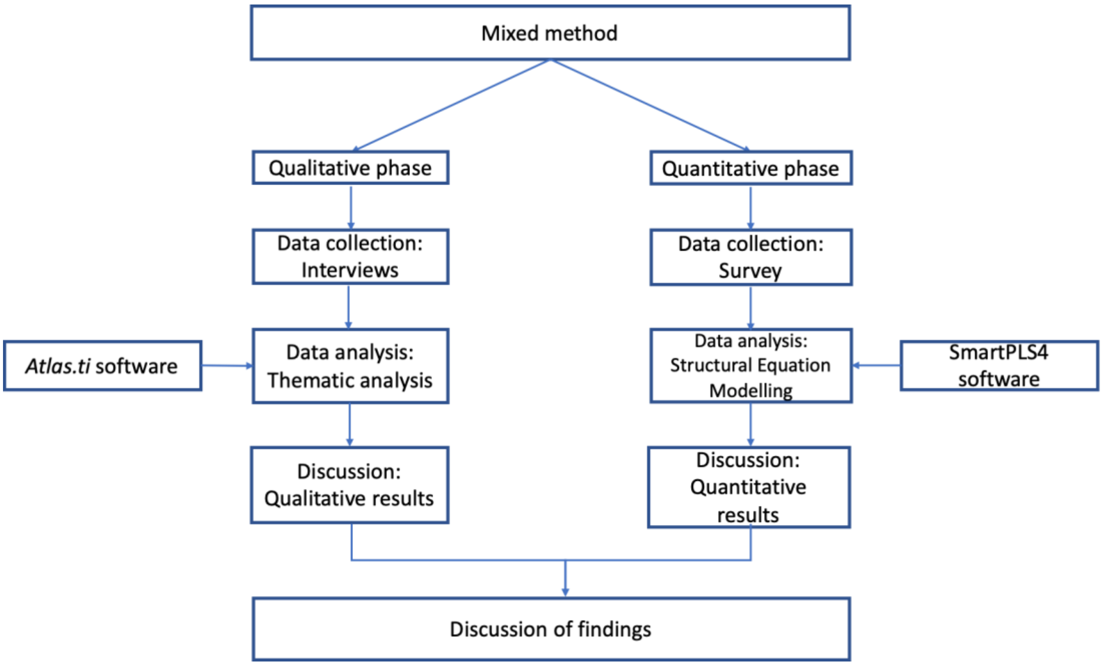

Figure 5-1 Mixed method research design

By adopting a mixed-method design featuring an initial qualitative exploration followed by a larger quantitative survey, this research capitalizes on the complementary strengths of both paradigms. The exploratory nature of the interviews illuminates context-specific drivers, barriers, and stakeholder perceptions essential to GSCM and Industry 4.0 adoption in African RE firms. Subsequently, the quantitative phase validates and measures these findings at scale, allowing for generalization and more definitive assessments of impact on sustainability performance. This Priority-Sequence Model (Morgan, 1998) and Sequential Exploratory Design (Creswell et al., 2011) ultimately generate a more holistic view of how digital technologies and green supply chain practices can synergistically address sustainability and SCM challenges in the RES, fulfilling the thesis' research objectives and primary research question.

5.4 Qualitative Research Method - Semi-Structured Interviews

The first phase of this mixed-method study involves an exploratory, qualitative investigation with experts from African RE firms, regulatory authorities, and other key stakeholders. As Patton (2014) notes, qualitative research entails "delving into the real world of organisations" to capture what unfolds in practice, especially when studying social and organizational phenomena under less clear or emergent conditions. Given the research questions, an in-depth qualitative approach is necessary to illuminate contextual nuances, challenges, and knowledge gaps.

According to Creswell (2021), qualitative methods are invaluable when aiming to obtain a rich understanding of a contemporary phenomenon within real-life contexts, especially when the phenomenon (in this case, the synergy of digital technologies with green supply chain practices) and its specific setting (African RESCs) remain not fully defined or understood. In this thesis, the qualitative strand addresses the exploratory dimension of the research questions uncovering the nature and breadth of sustainability and SCM issues in the African RES, clarifying the current level of GSCM and Industry 4.0 awareness, and identifying barriers or enablers from an insider's perspective.

At this stage, semi-structured interviews are particularly suited to probing multiple facets of organizational behaviour and strategic decision-making. Scholars such as Yin (2009) advocate for qualitative data collection methods in contexts where the lines between phenomenon and setting are blurry. In the African RES, complexities may include policy constraints, infrastructural deficits, cultural factors, and managerial philosophies regarding digital adoption or environmental stewardship. This kind of knowledge would likely be difficult to capture solely through a statistical instrument (Tukamuhabwa et al., 2017). Semi-structured interviews allow researchers to build rapport with participants generating in-depth reflections on organizational processes, perceived bottlenecks, and success stories that a survey alone might not reveal.

This exploratory qualitative phase provides conceptual clarity on the unique circumstances under which African RE firms operate. Such clarity feeds into and benefits questionnaire development for the main quantitative study, ensuring that key variables or constructs are rooted in actual sector realities. As recommended by Creswell et al. (2011), qualitative findings can refine hypotheses and measurement items, thus bridging the gap between abstract theoretical models and the concrete lived experiences of practitioners.

Moreover, the rich, context-specific data gleaned from interviews enhances the interpretive depth of the final analysis. When the quantitative results are later juxtaposed with these qualitative insights, the study can both generalize the prevalence and impact of Industry 4.0–enabled GSCM approaches and offer nuanced explanations as to *why* these strategies either thrive or falter in Africa. Ultimately, this two-phase approach bolsters the validity and reliability of the research, aligning methodologically with the Priority-Sequence Model (Morgan, 1998) and Sequential Exploratory Design (Creswell et al., 2011).

In summary, the semi-structured interviews employed during this initial qualitative phase serve to illuminate the underlying mechanisms, contextual drivers, and organizational realities that shape GSCM and Industry 4.0 adoption within the African RES. By capturing the voices and experiences of key stakeholders, the study lays a solid groundwork for the subsequent quantitative phase, ensuring that the survey instrument is well aligned with real-world challenges and that the final research outcomes are both empirically robust and practically relevant.

5.4.1 Selection of Participants

The qualitative segment of this research is premised on the need to obtain expert-driven, context-specific insights into how GSCM and Industry 4.0 solutions are applied or perceived within African RE operations. Given the interpretive nature of this phase, a non-probability sampling strategy was deemed most appropriate (Saunders, 2009). In particular, the study adopts purposive sampling to ensure that only individuals who possess substantive knowledge of sustainability and SCM challenges, as well as digital technology adoption, are included (Darby et al., 2019). According to Darby et al., (2019), the ideal number of informants (respondents) selected in the interpretive research approach falls between three and twenty informants, and this is because interpretive research method emphasizes the acquisition of a holistic understanding of the environment. Also, context selection in this approach is driven by understanding instead of generalisation (Akram et al., 2024).

Non-probability sampling approaches differ from probability-based methods in that sample selection is not random (Saunders, 2009). Instead, participants are chosen based on whether they can offer in-depth, relevant perspectives on the phenomenon under study. In interpretive research, the emphasis rests on depth and richness of information rather than broad generalization (Darby et al., 2019). This is especially pertinent to investigating real-world organizational contexts where gleaning expert insights often prove more critical than achieving statistical representativeness.

Within non-probability sampling**,** purposive sampling involves the researcher deliberately selecting participants based on their potential to provide valuable data (Pearlson et al., 2019). For this research, it was crucial to capture the experiences of those directly influencing or managing the RESCs, regulatory frameworks, and project financing. Consequently, eight organizations in Nigeria (operating in sub-Saharan Africa) were identified. These included mini-grid companies, solar home system providers, regulatory authorities, and a global banking institution. This selection process was facilitated by consultation with a professional possessing over ten years of experience in the African RES, to ensure diverse representation and maximal relevance.

Under this purposive sampling scheme, only individuals occupying senior roles such as CEOs, directors, managers, or project leads were approached. By targeting these positions, the study sought to capture strategic decision-making processes**,** operational realities, and policy-related aspects of GSCM and Industry 4.0 adoption. Each participant was informed that strict anonymity of both personal identities and organizational details would be upheld, thereby encouraging openness in discussing sensitive or strategic organizational matters.

In essence, the purposive sampling technique enriches the quality of the qualitative data by securing input from key informants who are intimately involved in supply chain processes and sustainability initiatives. This approach effectively captures nuanced, practice-oriented knowledge of the RES's challenges and innovations. As such, it lays a robust foundation for the subsequent quantitative phase, aligning with the broader mixed-method design and ensuring that the overall inquiry remains grounded in real-world experiences and expert perspectives (Pearlson et al., 2019). Table 5-1 provides a detailed overview of the study's participants, including their roles, organizational affiliations, and the size of their respective organizations. The diversity of participants, ranging from mini-grid companies to regulatory authorities and a global financial institution, reflects the multifaceted perspectives included in the analysis. This ensures the findings capture a holistic view of the challenges and solutions within the Nigerian RES.

Table 5-1 Research participants information

Organisation	Category	Role	Size (People)
1	Mini-grid	Founder/CEO	10-50
2	Mini-grid	Founder/CEO	10-50
3	Solar Home systems provider	Senior Manager	100-200
4	Solar home systems provider	Senior Manager	100-200
5	Global bank	Project/Operations Manager	5000-10000
6	Regulatory authority 1	Director	400-500
7	Regulatory agency	Manager	1300-1500
8	Regulatory authority 2	Managing Director	300-400

The qualitative phase of this study was conducted within Nigeria, while the subsequent quantitative phase extended to firms across multiple African countries. This design choice aligns with the principles of sequential mixed-method research, where an in-depth, context-specific exploratory phase is used to inform a broader confirmatory analysis (Creswell et al., 2011; Morgan, 1998).

Nigeria was selected as the qualitative case context due to its position as one of Africa’s largest and most active RE markets, characterised by diverse supply chain actors, regulatory bodies, and business models spanning mini-grids, solar home systems, and institutional finance. This diversity provides a rich empirical setting for uncovering complex supply chain and sustainability dynamics that are likely to be encountered, in varying forms, across other African RE contexts.

The purpose of the qualitative phase was not statistical generalisation, but analytical generalisation, namely, to surface key themes, challenges, and mechanisms related to GSCM practices and Industry 4.0 adoption in resource-constrained RESCs. Insights derived from this focused national context were subsequently used to refine constructs, inform questionnaire design, and ensure contextual relevance of measurement items in the larger, cross-country quantitative survey.

Extending the quantitative phase to a pan-African sample allowed the study to test the prevalence and strength of the relationships identified qualitatively, thereby enhancing external validity while retaining strong contextual grounding. This sequencing ensures that the broader empirical model is rooted in real-world operational realities rather than purely abstract theoretical assumptions.

5.4.2 Interview Protocol

This section outlines the interview protocol adopted for the qualitative exploratory phase of this research, focusing on how GSCM and Industry 4.0 technologies are perceived and practiced within African RE firms. Since the objective at this stage is to capture context-rich, expert-driven insights, semi-structured, face-to-face interviews were conducted.

The main goal of the interviews is exploring:

1. The structure and supply chain dynamics of Nigeria's RES,
2. The extent of environmental consciousness and awareness of GSCM within firms,
3. Key sustainability and SCM challenges encountered,
4. The techniques companies use to address these issues, and
5. The current adoption (or potential for the implementation) of Industry 4.0 technologies.

Following recommendations from Saunders et al. (2019), three preparatory steps were undertaken:

1. Gathering Organizational Context
   - Publicly available materials (company websites) were reviewed to understand each firm's operational scale, strategic focus, and any recognized efforts in digital or green initiatives.
2. Developing an Interview Guide
   - The open-ended questions below were structured around the research objectives namely understanding RESC realities, sustainability approaches, and Industry 4.0 adoption levels.
   - The guide was reviewed internally and refined to ensure questions were thematically aligned and logically sequenced.
3. Conducting Face-to-Face Interviews
   - All interviews were scheduled to take place in-person at participants' offices or a neutral meeting location. This setting fostered rapport and allowed informants to discuss sensitive topics more candidly.

Participants were initially briefed on the research aims and assured of confidentiality. The following questions served as the core structure of each interview, with follow-up probes used as needed to clarify or deepen certain topics:

1. How would you describe the structure of the RES in Nigeria?
   - *Rationale:* Elicit broad insights into the sector's key players, value chain segments (e.g., mini-grid, solar, finance), and how they interrelate.
2. How would you describe the sector's supply chain in Nigeria?
   - *Rationale:* Explore procurement logistics, distribution channels, and typical operational challenges relevant to RE (e.g., geographic constraints, import dependencies).

3. How would you describe the extent to which environmental consciousness is embedded in the management of your supply chain?
    - *Rationale:* Identify participants' views on GSCM principles, eco-friendly practices, and any strategic environmental objectives within their operations.
4. What would you say are the supply chain–related challenges within the sector?
    - *Rationale:* Gather data on key obstacles that hinder the efficiency or sustainability of RESCs.
5. What are the sustainability-related problems within the sector that you have encountered?
    - *Rationale:* Pinpoint specific environmental, social, or economic dilemmas impacting RE deployment, along with the broader context (e.g., regulatory barriers).
6. How would you describe the techniques adopted by companies to tackle such sustainability and supply chain problems?
    - *Rationale:* Identify practical strategies, tools, or frameworks that firms apply in addressing challenges.
7. How would you describe the adoption of Industry 4.0 technologies in the sector and is this something your company has considered?
    - *Rationale:* Investigate awareness and usage of digital solutions and clarify whether these are perceived as integral to resolving SCM or sustainability issues.

Each informant received a Participant Information Sheet highlighting the purpose of the study, the voluntary nature of participation and confidentiality, (Yin, 2003). In obtaining consent, participants were assured that all identifying details would remain anonymous in subsequent analyses or publications. Audio recording of interviews was done, ensuring accurate transcription. Non-verbal cues as well as observational details valuable for interpretive analysis were documented. The collected data were kept securely in compliance with institutional ethics guidelines.

5.4.3 Data Collection

To collect primary data based on the interpretive research method, the eight informants participated in semi-structured interviews with discussions focused on the research questions. Questions weren't strictly structured, rather, a conversational two-way exchange of information to understand the challenges faced within their supply chains with regards to sustainability and SCM (Birks et al., 2007). To explore how informants connect between their cognitive processes, experiences and lives, questions were made concise and open-ended so that these connections are established (Akram et al., 2024). Interview audios were carefully transcribed, and secondary data (industry reports and articles) was gathered to strengthen the primary data. This purposeful selection of case organizations aligns with the interpretive aim of capturing expert insights on GSCM and Industry 4.0 technologies (Pearlson et al., 2019). Each organization designated one participant with direct responsibilities or oversight in supply chain, operations, or strategic decision-making relevant to the RES's sustainability challenges.

All interviews took place between April and May 2023 at participants' respective business premises or a neutral location. Prior to each session, participants were given information sheets describing the study's objectives, the right of participants to voluntarily withdraw any time, and the confidential handling of any disclosed information (Saunders, 2009). Each participant was then asked to review and sign a participant consent form, formalizing their agreement to take part and to allow audio recording of the conversation. Any reluctance regarding recording was addressed by reaffirming strict anonymity and the option to halt recording at any time (Tukamuhabwa et al., 2017).

With participants' consent, digital audio recordings were made of the interviews, complemented by field notes capturing non-verbal cues and contextual details. Interviews typically ranged from 40 minutes to one and a half hours, depending on the participant's availability and the depth of discussion. Immediately following each session, the recorded data were transcribed verbatim, ensuring faithful representation of the participants' viewpoints. Pseudonyms (Respondent X) replaced organizational names, and identifying details of the informants were anonymized to maintain privacy.

By conducting face-to-face semi-structured interviews in real-world organizational settings, this research secures rich, contextual data regarding GSCM adoption levels, Industry 4.0 awareness, and specific sustainability challenges confronting the RES. The qualitative insights gained here serve as the foundation for developing or refining the subsequent quantitative research instruments, as well as for grounding the study's eventual recommendations in practical, expert-driven perspectives (Creswell, 2021).

5.4.4 Data Analysis

Transcripts of the interviews were thoroughly examined specifically to extract major themes that centre around sustainability and SCM issues in RES and their corresponding solutions found to be in practice or proffered by informants. This intra-textual exercise involved several reading and re-reading of transcripts to adequately understand the context. Each transcript was thoroughly examined, and summaries of key themes were made to visualise key findings and trends. Intertextual cross-examination was carried out for entire transcripts for the identification of recurring themes. Coding of data was performed manually to determine the emergence of themes and patterns after which the codes were imported into Atlas.ti software for qualitative data analysis so that a relationship could be established between themes and codes.

Files were uploaded onto *Atlas.ti* software and these were arranged in project folders and memos to keep the data structured to prepare for a seamless conduct of the next step. The data was carefully and thoroughly reviewed for a further understanding of context and content. Themes, patterns and concepts were identified and were manually annotated or highlighted in-text. On *Atlas.ti*, nodes were created corresponding to the manually generated codes where each node represented a theme. Relevant text sections were added under each corresponding node manually on the *Atlas.ti* platform after which the features of the software were leveraged to determine the relationships between codes. This was followed by creating queries, networks and visualisations while the "Code Document Table" was used to visualise how often code re-occurred in different documents.

Codes and code combinations were searched across the dataset using *Atlas.ti*'s query tools, the relationship between codes that appeared together frequently were identified using the "Code Co-occurrence" query. To capture reflections, thoughts and insights, memos were written on the software during this analytical process after which these memos were linked to specific documents and codes to uphold a record of analytical thinking. Conclusions and insights were drawn from identified patterns and relationships which were both synthesized through the continuous interpretation of themes and concepts while reviewing the coded data. Visual representation of findings and reports were generated for effective communication of findings, then these were exported to help in improving research presentation and reports. One of the most important steps in this data analysis was "data conceptualisation" that has to do with turning data groups into abstract concepts. This iterative process of analysing themes continued until the orientation frame of reference was properly defined.

According to Darby et al. (2019), to sufficiently understand observable relationships between variables, interpretive strategy is adopted to expand understanding of relationships beyond surface level understanding (Akram et al., 2024). Through the interpretive research strategy, constructing meaning and raising comprehension is aimed at. According to Darby et al., (2019), to investigate unique events in unique settings and to generate in-depth descriptions connected to their contexts, the interpretive research strategy excels. Figure 5-2 illustrates the iterative process of qualitative content analysis employed in this study, grounded in an interpretive research strategy. The cycle highlights key steps such as orienting the frame of reference, data examination, and theme identification, showcasing how insights into SCM and sustainability challenges were derived. This approach emphasizes depth in understanding context-specific issues.

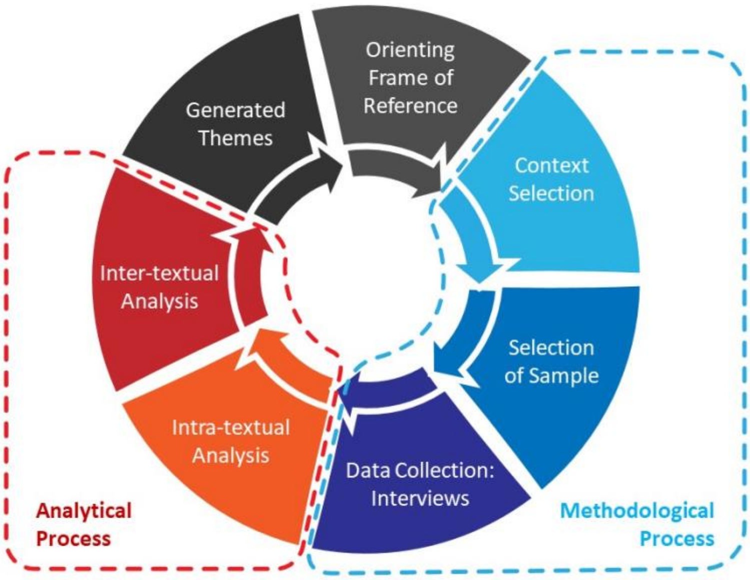

Figure 5-2 Process of qualitative content analysis (Hermeneutic circle)

The cycle starts with the orienting frame of reference which demonstrates relevance of the context in question (Darby et al., 2019). Through this approach, a more in-depth understanding of sustainability and SCM challenges within RES is provided alongside solutions based on GSCM practices and Industry 4.0 technologies. This study found the key elements in the orienting frame of reference in this research to be sustainability related issues in the RES, SCM related issues in the RES and the role of Industry 4.0 and GSCM practices towards tackling the issues identified.

To enhance transparency and clarity, the coding process resulted in a structured hierarchy comprising initial codes, higher-order categories, and overarching themes. Initial codes were derived directly from participants' statements and reflected concrete issues or practices reported during interviews. These codes were subsequently grouped into categories representing broader conceptual domains, which were then consolidated into key themes aligned with the study's research questions and conceptual framework. The resulting themes formed the basis for interpreting the qualitative findings and informed the operationalisation of constructs used in the subsequent quantitative phase. An illustrative overview of this coding structure is presented in Table 5-2.

Table 5-2: Summary of Interview Coding Structure

Overarching Theme	Category (Axial Coding)	Illustrative Open Codes (Derived from Interviews)	Link to Study Constructs
SCM challenges in RES	Importation-related issues	Customs delays; border clearance bottlenecks; high tariffs and levies; FX volatility	SCM challenges
	Logistics-related issues	High in-country transport costs; poor infrastructure; damaged or missing goods	SCM challenges
	Knowledge and skills gaps	Lack of trained personnel; absence of tracking capability; weak supplier assessment	Organisational readiness
	Regulatory issues	Weak enforcement; policy ambiguity; lack of regulatory synergy	Institutional constraints
	Economic issues	Exchange rate volatility; high financing costs; budget overruns	Economic sustainability
	Corruption-related issues	Bribery at checkpoints; compromised EIA processes; energy theft	Governance risks
Sustainability challenges in RES	Environmental consciousness	Low awareness among firms and customers; weak sustainability culture	Social sustainability
	End-of-life management	Absence of decommissioning plans; lack of take-back schemes	Environmental sustainability
	Waste disposal practices	Improper battery disposal; lack of recycling facilities	Environmental sustainability
GSCM-based solutions	Green procurement	Approved vendor lists; supplier vetting; preference for responsible suppliers	GSCM practices
	Lifecycle planning	Embedded decommissioning costs; refurbishment and reuse of modules	GSCM practices
	Reverse logistics and recycling	Partnerships with waste firms; recycling and retrofitting initiatives	GSCM practices

Overarching Theme	Category (Axial Coding)	Illustrative Open Codes (Derived from Interviews)	Link to Study Constructs
Industry 4.0-based solutions	Environmental management	Carbon footprint assessment; ISO certification; staff training	GSCM practices
	Digital monitoring	IoT-enabled smart metering; remote system control	Industry 4.0 technologies
	Data-driven planning	Analytics for site identification and demand planning	Industry 4.0 technologies
Complementary solutions	Human capital development	Training curricula; certification schemes	Enabling conditions
	Financial and policy support	Subsidies; de-risking initiatives; supply chain financing	Contextual enablers
	Information sharing	Digital platforms for project and data visibility	Supply chain coordination

5.5 Quantitative Research Method – Survey

The quantitative strand of this research adopts a survey method to gather empirical data on GSCM and Industry 4.0 technologies implementation within the African RES. This choice aligns with a deductive paradigm, wherein numerical evidence is systematically collected to test propositions gathered from earlier qualitative examination alongside reviewing pertinent literature (Bell et al., 2022). A survey, in this context, is particularly useful for uncovering broad-based patterns, relationships, and potential correlations among key constructs such as perceived benefits of digital innovations, and sustainability-related challenges that shape firms' adoption decisions in the sector.

Building on previous interpretive findings, the survey design aims to provide a complementary, more generalizable perspective (Saunders, 2009). By capturing responses from a diverse pool of managers and decision-makers across mini-grid companies, solar home system providers and other organisations within the African RES, the quantitative data can illustrate how widespread and embedded GSCM principles and Industry 4.0 tools are, as well as how these factors might intersect with organizational performance outcomes. Such a comprehensive approach follows the logic of explanatory sequential mixed-methods research, wherein initial qualitative insights inform hypothesis development and the subsequent large-scale testing of these hypotheses through structured, numeric measures (Creswell and Clark, 2011).

5.5.1 Sample Selection

This study administered an online survey to gather quantitative data from professionals within the African RES with the aim to capture a diverse range of managerial and technical perspectives. An initial contact list comprising of 450 professionals was developed through professional networks, LinkedIn outreach, and email databases, supplemented by collaboration with RE associations across multiple African countries, who kindly disseminated the survey link to their members. This strategy ensured wide geographical reach, and a representative cross-section of firms involved in different phases of the RESCs.

The survey invitation highlighted the study's objective of exploring GSCM practices and Industry 4.0 technologies adoption in RESCs, encouraging participants to voluntarily respond. Recipients included individuals holding mid- to senior-level roles with sufficient organizational knowledge to address the questionnaire items. Engaging these professionals was critical for securing insights into both day-to-day operational challenges and strategic sustainability practices in an emerging African context. Given the complexity of some topics, the questionnaire was carefully structured to facilitate accurate, self-administered responses within a short time frame.

A total of 101 valid responses were obtained, after removing any significantly incomplete entries or invalid submissions. Although the research employed volunteer sampling, the deliberate efforts to partner with sector-specific associations and use professional networking platforms provided a sufficiently robust sample for statistical analysis. The final data set reflects a range of firm sizes and operational scopes, thereby enhancing the generalizability of results to the broader African RES environment.

5.5.2 Construct Operationalisation and Measurement items

To ensure theoretical and contextual alignment, each construct was measured as a second-order construct comprising several first-order dimensions assessed using specific items. Industry 4.0 technologies adoption was conceptualized as a second-order construct comprising three dimensions: Digital Technology Adoption for Sustainability (DTAS), Data Management (DM), and Financial Planning (FP), measured using 11 items adapted from extant literature. GSCM practices were operationalized with 9 items grouped under Green Purchasing/Procurement (GPP), Eco-design (ECO), and Internal Environmental Management (IEM), drawn from prior studies. Sustainability performance was captured through three dimensions, Environmental Performance (ENP)**,** Economic Performance (ECP), and Social Performance (SCP)measured using 9 items. A full list of the measurement items, dimensions, and their sources is provided in **Appendix 3**. While these measurement items were drawn from validated prior studies, their selection and contextual emphasis were informed by themes emerging from the qualitative interviews, particularly those relating to supply chain constraints, sustainability challenges, and the practical application of digital technologies in African RE contexts. Table 5-3 presents construct definitions and measurement focus of each construct.

Table 5-3 Construct definitions and measurement focus

Construct	Definition	Measurement Focus	Key Sources
Green Procurement (GPP)	Environmentally conscious sourcing and supplier management practices.	Collaboration with suppliers, environmental audits, ISO 14000 certification.	Zhu et al. (2005); Umar et al. (2022a)
Eco-Design (ECO)	Integration of environmental criteria in product design.	Design for energy/material efficiency; recycling, reuse, recovery.	Karmaker et al. (2023a); Zhu and Sarkis (2004)
Internal Environmental Management (IEM)	Organizational processes for managing internal	Leadership support, cross-department collaboration, training, regulatory compliance.	Khan et al. (2022); Green Jr et al. (2012)

Construct	Definition	Measurement Focus	Key Sources
	environmental practices.		
Digital Technology Adoption for Sustainability (DTAS)	Use of digital tools (e.g., IoT, blockchain, AI) for sustainable supply chains.	Sustainability-driven use of digital tools in transparency, monitoring, logistics, end-of-life management.	Umar et al. (2022a); Rufino et al. (2022)
Data Management (DM)	Structuring, sharing, and securing digital data within the SC.	Infrastructure, stakeholder data sharing, cybersecurity.	Karmaker et al. (2023a); Eslami et al. (2023)
Financial Planning (FP)	Financial readiness for digital–green integration.	Digital risk management, funding, and control systems.	Umar et al. (2022c); Karmaker et al. (2023a)
Environmental Performance (ENP)	Reduction of ecological impact from operations.	Waste minimization, pollution control, environmental safety.	Acquaye et al. (2018); Zhu et al. (2005)
Economic Performance (ECP)	Financial gains from green practices.	ROI, cost savings in energy and waste management.	Karmaker et al. (2023a); Akhmatova et al. (2022)
Social Performance (SCP)	Organizational impact on societal well-being.	Working conditions, health and safety, public/environmental protection.	Ahmed and Sarkar (2019); Brenner and Hartl (2021)

5.5.3 Questionnaire Development and Design

In constructing the survey instrument, established guidelines for questionnaire design were followed to ensure clarity, objectivity, and systematic structure (Dillman, 2011). The initial draft emerged from the findings of the qualitative phase specifically; key themes identified in face-to-face interviews alongside insights gleaned from the literature on GSCM and Industry 4.0. This draft was iteratively refined in consultation with both academic supervisors and professional experts in African RESCs.

Once a workable version of the questionnaire was reached, pilot testing was conducted with a small group of sector specialists and managers. The feedback addressed question clarity, overall flow, and the effectiveness of specific items in capturing the constructs of interest. Minor adjustments were made to the wording and question order to better align with participants' real-world contexts. The final version aimed to achieve two core objectives: (1) capture data relevant to the hypotheses derived from the literature and qualitative study and (2) remain succinct and user-friendly to minimize respondent fatigue.

Consistent with the 'flowerpot approach' (Shiu, 2009), the questionnaire was organized from more general, introductory material to more detailed, topic-specific items. This design helps guide participants naturally from an initial overview of the study's aims toward increasingly focused questions on Industry 4.0 usage and GSCM practices. Specifically, the questionnaire was grouped into three main sections:

1. Introductory Section
    - Outlined the purpose of the survey, participant rights (e.g., voluntary involvement, right to withdraw), and confidentiality measures.
    - Provided a brief explanation on Industry 4.0 technologies and GSCM.
2. Core Items and Thematic Blocks
    - GSCM Practices (green procurement, eco-design, and internal environmental management).
    - Adoption of Industry 4.0 Technologies (blockchain for transparency, IoT for supplier collaboration, AI for predictive maintenance, etc.).
    - Sustainability Performance metrics (environmental, economic, and social performance indicators).
    - Items were closed-ended (Likert scales) so that hypotheses are analysed statistically (Creswell et al., 2011).
3. Demographics and Firm Characteristics
    - Respondent's position, years of experience, operational markets, firm size, and relevant ISO certification status.

A self-completion approach was used, where participants read and responded to items on their own (Bell et al., 2022). An online platform (Qualtrics) facilitated easy access via email and LinkedIn links, enabling broader geographic reach among African RE stakeholders. This approach also helped minimize interviewer effects and reduce administrative costs, though it carries the inherent risks of lower response rates and potential missing data (Shiu, 2009). To mitigate these concerns, the questionnaire remained concise requiring approximately five minutes to complete and was distributed along with clear instructions and follow-up reminders.

Each question was carefully worded to avoid double-barrelled statements, leading questions, or complex syntax. Five-point (1. Totally disagree 2. Disagree, 3. Neither agree nor disagree, 4. Agree and 5. Totally agree) Likert-scale items were used for all constructs, allowing participants to indicate degrees of agreement. Closed-ended questions enabled straightforward coding and statistical analysis, aligning with the deductive thrust of this quantitative phase to confirm or refute emergent propositions from the interpretive study. In sum, the survey was developed using iterative best practices: thorough pretesting, logical structuring under the flowerpot approach, and user-friendly formatting. By systematically aligning core items with both the qualitative insights and theoretical constructs of GSCM and Industry 4.0, the final questionnaire offers a robust tool to empirically test the relationships proposed in this mixed-methods study.

5.5.4 Questionnaire Pilot Testing

A pilot test was carried out involving five industry professionals (drawn from African RE firms) and four academic experts, consistent with recommendations by Rothgeb et al. (2007) and Babbie (2012). This pilot phase aimed to identify any problematic or ambiguous items and to confirm that the questionnaire's format and language were appropriate for a broad range of respondents. Building on the recommendations by Rothgeb et al., (2007), the questionnaire review focused on comprehension, retrieval of information, response selection, and clarity of instructions. This feedback stage allowed the researcher to detect areas that might pose difficulties for the survey participants. Critically, Babbie (2012) emphasizes involving not only potential respondents but also subject-matter experts to gain a well-rounded perspective on question ambiguity and overall structure.

A Questionnaire Appraisal System (QAS) framework, adapted from Forsyth et al. (1999), guided the pilot. This appraisal helped ensure that each question was unambiguous, comprehensible, and aligned with the study's objectives. Special attention was paid to the wording in the demographic section: participants in the pilot highlighted several terms as vague or subjective, prompting rewording to minimize confusion. The final questionnaire was deemed ready for online distribution to the target sample. By systematically addressing the pilot feedback, the researcher ensured that the instrument would be both credible and user-friendly for the larger African RE audience.

5.5.5 Survey Administration and Data Collection

A total of 450 survey invitations were distributed via professional networks, LinkedIn outreach, email databases, and collaboration with RE associations across Africa. The survey remained open from October 2024 to February 2025, during which 198 responses were received, yielding a 44% response rate. After data cleaning (discussed in greater detail in section 5.5.6), 101 valid responses remained. Respondents represented companies operating in solar (86.1%), hydro (8.9%), wind (2.9%), and biofuel (1.9%) segments, varying in size and digital maturity. The technology type question allowed respondents to select multiple applicable technologies. Geographic representation spanned 17 African countries, including RE hubs such as Nigeria, Kenya, South Africa, Egypt, Morocco, and Ethiopia. Notably, these countries and RE segments were not pre-selected; rather, they reflect the affiliations of respondents who chose to participate.

5.5.6 Sample Characteristics

This section provides the characteristics of respondents and the composition of the sample as well as the relevance of their perspectives to the fulfilment of the research aim of this study. The survey targeted mid- and senior- level managers working within the RES across multiple African countries, specifically those in SCM, procurement, purchasing, and operations roles. These respondents were selected due to their direct involvement in strategic decision-making and operational processes connected to industry 4.0 adoption and GSCM practices. The demographic profile of respondents includes variations in industry experience, organisational size, years of experience among others. This is to ensure that the findings capture diverse perspectives across different levels of supply chain maturity.

Benitez et al. (2020) asserts that to conduct a statistical power analysis before data collection is believed to be beneficial, as it helps the researcher to determine the minimum required sample size that offers sufficient statistical precision and detect meaningful effects within the population. In line with this recommendation, with the *G*Power software,* a statistical tool commonly used to estimate the minimum required sample size for hypothesis testing (Faul et al., 2009), a power analysis carried out (Hair et al., 2017) which indicated that the minimum recommended sample size was 98, in line with the following parameters as suggested by Hair et al. (2017): effect size set at 0.15, statistical power set at 0.8, significance level set at 0.05, with six predictors. To ensure robustness in both data collection and analysis, the questionnaire was administered through *Qualtrics*, a widely used online survey platform.

The probability of the detection of a true effect is referred to as statistical power, with a power of 0.8 (80%) denoting 80% chance of appropriately rejecting a false null hypothesis, thereby minimizing Type II errors (Cohen, 2013). The magnitude of the relationships among variables is measured by effect size, with 0.15 categorised as medium, implying that the expected relationships are of moderate strength (Cohen, 2013). The significance level (α = 0.05) sets the maximum threshold pertaining statistical significance, implying a 5% probability of rejecting the null hypothesis incorrectly, thus controlling for Type I errors (Cohen, 2013). Finally, six predictors mean the independent variables included in the model to explain variations in the dependent variable, ensuring a comprehensive examination of factors influencing sustainability performance (Hair et al., 2019). Table 5-4 presents further details of the characteristics of respondents.

Table 5-4 Characteristics of respondents (n=101)

Metric	Percentage	Count
ISO certification		
Yes	39.6%	40
No	40.5%	41
On the process of certification	18.8%	20
Renewable energy technology type		
Solar	86.1%	87
Wind	2.9%	3
Hydro	8.9%	9
Biofuel	1.9%	2
Designation		
Founder/Owner	19.8%	20
CEO	14.8%	15
Director	9.9%	10
Senior Manager	18.8%	19
Manager	14.8%	15
Years of experience		
Less than 4 years	15.8%	16
5-10	33.6%	34
11-16	30.6%	31
17-22	8.9%	9
More than 22 years	10.8%	11
Number of employees		
Less than 50	50.4%	51
50-200	20.7%	21
201-350	4.9%	5
351-500	4.9%	5
More than 500	18.8%	19

5.5.7 Data Cleaning and Preparation

A total of 198 responses (n=198) were recorded through Qualtrics; however, not all responses were valid for inclusion in the final dataset. Following the recommendations of Hair et al. (2017), responses that have higher than 15% missing data were excluded, as excessive missing values could undermine the integrity of statistical analysis and present biases. Moreover, further data screening was done to confirm response consistency and reliability. Specifically, responses were examined for unrealistically low variability in answer patterns, such as cases where respondents selected the same score (e.g., consistently rating all items as "5") across all survey items. Such uniform response patterns suggested a lack of engagement or response bias and were therefore removed from the dataset.

After applying these screening criteria, 101 cleaned responses remained, exceeding the minimum recommended sample size established by the power analysis. This ensures that the dataset possesses sufficient statistical power and robustness, allowing for reliable hypothesis testing and meaningful insights into the interplay between the main constructs in African RESCs. The data cleaning process reinforces the study's commitment to maintaining high-quality, reliable responses, enhancing the validity and credibility of the empirical findings. Figure 5-3 presents a flowchart of the data cleaning process.

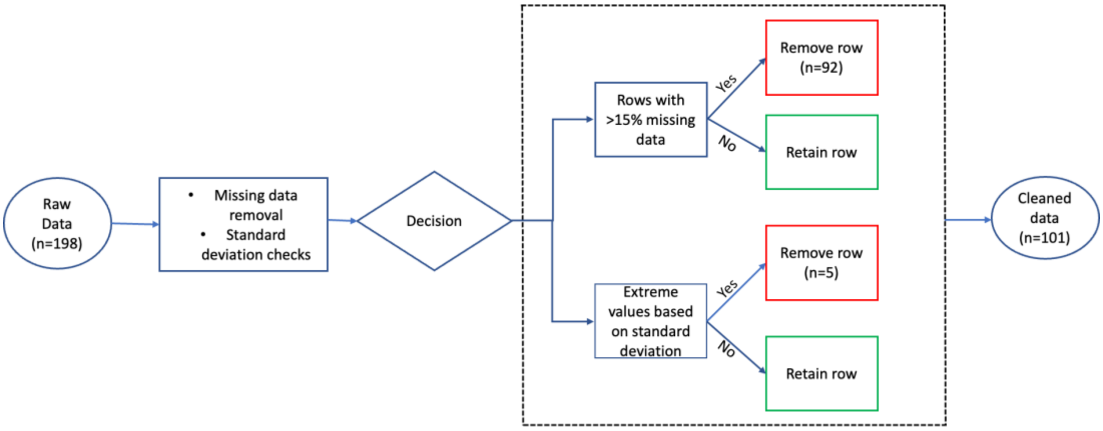

Figure 5-3 Data cleaning process.

Furthermore, since the data collected was gathered through self-reporting, it is inherently prone to common method bias (CMB) (Podsakoff et al., 2012). To mitigate this potential risk, some measures were implemented. First, anonymity was ensured during the initial data collection phase to minimize CMB. Second, Harman's single-factor test was carried out in SPSS, in line with recent studies (Zhang et al., 2022). The Harman's single factor test is one of the most widely used diagnostic techniques for assessing **CMB** in survey-based research (Podsakoff et al., 2012).

CMB refers to systematic variance attributable to the measurement method rather than the constructs being studied, and if present, it can inflate or deflate observed relationships, thereby threatening the validity of findings (Podsakoff et al., 2003). The test involves subjecting all measurement items to an unrotated exploratory factor analysis and examining whether a single factor emerges or whether one general factor accounts for most of the variance. As shown in Table 5-5, the first factor explained 37.094% of the total variance, which is well below the conventional 50% threshold commonly adopted in the literature as an indicator of problematic CMB. This suggests that no single latent factor dominated the dataset and that the responses were not unduly influenced by a common source of bias. In other words, the variance is more evenly distributed across multiple factors, confirming that the data is not substantially compromised by CMB. Taken together with the prior data cleaning steps including handling of missing values and checks for response variability, these results enhance confidence in the accuracy, consistency, and reliability of the dataset before proceeding with subsequent structural equation modelling.

Table 5-5 Harman’s single factor

Total Variance Explained						
	Initial Eigenvalues			Extraction Sums of Squared Loadings		
Factor	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	11.366	39.192	39.192	10.757	37.094	37.094
2	5.018	17.302	56.494			
3	1.552	5.353	61.848			
4	1.286	4.436	66.283			
5	1.081	3.728	70.011			
6	0.931	3.209	73.221			
7	0.891	3.073	76.294			
8	0.735	2.533	78.827			
9	0.652	2.248	81.075			
10	0.608	2.095	83.17			
11	0.582	2.006	85.176			
12	0.493	1.699	86.875			
13	0.462	1.594	88.469			
14	0.417	1.439	89.908			
15	0.385	1.328	91.236			
16	0.373	1.286	92.523			
17	0.303	1.046	93.568			
18	0.264	0.912	94.48			
19	0.239	0.824	95.304			
20	0.219	0.755	96.059			
21	0.204	0.705	96.763			
22	0.19	0.656	97.42			
23	0.155	0.533	97.953			
24	0.149	0.513	98.466			
25	0.121	0.416	98.882			
26	0.104	0.358	99.24			
27	0.087	0.301	99.541			
28	0.079	0.271	99.812			
29	0.054	0.188	100			

Data preparation in this study involved a comprehensive sequence recommended by Shiu (2009), “data validation, data editing and coding, data entry, and data tabulation aimed at ensuring all collected online survey responses were accurate and reliable for further statistical analysis. The process began with *data validation*, confirming that the online survey was distributed correctly to knowledgeable professionals in Africa’s RES and that any irregular submissions were removed. Because responses were self-completed online, the researcher monitored for inconsistencies, such as extremely rapid completion times or repeated IP addresses suggesting potential fraud or hasty submissions.

Once the dataset was deemed valid, the researcher proceeded to *data editing and coding*. Each set of responses was checked for errors to confirm a consistent and logical flow of answers. A standardized coding scheme was then applied, assigning numeric values to Likert-scale items. By using uniform numerical assignments (e.g., 1 denoting "Totally disagree" and 5 denoting "Totally agree"), it became straightforward to merge all participants' data into a single dataset for analysis.

After coding, data export from the online platform took place to a spreadsheet environment, facilitating *data entry* with minimal risk of human transcription errors. Any anomalies detected in the export were reconciled using the coding guide; incomplete or contradictory responses were excluded as detailed in Figure 5-1, preserving dataset integrity. Finally, the dataset underwent *tabulation*, systematically arranging all variables and responses into an organized matrix ready for statistical processing. Preliminary frequency checks of each question were made to detect any residual data inconsistencies. This coherent approach to data preparation ensured that only high-quality, consistent responses would be used in subsequent analyses of the interaction among GSCM practices, Industry 4.0 technologies, and sustainability performance in the Africa's RESCs.

5.5.8 Quality of Survey Data: Validity

Validity signifies the level at which a survey instrument precisely captures or measures the concepts it was designed to study (Bell et al., 2022). In a research context that explores the interaction of GSCM and Industry 4.0 within African RE firms, ensuring robust validity is crucial for drawing meaningful conclusions. This section details the key forms of validity addressed in the design and evaluation of the survey instrument.

A central consideration was face validity, which examined whether the survey items appear to measure the intended constructs (Babbie, 2012). Even though many of the measures in this study drew on established scales from prior work, a pilot test with academic professionals and industry experts allowed for refinements to ensure that each question not only made logical sense but also corresponded directly to GSCM and Industry 4.0 constructs. Before sending out the survey, feedback from these knowledgeable reviewers led to revisions of ambiguous wording and further clarification of certain items, strengthening the instrument's perceived relevance and appropriateness.

Beyond face validity, content validity was considered by examining the breadth of the questionnaire in covering the wide-ranging components of GSCM and industry-specific digital innovations (blockchain, IoT, BDA). According to Adcock and Collier (2001), content validity requires that survey items collectively represent the full domain of the construct under study. This study ensured a comprehensive set of questions that included environmental, economic, and social performance indicators for sustainability, thus reflecting the key challenges and facets of RESCs in Africa.

Additionally, discriminant and convergent validity were relevant for cases where multiple items measured latent constructs, such as sub-dimensions of Industry 4.0 usage. Discriminant validity ensures that each scale for a specific concept is empirically distinctive compared to other constructs measured in the instrument (Hair et al., 2019). Convergent validity, by contrast, checks whether items that theoretically belong together do indeed correlate strongly (Hair et al., 2019). Therefore, sections requiring multi-item constructs could be tested for these validity properties via structural equation modelling and examining average variance extracted (AVE) or the Heterotrait-Monotrait Ratio (HTMT).

In summary, validity was protected through careful questionnaire development, pilot testing with experts, and the adoption of existing validated measures where appropriate in line with literature (Babbie, 2012, Hair et al., 2019). By addressing face validity (surface reasonableness of questions), content validity (completeness of coverage), and discriminant/convergent validity (empirical distinctiveness and internal consistency), the survey instrument enhances confidence in the accuracy of the measured constructs. Consequently, the research findings can more reliably inform understanding of GSCM and Industry 4.0 synergies in Africa's RES.

5.5.9 Quantitative data analysis strategy

This study's quantitative data analysis employed SEM, a second-generation multivariate technique that examines interrelationships among observed and latent variables in one cohesive framework (Hair et al., 2019, Schumacker and Lomax, 2004). SEM includes two main components: first, a structural set of equations that capture causal links among constructs, and second, a measurement model that translates latent variables into observable indicators (Panahifar et al., 2018). Common steps in SEM involve creating composite variables weighted combinations of measured indicators and assigning numerical values to categorize and scale these measures (Hair et al., 2019).

Researchers typically choose between covariance-based SEM (CB-SEM) and partial least squares SEM (PLS-SEM) (Hair et al., 2019). While CB-SEM has historically dominated contexts where model fit to the covariance matrix is paramount, PLS-SEM emphasizes a "causal-predictive" framework that prioritizes the explanatory and predictive power of the model rather than adherence to classical fit indices (Hair et al., 2019). PLS-SEM can also manage complex models with multiple constructs, nonnormal data distributions, and advanced features such as moderators or nonlinear relationships (Sarstedt et al., 2014). These characteristics make PLS-SEM particularly suitable for exploratory or emergent theoretical applications where some constructs may be relatively new or continuously evolving.

In this thesis, the conceptual framework draws on both the RBV and the NRBV to explain how unique intangible resources, environmental capabilities, and digital innovations can collectively foster sustainable competitive advantage. By adopting PLS-SEM, the study can investigate how GSCM practices and Industry 4.0 technologies interact to drive desired sustainability outcomes. Such a focus on resource orchestration and performance aligns with the NRBV premise that addressing environmental imperatives can generate significant operational and competitive benefits.

The decision to employ PLS-SEM is further supported by the approach's strengths in handling innovative constructs, relatively flexible data conditions, and a balanced emphasis on predictive utility (Hair et al., 2019). Because this work aims to integrate digital transformation and environmental sustainability in a sector, African RESCs, where certain measures and constructs may be at an emergent stage, PLS-SEM is well-suited to illuminate how these theoretical elements unfold in practice. The method's causal-predictive orientation aligns with the RBV/NRBV lens by highlighting how resource configurations influence real-world outcomes, thus contributing both to theoretical development and to a nuanced understanding of management strategies in RE contexts.

5.6 Research ethics

Ethical principles are fundamental in guiding academic research, ensuring a careful balance between researchers' pursuit of knowledge and the rights and well-being of participants (Creswell, 2021). As noted by Cooper and Schindler (2014), ethics consists of norms or standards that shape moral choices regarding personal conduct and interpersonal interactions. In research contexts, these norms help safeguard participants from undue harm such as risks related to divulging sensitive information, potential threats to their employment, or breaches of confidentiality.

This study received ethical clearance from the Department of Design, Manufacturing and Engineering Management at the University of Strathclyde, Glasgow. All participants who took part in interviews were informed of their voluntary role and asked to sign a consent form affirming their informed agreement to participate. The research was presented as carrying no identifiable risk, given that it did not involve any clinical or psychological trials, nor address national or corporate security issues. Nonetheless, the potential benefits, such as insights for improving supply chain resilience and sustainability, were clearly articulated.

Jackson et al. (2015) proposed ten principles for ethical practice, including the imperative to avoid harm to participants, respect their dignity, obtain informed consent, preserve data confidentiality, ensure anonymity, and maintain honesty and transparency in all research communication. This study heeded these principles by fully informing interviewees of the research aims, data usage, and any associated implications. Participants were encouraged to raise concerns or questions at any point. Anonymity was guaranteed, and organizations' identities remain confidential throughout the reporting process. Researchers also disclosed institutional affiliations, funding sources, and any potential conflicts of interest.

For the quantitative survey portion, comparable ethical standards were upheld. An introductory information sheet appeared at the beginning of the questionnaire, clarifying the study's purpose, scope, and implications. Respondents were reassured that they should not disclose personal or organizational names, thereby preserving their anonymity. Although participants could supply an email address to obtain a brief account on findings, these addresses have been stored separately and do not appear anywhere in the thesis. By observing such ethical practices, the study guarantees respect for participants' rights and privacy, thereby fostering trust and integrity in the overall investigation.

5.7 Chapter summary

A comprehensive and systematic research methodology for the study has been established in the chapter, aligning it with both the theoretical framework and the research objectives. By adopting a mixed-method approach, the methodology captured the multifaceted dimensions of GSCM and Industry 4.0 adoption within African RESCs, ensuring a balanced analysis of quantitative and qualitative insights. The integration of theoretical perspectives from RBV and NRBV underpins the research design, reinforcing the strategic resource optimization and ecological imperatives focus of this study.

Building on the foundation laid in this chapter, the subsequent chapter presents results and findings of this research. It will detail the findings from the empirical investigation, offering insights into how Industry 4.0 technologies and GSCM practices offer impactful contributions towards sustainability outcomes in RESCs. By contextualizing the results within the theoretical framework, the aim is providing a nuanced account of the relationships explored in this research and their practical implications.

6 Qualitative Findings (Thematic Analysis)

6.1 Chapter Introduction

This chapter covers the qualitative results obtained from in-depth thematic analysis of interviews conducted with key stakeholders in the RES. The primary objective of this qualitative investigation is to uncover the critical challenges, barriers, and emerging opportunities in the adoption of GSCM practices and Industry 4.0 technologies. The chapter is structured around the major themes identified during the interviews, including SCM issues, sustainability concerns, and potential solutions proposed by industry experts. The findings reveal a complex interplay of economic, regulatory, and infrastructural factors that shape the operational realities of firms engaged in the RES. By capturing first-hand insights from practitioners, this qualitative analysis provides an empirical groundwork for the subsequent quantitative modelling in the next chapter.

The thematic analysis underscores six major categories of SCM challenges in the Nigerian RES: importation-related issues, logistics inefficiencies, knowledge and skill gaps, economic barriers, regulatory shortcomings, and corruption-related obstacles. Additionally, sustainability issues such as lack of environmental consciousness, poor end-of-life management, and weak enforcement of disposal regulations are explored. The chapter also discusses proposed solutions categorized into GSCM strategies, Industry 4.0 technological interventions, and other policy-driven recommendations. By delving into these qualitative insights, the chapter lays the groundwork for a better comprehension of the systemic issues in the sector and the interaction between GSCM and industry 4.0 technologies, which is subsequently quantified and empirically tested in Chapter 7.

6.2 Supply chain management issues in RES

Informants have mentioned a plethora of SCM related issues in the RES and these generally fall under six categories, namely, importation, knowledge and skill gap, logistics, regulation, economy and corruption related issues. Figure 6-1 depicts the network perspectives of the SCM issues and their respective categories.

6.2.1 Importation related issues

The entirety of interviewees mentioned that the Nigerian RES is faced by issues that impact their businesses negatively due to some impediments that are related to importation and border clearance. Respondent 1 said: “most of this hardware equipment, we only have assembly plants here, most of them are imported. And then you have all this hassle of importation, FX, and then down to even when it gets to our Nigerian borders, there are multitudes of bottlenecks.” Respondent 4 commented on how lead times are affected negatively due to customs and clearance delays: “…customs, the clearing and all that. So, most times we end up spending even far above the cost of the purchase of those items in trying to clear and it takes a long time there. I think there are situations where it takes between three to six months to clear goods...”.

6.2.2 Knowledge and skills gaps related issues

Knowledge and skills gap is another area in which the Nigerian RES is suffering from as alluded by respondents. Respondent 7 stated the lack of manpower capacity and expertise in terms of effective technology deployment: “There is currently no certified training scheme curriculum for building such in our institutions. I think that along the value chain, we need to have institutions that train people… most of the people that are going to deploy are not trained, they are just people that get to learn on the job”. Respondent 1 raised another organisational knowledge gap which is the issue of the lack of knowledge and capability of tracking the activities of a company’s own supply chain, “I think one of the problems is, as a global institution, we have the ability, we have tracking tools that we can actually track some of this. So, if there are any issues, we can actually tell right…, as part of our responsibility working with the client is to also improve on their systems, right. I am not aware of any tracking tool that speaks to how to even quantify some of these challenges, and then how to actually even address them. I don't think Nigeria is actually at that level, unfortunately.” Respondent 6 added: “In terms of sourcing materials from local vendors, we don't really look at their own environmental standards.”

6.2.3 Logistics related issues

Some of the SCM issues include expensive in country logistics as well as infrastructure deficit that stifles smooth logistical operations. Respondent 2 touched on that saying: "…in-country logistical requirements that are there, the cost of that… Someone will tell you that the cost of transporting an equipment from Europe to Lagos is cheaper than transporting that same equipment from Lagos to Kano… Then the infrastructure requirements also moving this equipment from one place to another is also something of a concern". Talking about damages that happen to goods on transit, Respondent 4 said: "…when they (goods) finally arrive, you will see a lot of damages, you see sometimes a lot are missing, some will be missing from the ports,"

6.2.4 Regulation related issues

Lack of effective government policies on RE development, lack of regulation/policy implementation, lack of clarity or synergy among regulatory authorities were all mentioned by respondents. Respondent 1 stressed that "…having all these things properly spelled out in our regulations is not the issue, the issue is the inability of the regulatory bodies to implement… We are not in short of all these regulatory bodies." Respondent 2 also stated: "At times, there's lack of clarity also in terms of… okay for this category of equipment, this has this kind of tariff, levy or… this is it! so there's a lot of mismatches… there is lack of clarity in policy implementation". Respondent 6 spoke on the lack of enforcement of regulations related to sustainable disposal of batteries "…the gap is there because also since companies are not held accountable, or forced to do this waste management, they don't see any reason to pay anybody to dispose of this…". Respondent 7 commented on lack of effective RE development policies: "there has not been policies that are in place that push for them to be formed normal, there was a policy of government on RE, but they are not effective".

6.2.5 Economy related issues

High taxes and tariffs were among the issues raised by respondents, Respondent 8 who works for a government department stated that: "the RE has an abridged process because it is an intervention project and is considered environment friendly project. However, the timelines and cost implications sometimes affect the promoters of the projects, and it can also affect the financial angle especially for investors that are not used to the process. The other charges, the tax and the rest of them in the country as well as some socio-cultural issues". Respondent 5 talked about exchange rate volatility affecting businesses negatively in terms of their SCM: "because of the exchange rates, sometimes you cannot predict how much you're going to spend, and in that process, because of that, usually it affects the project implementation because you may have budgeted to spend, let's say, 100 million Naira (£50,000) in the mini-grid project, but due to the volatility in the exchange rates, at the end of the day before you conclude you might see that your cost is running to 120 or 130 million Naira"

6.2.6 Corruption related issues

Corruption is another issue that affects the Nigerian RES, Respondent 7 who works for a regulatory authority in the Nigerian government talked about the issue of corruption and infidelity by Environmental Impact Assessment (EIA) consultants of RE projects: "…they have some consultants who are accredited as consultants on ESIA [Environmental and Social Impact Assessment] who you must go to, pay them that amount, they write a report for you, sometimes they don't even visit the place. The mini-grid projects are going on around the country, each of them is supposed to get SIA [Social Impact Assessment] report, but you get somebody apply for mini grid project today, by tomorrow he gets an EIA report, when was the study done!" Respondent 4 who works for a mini-grid company added that there is corruption among customs and security agents on the roads stating: "but like the security agencies, they stop at every checkpoint… especially those transporting to the southern part of the country, they have lots of checkpoints on the road and most times you need to be settling… In a nutshell, corruption is a big challenge."

Energy theft is one of the issues stated by respondents, Respondent 5 said: "so one of the problems we have in the mini grid space is issues that have to do with energy thefts, energy through bypass and a lot of commercial losses". Respondent 4, a mini grid company representative, added: "we have scenarios where you give a customer your products, and then they destroy, they open up the pack and then throw away the containers”. Figure 6-1 categorizes the SCM challenges identified during the study into six broad areas: importation, logistics, economy, regulation, knowledge and skill gaps, and corruption. The relationships between these categories are depicted, demonstrating how interconnected challenges impact the RES. This visualization aids in understanding the systemic nature of these issues and their implications for stakeholders.

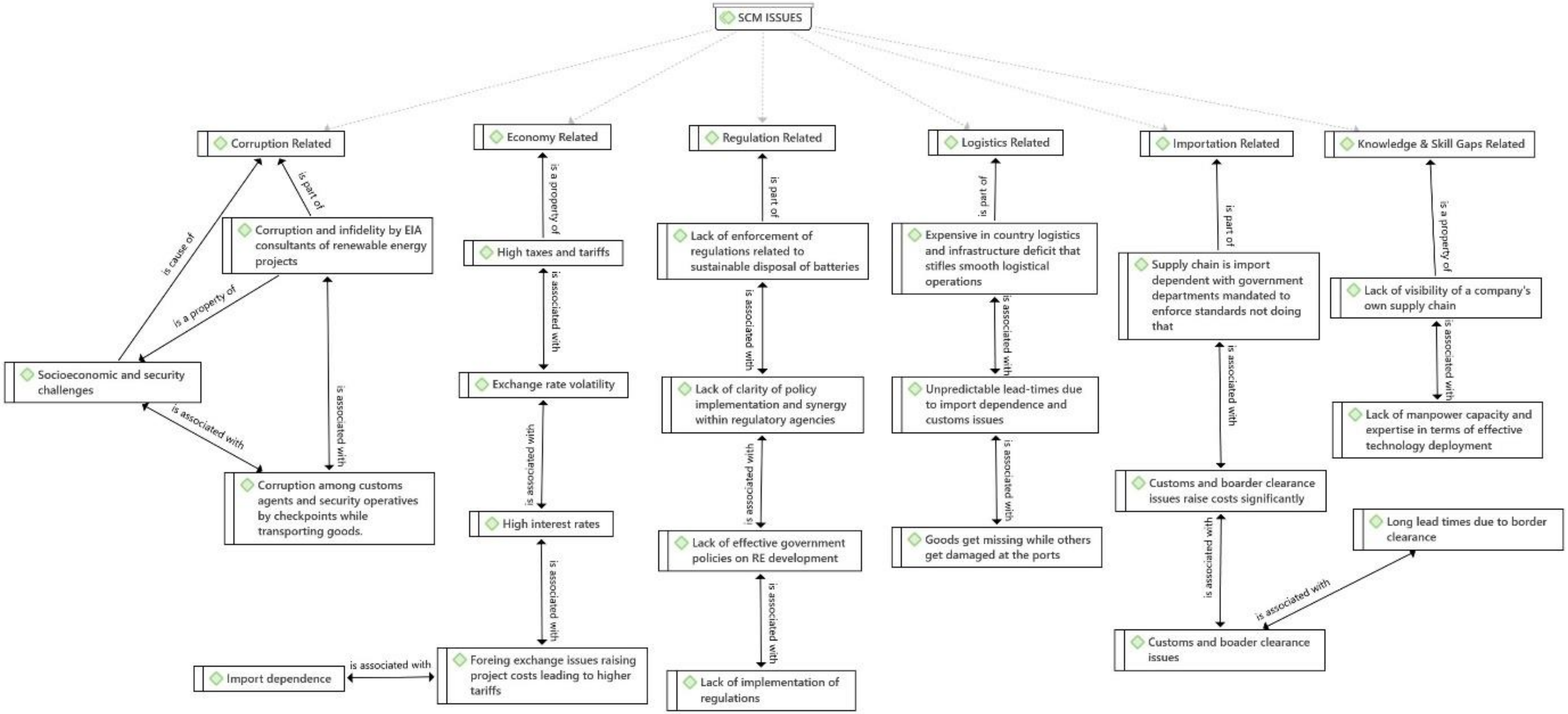

Figure 6-1 SCM issues in Nigerian RES based on empirical findings.

Dotted lines between the topmost cell and the first row beneath it symbolise a subset relationship while the undotted lines depict other types of relationships that are clearly marked.

Figure 6-1 provides a visual synthesis of the major SCM challenges identified through thematic analysis of the interview data. The figure illustrates how importation constraints, logistics inefficiencies, economic pressures, regulatory weaknesses, knowledge gaps, and corruption-related issues jointly shape supply chain operations in the Nigerian RES. The interconnected nature of these categories highlights that SCM challenges in the sector are systemic rather than isolated, reinforcing the need for integrated rather than piecemeal interventions.

6.3 Sustainability issues in RES

Key sustainability challenges identified include:

1. **Lack of Environmental Consciousness**: Respondent 4 said: "I think there is a huge gap… I don't think we have this consciousness of the environment."
2. **Absence of End-of-Life Management Plans**: Respondent 7 noted: "…project involving rural areas, now they are deploying solar panels in villages, but what would happen to them at their end-of-life? So, is there a program to bring them back? Whether for recycling or disposal or remanufacturing, currently there is no plan!". Respondent 4 added: "they dispose those batteries and sometimes our staff they go and say, I saw part of our product in the waste bin…".
3. **Unsustainable Disposal Practices**: Lack of enforcement leads to improper disposal. Respondent 6 said: "the gap is there because also since companies are not held accountable or forced to do this waste management". Respondent 7 mentioned: "…and it's even only one battery company that has the capability to actually dispose of lead acid batteries properly in Nigeria… lithium-ion batteries to dispose of them properly, they have to fly out to the UK and crush. So, there is a gap in terms of waste management".

To further confirm the SCM and sustainability issues obtained in this study and to ascertain how experts perceive these to be pressing, in other words, how important are individual issues to be tackled. Each respondent was provided with the highlights of categories of SCM and sustainability issues. They were asked to assess each issue on a scale of 1 to 10, 1 being least important and 10 being most important to be addressed. The scores assigned to individual categories of issues were compiled to ascertain the weightage scores of each issue by taking the average of entire scores assigned to each issue category. Assigning these scores to issues helps stakeholders and firms to prioritize their efforts and allocate resources where due at the right time. This approach is adopted from Akram et al., (2024). Table 6-1 quantifies the relative importance of identified challenges based on participant evaluations. By assigning weightage scores, it prioritizes issues that require immediate attention, such as economic barriers, importation challenges, and logistics inefficiencies. The data serves as a decision-making tool for stakeholders to allocate resources effectively and address the most critical barriers in the sector. Figure 6-2 categorizes the sustainability challenges faced in the Nigerian RES, such as a lack of environmental consciousness, unsustainable waste management practices, and inadequate regulatory enforcement. The relationships between these issues are depicted, highlighting systemic gaps that hinder the adoption of sustainable practices. The visualization underscores the need for integrated approaches to address these challenges.

Table 6-1 SCM and sustainability issues weightage scores

SCM issues		**Sustainability issues**	
Category	***Weightage score***	***Issue***	***Weightage score***
Importation related issues in the sector (customs and border clearance issues, high levies and taxes, substandard goods flooded into RE market)	8.4	Logistics are fossil based and there is absence of any plans to green the logistics.	6.8
Economy related issues in the sector (foreign exchange issues, access to finance, high interest rates)	9	Lack of environmental consciousness among vendors as well as customers within the sector.	6.6
Regulatory issues in the sector (Lack of clarity on policy implementation and synergy among regulatory	5.2	Unsustainable disposal of solar modules like batteries by customers.	6

agencies, lack of effective policies, lack of enforcement of policies)			
Corruption related issues in the sector (Goods missing and damaged at port, corruption among customs agents, security operatives at checkpoints and EIA consultants, energy theft)	6.8	Lack of firms that recycle and sustainably dispose of batteries in Nigeria.	6.6
Logistics related issues in the sector (Expensive in-country logistics, long lead times due to border clearance and high cost of border clearance)	7.4	Lack of enforcement of regulations related to sustainable disposal of batteries.	6.2
Knowledge and skill gap related issues in the sector (Lack of knowledge and capability of tracking SCs, lack of manpower in effective technology deployment)	6.2	There are often no plans for end-of-life management of RE modules.	7.4

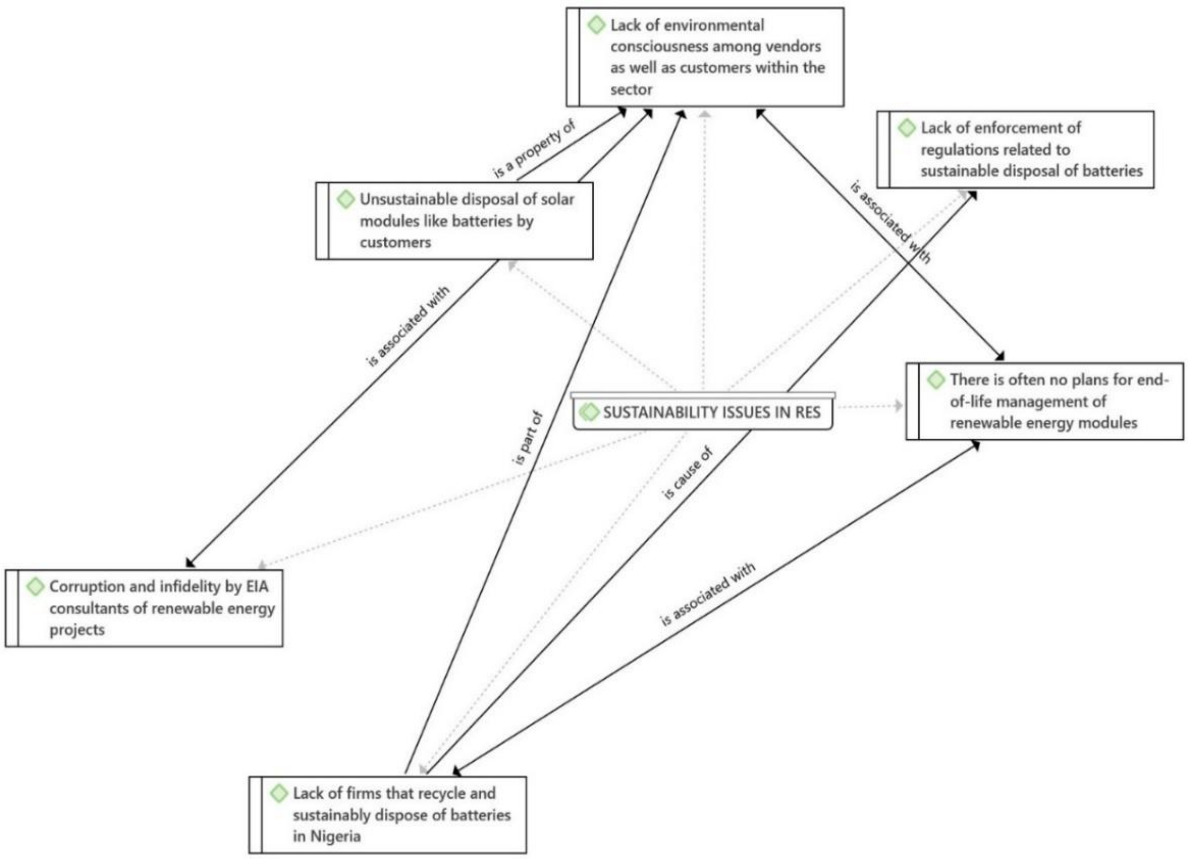

Figure 6-2 Sustainability issues in the Nigerian RES based on empirical findings

Figure 6-2 visually reinforces the sustainability-related barriers confronting firms in the Nigerian RES, particularly the absence of structured end-of-life management and limited environmental accountability. These findings align directly with the study's objective of identifying sustainability bottlenecks that GSCM and Industry 4.0 technologies may help address. The figure therefore provides empirical grounding for the subsequent exploration of solution pathways.

6.4 Solutions to SCM and sustainability issues

During this empirical study, several solutions proffered by respondents to tackle some of these SCM and sustainability issues in the RES were gathered. Experts proposed several solutions to address the identified challenges, categorized into GSCM solutions, Industry 4.0 solutions, and other approaches. Figure 6-3 depicts the solutions proffered based on GSCM and Industry 4.0 among other solutions. In the following subsections, GSCM and Industry 4.0 solutions to SCM and sustainability issues in RES are discussed.

6.4.1 GSCM solutions to Nigerian RES issues

The following GSCM solutions were identified through the empirical study.

1. **Approved Vendor Lists**: Maintaining databases of vetted, responsible suppliers. Respondent 1 said: "we have identified companies that are credible, that also through their backend SCs, there is predictability in terms of how they source their raw materials, how they interact with people, and they interact with environment and all that. So, we have a database that speaks to companies that we've vetted".
2. **Carbon Footprint Assessment**: Conducting assessments to understand emissions. Respondent 3 suggested: "assess where we are and then also have a pathway to reducing our carbon emission and I think that is not just internally as companies, but also you know the components and factors of production that are coming into your business, especially from your vendors."
3. **Embedding Decommissioning Costs**: Including decommissioning in budgets. Respondent 7 proposed: "We have what we call decommissioning cost, which is built in the budget, so that as you are collecting your money, you can also keep that amount… So, over time that money that has accumulated, and is grown, it can be used to tackle that issue."
4. **ISO 9001 Certification**: Pursuing environmental management standards. Respondent 3 said: "we are actually trying to get the ISO certification. I believe is ISO 9001, environmental management system… so, we are definitely very curious about making sure that we have the right structures in place to sustain very high environmental standards as well as quality standards."
5. **Partnerships with Waste Disposal Firms**: Collaborating for proper recycling. Respondent 3 added: "RE wastes in the environment and we have partnerships with some waste disposal firms who are focused in the sector for ensuring that whenever we have batteries that have reached end of life, we can actually hand them over to them for appropriate recycling."
6. **Refurbishing and Reusing Modules**: Reducing importation through refurbishment. Respondent 4 mentioned: "but in the last six months, I don't

think we have imported any items from outside. So, most times what we've been doing for this period, is mostly refurbish."

7. **Recycling and Retrofitting Initiatives**: Encouraging full recycling. Respondent 1 emphasized: "And that is why I said as part of the ESMP for the projects, there is a need to ensure that there is full recycling or full retrofitting, and most of these assembly plants that we have, we're encouraging them to see how they can also retrofit." Respondent 5 stressed the importance of reusing modules: "I mean this has been one of the challenging aspects that at the end of the lifetime of your equipment what are you going to do with them? So, starting with the solar panels... they are being reused… which also increases the sustainability, that re-usage".
8. **Logistics Incentivization and Importation Waivers**: Seeking government support. Respondent 1 suggested: "So in terms of logistics challenges, and then importation and then getting them down to individual project sites, you know, I did mention something about waiver, that's our own way of providing a solution to that challenge"
9. **Promoting Environmental Education**: Enhancing consciousness. Respondent 6 said: "we've tried our best and since we mandate our customers already, staff in the warehouse have been trained. So, in terms of the organization, yes, the mindset of sustainability is there... Government has to force people, and government has to train the population. If you don't do that, it's not going to happen."

6.4.2 Industry 4.0 solutions to Nigerian RES issues

Adoption of Industry 4.0 technologies is currently limited but focused on the following solutions:

1. **IoT for Smart Metering**: Implementing smart meters for energy management. Respondent 2 said: "Yeah, so the IoT thing, smart metering is a key thing that we definitely do... because that is what shows that revenue comes from it." Respondent 4 added: "what we use is IoT. So, because it helps you… the

remote control of the device itself... to be able to control the unit, switch on switch off, you know, tests to see the power, how well the unit is working."

2. **Data Analytics for Site Identification and Planning**: Utilizing analytics for planning. Respondent 2 mentioned: "Village Intelligence Data Analytics that we use a lot it helps in identification of sites and creating some socio-economic data of the site, which shows whether that site has the viability for a particular capacity of a mini grid to be developed."

6.4.3 Other solutions to Nigerian RES issues

Other solutions obtained in the study that are not directly related to GSCM or Industry 4.0 are discussed below.

1. **Human Capital Development**: Developing curricula and training programs. Respondent 1 said: "so we're working with NAPTIM, we're also working with NEMSA, the technical regulatory body, we're also working with them coming up with different curriculums to see how to also engage people in installation, certification, operation, O and M."
2. **De-risking the Sector through Incentives**: Providing financial incentives. Respondent 2 stated: "we de-risk the sector so that we get more private sector to come and participate in the RES and one of it is now provided this um, this Nigeria Electrification Project where we provide um the subsidy grants to private sector just purposely to incentivize them in um harnessing the opportunities in the sector."
3. **Supply Chain Financing Initiatives**: Establishing procurement processes with reduced upfront costs. Respondent 5 said: "…companies who are enablers of RE, …so what they did recently, they just launched a RESC or procurement kind of enabling process where if you have a project you want to embark on, you can engage them... You can just pay 10% or let's say 10 to 30% of that amount."
4. **Information Sharing Platforms**: Utilizing digital platforms for collaboration. Respondent 5 added: "all the projects now come in through odyssey platform. So you go on odyssey, create your own account register that project and for

> what purpose, and with that, you are not only entering, you're also entering all the relevant databases... when you're looking for information on RE projects in Africa, or in Nigeria you can go to odyssey, all the projects that have been completed or under construction, or ongoing or planned projects that are yet to come."

Figure 6-3 presents a comprehensive framework of solutions categorized into GSCM practices, Industry 4.0 technologies, and other innovative strategies. The figure emphasizes actionable approaches, such as recycling, smart metering, and capacity building, illustrating how these interventions can tackle interconnected challenges in the sector. This provides a roadmap for stakeholders to enhance sustainability and efficiency.

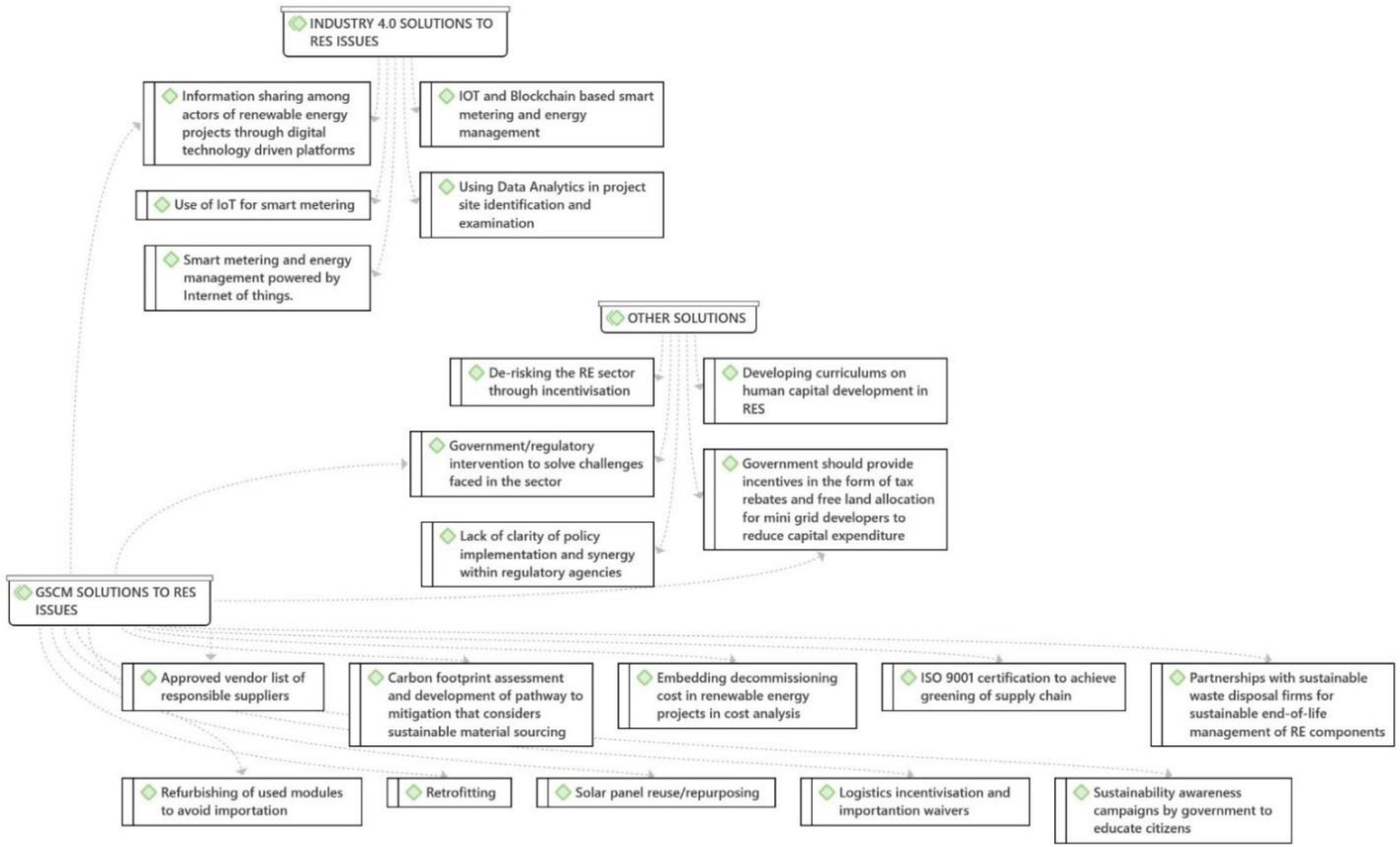

Figure 6-3 Solutions to SCM and sustainability issues in Nigerian RES.

Figure 6-3 presents a consolidated overview of the solutions proposed by interview participants to address SCM and sustainability challenges in the Nigerian RES. These solutions are grouped into GSCM practices, Industry 4.0 technologies, and complementary policy and capacity-building measures. The figure illustrates that practitioners perceive sustainability challenges as requiring multi-layered responses rather than reliance on a single intervention.

6.5 Chapter summary

This chapter has presented a thematic analysis of qualitative data collected from industry practitioners, providing in-depth insights into the multi-faceted challenges and potential solutions surrounding sustainability, SCM, and the adoption of Industry 4.0 technologies in Nigeria’s RES. In line with the first research objective and sub-question, the findings identified six critical categories of SCM challenges (importation constraints, high logistics costs, knowledge and skill shortages, economic difficulties, regulatory inefficiencies, and corruption-related impediments) as well as pressing sustainability challenges such as poor environmental consciousness, inadequate end-of-life management, and weak regulatory enforcement. Together, these to some extent highlight the systemic barriers that shape the operating environment of African RESCs.

By capturing practitioner perspectives, the chapter also makes progress toward the second research objective and sub-questions, illustrating how Industry 4.0 technologies particularly IoT-enabled smart metering and data analytics are beginning to facilitate GSCM adoption by improving monitoring, planning, and control. However, their application remains limited due to infrastructural deficits, cost barriers, and knowledge gaps, underscoring the contingent nature of digital–green integration in African contexts.

Finally, the solutions proposed by experts ranging from GSCM practices such as approved vendor lists, carbon footprint assessments, and waste recycling partnerships, to Industry 4.0-driven interventions and broader capacity-building and policy reforms inform the third research objective. They reveal how the combined application of digital technologies and green practices can potentially enhance RE firms, provided systemic barriers are addressed.

Overall, this qualitative phase not only fulfils the objective of identifying and analysing key challenges but also demonstrates how GSCM and Industry 4.0 can jointly offer pathways to overcome them. In doing so, it provides empirical groundwork that links directly to the primary research question on how integration affects sustainability performance in African RESCs. The chapter thus establishes a contextually grounded basis for the quantitative analyses in Chapter 7, where these relationships are statistically tested and validated across environmental, economic, and social dimensions.

The themes identified in this chapter provided the empirical basis for refining the survey constructs and measurement items presented in Appendix 3 and tested quantitatively in Chapter 7.

To further synthesise these findings and to highlight the contextual distinction between African RESCs and those predominantly examined in the extant literature, Figure 6-4 presents a comparative synthesis of literature-derived insights and empirical evidence from the Nigerian RES. The figure illustrates how prior studies largely emphasise balanced upstream–downstream dynamics, advanced GSCM practices, and mature Industry 4.0 applications, whereas the qualitative findings reveal a downstream-dominated challenge structure, high import dependence, and limited digital–green integration. This visual synthesis clarifies the contextual gap addressed by this study and explains how the qualitative phase informed the development of the conceptual model and hypotheses subsequently tested in Chapter 7.

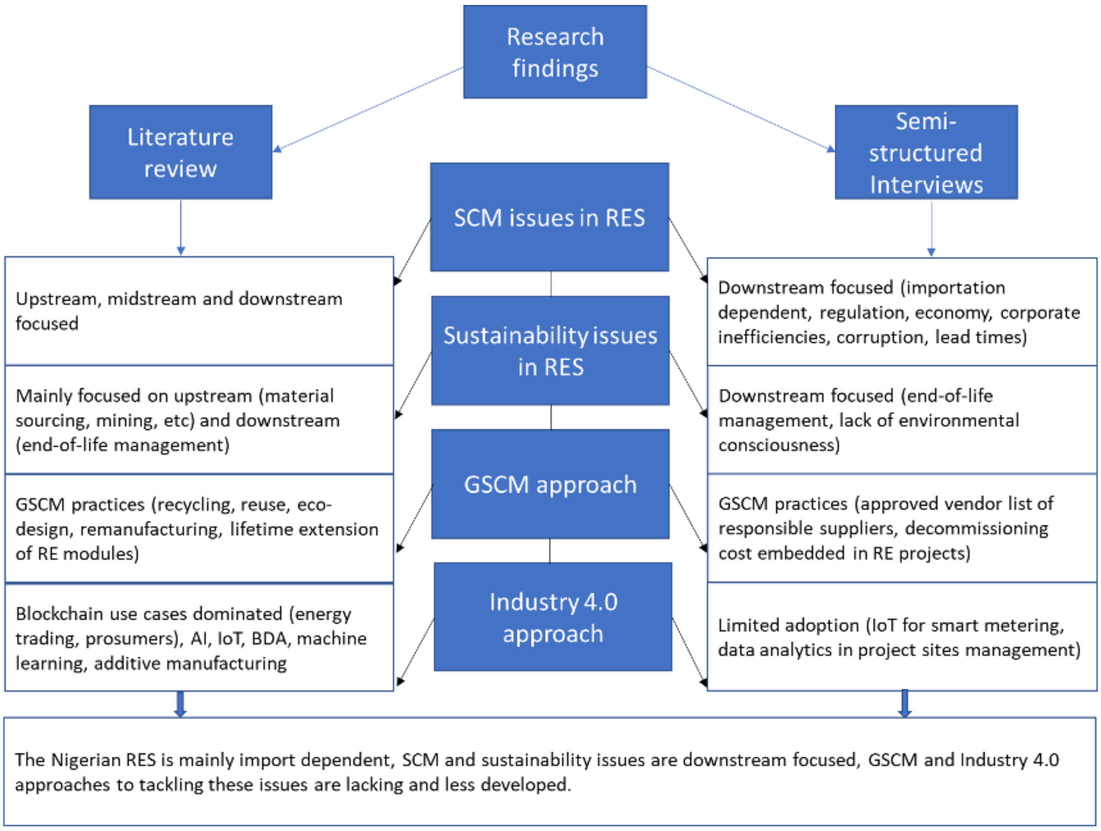

Figure 6-4 Comparative synthesis of literature-based perspectives and qualitative findings in the Nigerian RE supply chain.

7 Quantitative Results and Interpretation

7.1 Chapter introduction

Building upon the qualitative insights presented in Chapter 6, this chapter provides a quantitative analysis to empirically validate the relationships between Industry 4.0 technologies, GSCM practices, and sustainability performance within the RES. The qualitative phase revealed context-specific challenges and solution pathways in the Nigerian RES, while also highlighting structural distinctions between African RESCs and those predominantly examined in the extant literature. These insights informed the development of the conceptual research model and hypotheses tested in this chapter.

By leveraging PLS-SEM, this chapter statistically examines the proposed hypotheses across a broader African context, thereby extending the depth of the qualitative findings through wider empirical generalisation. The key objective here is to test how Industry 4.0 technologies influence GSCM adoption, and how this interplay impacts sustainability performance across economic, environmental, and social dimensions.

To achieve this, the study employs a survey-based quantitative approach, drawing on 101 valid responses from firms operating in the RES across multiple African countries. This broader geographic scope enables the study to assess whether the relationships identified qualitatively are robust across diverse institutional, infrastructural, and market conditions. The dataset undergoes rigorous statistical validation, including data purification, reliability and validity testing, and structural model assessment.

This quantitative analysis is critical in validating the conceptual model derived from the integrated RBV–NRBV framework and in providing empirical support for the theoretical mechanisms identified earlier in the study. The findings presented in this chapter further inform policy recommendations and strategic implications for RE supply chain organisations seeking to enhance sustainability performance through Industry 4.0–enabled GSCM strategies.

7.2 Partial least squares-structural equation modelling results

7.2.1 Measurement Model Assessment

Measurement model was tested using PLS-SEM to ensure construct validity and reliability, following established guidelines in existing studies (Hair et al., 2017, Benitez et al., 2020). The evaluation focused on indicator reliability, construct reliability (Composite Reliability and Cronbach's alpha), construct validity (convergent validity and discriminant validity) to confirm that constructs accurately represent the theoretical dimensions they are intended to measure. Factor loadings exceeding 0.708 additionally supported model's validity, nonetheless, only 1 indicator (DM3) exhibited slightly weaker outer loading of 0.667 below 0.708, though according to Hair et al. (2019) that is an acceptable value especially in exploratory research, hence that was retained.

Moreover, the results showed that the entirety of constructs exceeded recommended threshold (0.70), affirming internal consistency of measurement model. Composite reliability ranged between 0.849 and 0.936, indicating that the underlying theoretical dimensions are effectively captured by the constructs. To establish convergent validity, the model was tested by factor loadings and Average Variance Extracted (AVE), to ensure that every construct elucidates a minimum of 50% of its indicator's variance. It was established through the analysis that each construct has fulfilled the AVE threshold (0.50), where values range between 0.673 to 0.831. Table 7-1 presents the measurement model evaluation results.

Table 7-1 Measurement model evaluation and construct indicators

Indicator	Loadings	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Data Management (DM)		0.769	0.833	0.865	0.685
DM1	0.910				
DM2	0.884				
DM3	0.667				
Eco-design		0.643	0.643	0.849	0.737

ECO1	0.854				
ECO2	0.863				
Economic Performance (ECP)		0.838	0.845	0.902	0.755
ECP1	0.892				
ECP2	0.867				
ECP3	0.847				
Environmental Performance (ENP)		0.843	0.846	0.906	0.763
ENP1	0.878				
ENP2	0.924				
ENP3	0.814				
Financial Planning (FP)		0.874	0.889	0.923	0.799
FP1	0.839				
FP2	0.931				
FP3	0.909				
Green Purchasing/Procurement (GPP)		0.756	0.761	0.86	0.673
GPP1	0.764				
GPP2	0.857				
GPP3	0.836				
Internal Environmental Management IEM		0.838	0.848	0.893	0.678
IEM1	0.799				
IEM2	0.914				
IEM3	0.860				
IEM4	0.706				
Digital Technology Adoption for Sustainability (DTAS)		0.913	0.914	0.935	0.742
DTAS1	0.835				
DTAS2	0.853				
DTAS3	0.850				
DTAS4	0.895				
DTAS5	0.874				
Social Performance (SCP)		0.898	0.914	0.936	0.831
SCP1	0.910				
SCP2	0.953				
SCP3	0.870				

It is worth noting that the Cronbach's alpha and rho_a values for the **Eco-design (ECO)** construct (0.643) fall slightly below the conventional 0.70 threshold. However, this does not necessarily undermine the construct's reliability. First, both **composite reliability (0.849)** and **AVE (0.737)** for ECO are comfortably above the recommended thresholds of 0.70 and 0.50 respectively, indicating strong internal consistency and convergent validity (Hair et al., 2017; Benitez et al., 2020). Second, prior methodological literature acknowledges that Cronbach's alpha can underestimate reliability in constructs with a limited number of indicators (Cortina, 1993, Hair et al., 2019). Since ECO is measured with only two indicators, lower alpha values are statistically expected and should be interpreted cautiously. In such cases, composite reliability and AVE provide more robust criteria for judging construct adequacy. Following this rationale, and consistent with recent empirical studies in supply chain and sustainability research (e.g., Trujillo-Gallego et al., 2022b; Umar et al., 2022b), the ECO construct is considered reliable and was retained for further analysis.

Discriminant validity got tested using the duo, Heterotrait-Monotrait (HTMT) Ratio and the Fornell and Larcker Criterion (Henseler et al., 2014). Based on the Fornell and Larcker analysis, it was confirmed that the square root of every construct's AVE exceeded inter-construct correlations, suggesting that the constructs are dissimilar from each other. Additionally, to further validate discriminant validity, HTMT ratio was employed, with every construct presenting value below the 0.90 threshold, this is indicative of sufficient construct distinctiveness further supporting discriminant validity (Hair et al., 2017).

While HTMT value for the ECO–ECP pair is close to the 0.90 threshold, it is still within the acceptable range for discriminant validity assessment (Hair et al., 2017). Prior research works (Trujillo-Gallego et al., 2022b, Umar et al., 2022b) have reported HTMT values slightly below the threshold. Given the theoretical interconnectedness of ECO and ECP, a marginally high HTMT value doesn't necessarily denote a lack of discriminant validity, rather, it reflects their expected conceptual overlap while still maintaining statistical separability. Table 7-2 and 7-3 present discriminant validity results (Fornell-Larcker Criterion and HTMT respectively).

Table 7-2 Discriminant Validity in SEM using Fornell-Larcker Criterion

	DM	**ECO**	**ECP**	**ENP**	**FP**	**GPP**	**IEM**	**DTAS**	**SCP**
DM	**0.828**								
ECO	0.322	**0.858**							
ECP	0.244	0.591	**0.869**						
ENP	0.400	0.513	0.726	**0.873**					
FP	0.657	0.225	0.178	0.185	**0.894**				

GPP	0.496	0.352	0.337	0.388	0.420	**0.820**			
IEM	0.450	0.525	0.671	0.706	0.317	0.575	**0.823**		
DTAS	0.669	0.303	0.254	0.334	0.750	0.440	0.431	**0.861**	
SCP	0.257	0.563	0.766	0.725	0.139	0.368	0.593	0.224	**0.912**

Table 7-3 Discriminant Validity in SEM using HTMT Ratio

	DM	**ECO**	**ECP**	**ENP**	**FP**	**GPP**	**IEM**	**DTAS**	**SCP**
DM									
ECO	0.467								
ECP	0.279	0.803							
ENP	0.477	0.697	0.850						
FP	0.780	0.294	0.206	0.213					
GPP	0.630	0.499	0.425	0.491	0.504				
IEM	0.542	0.717	0.794	0.840	0.367	0.719			
DTAS	0.783	0.394	0.283	0.379	0.838	0.517	0.492		
SCP	0.284	0.733	0.874	0.840	0.160	0.448	0.681	0.246	

These results therefore established that the research model confirmed a convincing internal consistency, convergent validity, reliability, as well as discriminant validity, strengthening its empirical robustness. Generally, with the results above, it is confirmed that measurement model is both valid and reliable, providing a solid empirical foundation for the next phase of the analysis. Having established validity and reliability of the measurement model, the following section focuses on evaluating the structural model, where the hypothesized interactions among Industry 4.0 technologies, GSCM practices, and sustainability performance will be tested.

7.2.2 Hypothesis Testing Results and Structural Model Assessment

During structural model assessment, the higher-order constructs were validated as well as the individual lower order constructs. Each construct was evaluated for validity and reliability so that robustness in measurement is ensured. Moreover, the higher-order construct's discriminant validity in relation to lower-order constructs was examined, following the recommendations of Sarstedt et al. (2014). Validity and reliability criteria were both met as affirmed by the results, indicating the measurement framework's robustness.

Internal consistency and convergent validity of every construct was confirmed. The AVE values recorded were higher than 0.50 and the reliability values exceeded 0.70, indicating a sufficient fraction of variance elucidated by the latent constructs (see Table 7-4). Besides the assessment of validity and reliability, discriminant validity of higher-order construct relative to the lower-order constructs was also evaluated.

Table 7-4 Higher order constructs reliability and validity

	Cronbach 's alpha	**Composite reliability (rho_a)**	**Composite reliability (rho_c)**	**Average variance extracted (AVE)**
GSCM Practices	0.738	0.764	0.851	0.657
Industry 4.0 Adoption	0.871	0.891	0.920	0.793
Sustainability Performance	0.895	0.895	0.934	0.826

Fornell and Larcker (1981) criterion results confirmed that the square root of higher-order constructs' AVE was higher than its correlations with every other construct, affirming discriminant validity (see Table 7-5). This means that each construct shares more variance with its own indicators than with other constructs, thereby demonstrating that the constructs are empirically distinct. These findings all together affirm the rigor and higher-order construct's validity, ensuring its appropriateness for inclusion in the structural model.

Table 7-5 Fornell-Lacker criterion

	GSCM Practices	**Industry 4.0 Adoption**	**Sustainability Performance**
GSCM Practices	**0.811**		
Industry 4.0 Adoption	0.528	**0.890**	
Sustainability Performance	0.729	0.315	**0.909**

7.2.3 Hypothesis Testing Results

With 5,000 subsamples, a bootstrapping procedure was conducted to evaluate the proposed hypotheses and to determine path coefficients (standardized beta), t-values, and p-values. The findings indicate that **H1** is not supported, demonstrating that Industry 4.0 technologies lack significant positive direct interaction with sustainability performance (H1- $\beta = -0.097$, $t = 1.148$, $p > 0.05$).

For **H2**, which examines the impact of Industry 4.0 technologies on GSCM practices, results reveal a significant and positive effect (H2- $\beta = 0.528$, $t = 7.543$, $p < 0.05$), confirming the hypothesis. Similarly, **H3**, which investigates whether GSCM practices positively influence sustainability performance, is also supported, a positive and significant association was indicated (H3- $\beta = 0.780$, $t = 10.052$, $p < 0.05$). Generally, these results confirm the proposed relationships, reinforcing the impactful role of Industry 4.0 technologies on GSCM practices implementation, as well as the latter's positive influence on sustainability performance. Hypothesis testing examination findings are presented in Table 7-6.

Table 7-6 Results of hypotheses tests

	β	**t-value**	**P values**	**Status**
H1: Industry 4.0 Adoption -> Sustainability Performance	-0.097	1.148	0.126	Not supported
H2: Industry 4.0 Adoption -> GSCM Practices	0.528	7.543	0.000	Supported
H3: GSCM Practices -> Sustainability Performance	0.780	10.052	0.000	Supported

Mediating effect of GSCM practices in sustainability performance-Industry 4.0 technologies relationship was analysed to test **H4**. The total effect was recorded to be insignificant and positive (H1- $\beta = -0.097$, $t = 1.148$, $p > 0.05$). With GSCM practices serving as a mediator construct, this effect changed, thus it was recorded to be positive and significant (H4- $\beta = 0.412$, $t = 5.202$, $p < 0.05$). This result therefore suggests complete mediation, indicating that GSCM practices fully mediate the relationship between Industry 4.0 technologies and sustainability performance. Thus, **H4** is statistically supported. The mediation analysis results reinforce the impactful role of GSCM practices being key channels through which Industry 4.0 technologies influence sustainability performance in firms. The mediation analysis result is presented in Table 7-7.

Table 7-7 Mediation (Indirect effect) analysis

	β	**t-value**	**P values**	**Status**
H4: Industry 4.0 Adoption -> GSCM Practices -> Sustainability Performance	0.412	5.202	0.000	Supported

A comparison of H1 and H4 provides important theoretical and practical insights. H1 was not supported, as Industry 4.0 adoption showed no significant direct effect on sustainability performance ($\beta = -0.097$, $t = 1.148$, $p > 0.05$). This suggests that digital technologies alone do not automatically translate into improved environmental, economic, or social outcomes. In contrast, H4 was supported, showing a significant indirect effect when GSCM practices mediated the relationship between Industry 4.0 and sustainability performance ($\beta = 0.412$, $t = 5.202$, $p < 0.05$). This indicates that the impact of Industry 4.0 on sustainability performance is realized only when digital tools are embedded within structured GSCM frameworks. Taken together, the rejection of H1 and support for H4 highlight that in African RESCs, Industry 4.0 technologies function as enablers rather than standalone drivers of sustainability performance, reinforcing the NRBV's view that environmental capabilities must complement technological resources for firms to achieve meaningful sustainability gains. To visually summarise the tested relationships, standardized path coefficients, and mediation effects discussed above, Figure 7-1 presents the final structural equation model estimated using PLS-SEM.

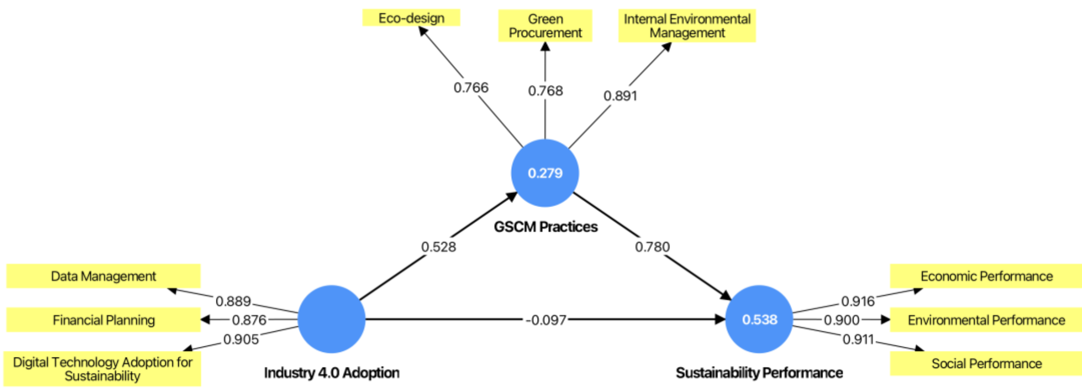

Figure 7-1 Final Structural Equation Model Showing Hypothesis Testing Results

The figure presents the final structural equation model with standardized path coefficients obtained through PLS-SEM bootstrapping. The directional arrows represent the hypothesised causal relationships among the latent constructs, while the numerical values on each path indicate standardized beta coefficients reflecting the strength and direction of these relationships.

Furthermore, the coefficient of determination, or R-square (R^2) values of the proposed hierarchical component model were calculated. The R^2 value represents measure of how independent variables describe variance recorded in dependent variables. Computed R^2 values for GSCM practices and Sustainability performance were 0.279 and 0.538 respectively. Based on Sarstedt et al. (2014), R^2 is categorised as weak (≥0.19), moderate (≥0.33), and substantial (≥0.67). Results of the current study show that R^2 values are within moderate and acceptable range, demonstrating a reasonable level of explanatory power (Sarstedt et al., 2014).

Moreover, quality of the inner model is also determined by its predictive capability for endogenous variables (Hair et al., 2019). Inner model evaluation is conducted using the (R^2) to measure the influence of exogenous variables upon endogenous variables, while Q^2 assesses the model's cross-validation to ensure predictive relevance (Hair et al., 2017). Additionally, Q^2 measures cross-validation redundancy, which evaluates model's relevance and predictive accuracy (Hair et al., 2017). Q^2 value In PLS-SEM must be greater than 0 for predictive relevance of model to be affirmed. Based on the results obtained, all constructs exhibit values higher than 0, there by substantiating predictive relevance of the model. Table 7-8 presents the computed R^2 and Q^2 values, illustrating model predictive power.

Table 7-8 Model predictive quality

	R^2	Q^2
GSCM Practices	0.279	0.252
Sustainability Performance	0.538	0.076

7.3 Chapter summary

This chapter has presented a comprehensive quantitative analysis of the relationships among Industry 4.0 technologies, GSCM practices, and sustainability performance within RESCs. Using PLS-SEM, the study empirically tested its hypotheses and provided statistical validation for the proposed conceptual model.

The results yielded several important insights. First, Industry 4.0 technologies do not directly improve sustainability performance (H1 not supported). This finding challenges assumptions in parts of the literature that view digital transformation as an automatic driver of sustainability and instead reinforces the argument that technology alone is insufficient to deliver environmental, economic, or social gains. Second, Industry 4.0 technologies significantly enhance GSCM adoption (H2 supported), confirming that digitalization acts as an enabler by strengthening capabilities such as visibility, traceability, and efficiency in supply chain processes. Third, GSCM practices exert a strong and positive influence on sustainability performance (H3 supported), underscoring the central role of practices such as GPP, ECO, and IEM in driving triple bottom line outcomes. Finally, the analysis revealed that GSCM fully mediates the relationship between Industry 4.0 technologies and sustainability performance (H4 supported). This indicates that while Industry 4.0 provides the digital infrastructure and tools, sustainability benefits only materialize when these technologies are strategically embedded within structured green supply chain frameworks.

Taken together, these findings confirm that in African RESCs, Industry 4.0 technologies should be understood as capability enablers rather than standalone drivers of sustainability performance. The chapter thereby advances the study's second and third objectives, demonstrating empirically that (1) digital technologies facilitate the adoption of GSCM practices, and (2) the integration of Industry 4.0 with GSCM practices is essential for achieving sustainability outcomes.

In the next chapter, these results are synthesized into a broader discussion of theoretical contributions, managerial implications, policy recommendations, and avenues for future research, providing a holistic understanding of how digital–green integration can drive sustainable transitions in RESCs.

8 Discussion

8.1 Chapter Introduction

This chapter gives a comprehensive discussion of the key findings of this study, situating them within the broader academic discourse and theoretical frameworks that underpin the research. The study aimed to examine the interplay between GSCM practices and Industry 4.0 technologies in enhancing sustainability performance within RESCs, particularly focusing on Africa. In pursuit of this objective, the study sought to answer three fundamental research questions: (1) What are the key sustainability and SCM challenges confronting African renewable energy firms? (2) How do Industry 4.0 technologies influence the implementation of GSCM practices in African RE firms? and (3) What is the combined impact of Industry 4.0 technologies and GSCM practices on sustainability performance encompassing environmental, economic, and social dimensions within Africa's RESCs?

As was mentioned in Chapter 4, this research employed the RBV and the NRBV as its theoretical lenses to explore the relationships among Industry 4.0 technologies, GSCM practices, and sustainability performance. For the sake of empirically testing these relationships, four hypotheses were initially developed: **H1**, proposing that *Industry 4.0 technologies significantly enhance a firm's sustainability performance through the enablement of real-time environmental monitoring, resource efficiency, and transparency in their supply chains*; **H2**, suggesting that *Industry 4.0 technologies enhance the implementation of GSCM practices by enabling supply chain transparency, real-time environmental monitoring, and data-driven collaboration with green partners*; **H3**, asserting that *GSCM practices significantly improve sustainability performance by enhancing resource efficiency, environmental accountability, and environmental coordination of supply chain activities*; and **H4**, hypothesizing that *the positive and significant impact of Industry 4.0 technologies on sustainability performance is enabled through the implementation of GSCM practices*.

This chapter is structured to provide a critical analysis of research findings, highlighting theoretical, practical, and policy implications. The discussion begins with an interpretation of the key findings and contributions, wherein the research outcomes are critically examined in relation to the objectives of the study establishing comparison with extant literature to identify points of convergence, divergence, and knowledge advancement. This is followed by a discussion of the theoretical contributions, detailing how the findings refine and extend existing theories in supply chain sustainability and digital transformation, particularly within the RBV and NRBV frameworks. The chapter then presents the practical contributions, outlining actionable insights for businesses, policymakers, and supply chain managers, particularly concerning the integration of Industry 4.0 technologies into GSCMPs. Limitations and future research directions are subsequently discussed, acknowledging methodological, contextual, and theoretical constraints while identifying opportunities for further scholarly inquiry. Lastly, the chapter finishes with an account on the findings of this thesis, reinforcing the study's significance and outlining its implications for advancing research, policy, and practice in sustainable and digitally enabled supply chains.

8.2 Summary of findings

In line with the first research question that seeks to discover sustainability and SCM challenges faced by RE firms operating in Africa, this study found a plethora of SCM challenges which were then categorized as being importation-related issues, logistics inefficiencies, knowledge and skill gaps, economic barriers, regulatory shortcomings, and corruption-related obstacles. Also, sustainability issues such as lack of environmental consciousness, poor end-of-life management, and weak enforcement of disposal regulations are explored. Additionally, some proposed solutions categorized into GSCM strategies, Industry 4.0 technological interventions, and other policy-driven recommendations were obtained.

To answer the second and third research questions (see 8.1) and to test the developed hypotheses, a quantitative analysis to empirically validate the associations among Industry 4.0 technologies, GSCM practices, and sustainability performance within the African RES reveals that Industry 4.0 technologies do not directly improve sustainability performance (H1 not supported), Industry 4.0 technologies significantly enhance GSCM adoption (H2 supported), GSCM practices have a strong, positive effect on sustainability performance (H3 supported) and that GSCM practices fully play the mediator role in the interplay between Industry 4.0 technologies and sustainability performance (H4 supported).

8.3 Discussion of Qualitative Findings

The findings of this study reveal that African RESCs are plagued by significant SCM challenges, many of which stem from importation-related barriers. These challenges manifest as customs delays, excessive tariffs, and high costs associated with the clearance of goods. Border inefficiencies and corruption exacerbate these problems, leading to prolonged lead times and elevated operational costs. The research highlights corruption as a pervasive issue in African RESCs, particularly in interactions with customs and clearance agents. Additionally, irregularities involving EIA consultants further hinder the approval process for RE projects, adding bureaucratic delays and financial burdens.

Research Question 1:

What sustainability and SCM challenges do African RE firms face?

To address this question, the study identified six broad categories of SCM challenges related to importation, logistics, knowledge and skill gaps, regulatory barriers, economic constraints, and corruption, as well as three major sustainability concerns, namely low environmental consciousness, lack of end-of-life management, and unsustainable disposal practices. These issues reflect the systemic weaknesses in African RESCs that limit efficiency, raise operational costs, and hinder sustainability integration. Table 8-1 provides an overview of these challenges before they are discussed in detail.

Table 8-1: Summary of SCM and Sustainability Challenges in Nigerian RESCs

Category	Key Issues Identified
Importation	Customs delays, high tariffs, foreign exchange volatility, clearance bottlenecks leading to long lead times
Logistics	High in-country transport costs, poor infrastructure, goods damaged/lost in transit
Knowledge and Skills	Lack of formal training curricula, on-the-job learning, absence of supply chain tracking
Regulation	Weak enforcement, fragmented agencies, unclear tariffs, poor waste management regulation
Economic Constraints	High taxes, unpredictable policies, foreign exchange volatility, investment risk
Corruption	Bribes at customs, extortion at checkpoints, fraudulent EIAs
Sustainability Issues	Low environmental consciousness, lack of end-of-life planning, unsustainable disposal of panels/batteries

SCM challenges

The findings show that African RESCs, particularly in Nigeria, are heavily dependent on imported components for RE projects. This reliance creates systemic vulnerabilities: customs clearance delays can extend up to six months, tariffs and foreign exchange fluctuations inflate project costs, and bureaucratic inefficiencies reduce competitiveness. One striking insight is that clearing costs at borders can surpass the purchase cost of equipment, illustrating the disproportionate burden of import dependence. These findings corroborate prior research highlighting importation inefficiencies as a central barrier in emerging economies (Gebreslassie, 2021, Davy et al., 2024). This study advances SCM literature by showing that importation-related inefficiencies pose a critical bottleneck for African RESCs.

Beyond importation, in-country logistics costs are disproportionately high. The study finds that transporting equipment within Nigeria can cost more than shipping it from Europe, reflecting severe infrastructure deficits and weak regulatory oversight. Additional problems such as frequent damage or theft during transit exacerbate financial losses and delay projects. These findings echo Tukamuhabwa et al. (2017)

and Peter et al. (2023), who note that poor infrastructure and fragile transport systems inflate costs in African supply chains. The research contributes new empirical evidence that domestic logistics inefficiencies magnify the costs of import dependency, creating a double burden.

The study highlights significant human capital shortages. There are no certified training programs for RE deployment, leaving firms reliant on unstructured on-the-job learning. As a result, technical errors, inefficiencies, and limited capacity to track supply chain activities persist. Local vendors are rarely vetted for environmental performance, further undermining sustainability. These findings align with earlier research on human capital constraints in African supply chains (Amir and Khan, 2022, Ugwu et al., 2022).

Although policies exist, weak enforcement and fragmented responsibilities across regulatory bodies create uncertainty. Respondents pointed to a lack of clarity on tariffs and levies, as well as poor accountability for waste management. This leads firms to neglect sustainable disposal practices without consequence. These findings resonate with prior work noting the failure of weak regulatory frameworks to enforce sustainability in African contexts (Nkrumah et al., 2021, Ugwu et al., 2022, Ilankoon et al., 2018, Ayeleru et al., 2020). The study therefore contributes to the supply chain literature by showing how fragmentation across agencies amplifies compliance costs while simultaneously undermining sustainability outcomes in African RESCs.

Macroeconomic instability particularly foreign exchange volatility poses major risks for firms. Sudden devaluations disrupt budgets, increase project costs, and deter long-term investments. High tariffs and unpredictable tax policies further discourage expansion. This reflects broader evidence that volatile economic conditions destabilize supply chain financing in developing economies (David et al., 2010, WOODE, 2024). The research highlights that financial volatility interacts directly with sustainability transitions, as firms deprioritize green practices when project costs escalate unpredictably.

The study found that corruption permeated customs operations, security checkpoints, and regulatory compliance processes. Unofficial payments inflate costs, while fraudulent EIA reports undermine environmental oversight. This confirms earlier findings that corruption is a systemic barrier to SCM efficiency and sustainability compliance (Kagande et al., 2022, Jia et al., 2018). This study implies that corruption does not merely add transactional costs but erodes trust in sustainability governance, undermining the legitimacy of environmental regulations.

Sustainability Issues

In addition to SCM barriers, the study identified three interrelated sustainability challenges that constrain the effectiveness of green supply chains in African RESCs. These issues are particularly significant as they directly undermine the sector's ability to achieve long-term environmental objectives.

First, the findings reveal a widespread lack of environmental consciousness among firms, vendors, and consumers. Sustainability considerations are often sidelined in decision-making, with operational and financial concerns taking precedence. This aligns with Nkrumah et al. (2021), who argue that low environmental awareness in developing economies limits the mainstreaming of sustainable practices within supply chains. Without systematic environmental training programs, corporate sustainability commitments, and regulatory mandates, sustainability will continue to be treated as an afterthought rather than a fundamental operational priority.

Second, the study highlights the absence of structured end-of-life management plans for key RE components such as solar panels and batteries. Without frameworks for recycling, remanufacturing, or safe disposal, obsolete equipment is left to accumulate, creating long-term waste management problems. This resonates with Duran et al. (2022), who emphasize that inadequate end-of-life strategies in RE systems pose serious ecological risks. The absence of such strategies in African RESCs highlights an urgent need for policy-driven interventions, corporate sustainability commitments, and investment in waste management technologies.

Third, unsustainable disposal practices are prevalent due to weak regulatory enforcement and inadequate infrastructure. Firms are rarely held accountable for the unsustainable disposal of energy equipment, while recycling facilities remain scarce. As Rufino et al. (2022) observe, such infrastructural and institutional gaps leave firms with few options other than improper disposal or costly export of waste to external markets. The findings of this study further buttress that lack of local recycling infrastructure forces firms to either improperly dispose of waste or incur exorbitant costs shipping discarded components to other countries for treatment. This situation is unsustainable in the long term, as the growing adoption of RE technologies will inevitably lead to higher volumes of electronic waste.

In summary, this research confirms that Nigerian RESCs face intertwined SCM and sustainability challenges that extend beyond operational inefficiencies to include systemic regulatory, economic, and socio-cultural barriers. By categorizing and contextualizing these issues, the study not only validates prior findings from broader SCM literature but also identifies context-specific contributions that explain why sustainability transitions remain slow in African RE markets. These insights provide the foundation for addressing RQ2 and RQ3, which examined how Industry 4.0 technologies and GSCM practices could mitigate these barriers and enhance sustainability performance.

While these challenges highlight the structural, regulatory, and operational weaknesses of Nigerian RESCs, the interviews also revealed a range of innovative strategies that firms are adopting to mitigate their impact. Rather than viewing the barriers as insurmountable, companies are experimenting with GSCM practices that both address immediate operational bottlenecks and lay the groundwork for longer-term sustainability. Alongside GSCM strategies, firms are beginning to leverage Industry 4.0 technologies, albeit in limited and highly targeted ways, to enhance efficiency, improve transparency, and enable smarter decision-making. In addition, other supportive measures, such as financial de-risking, workforce development, and information-sharing platforms, are being pursued to strengthen the resilience and competitiveness of the sector. The following sections discuss these solutions in turn, beginning with GSCM practices, before moving to Industry 4.0 applications and other cross-cutting interventions. Table 8-2 provides an overview of these solutions.

Table 8-2: Solutions to SCM and Sustainability Challenges in Nigerian RESCs

Category	Solution	Description
GSCM Solutions	Approved Vendor Lists	Maintaining databases of vetted, responsible suppliers to ensure sustainability compliance.
	Carbon Footprint Assessment	Monitoring corporate and supplier-level emissions to reduce carbon output.
	Embedding Decommissioning Costs	Allocating project funds for end-of-life management of RE equipment.
	ISO 9001 Certification and Environmental Standards	Pursuing ISO certification to strengthen sustainability and transparency.
	Partnerships with Waste Disposal Firms	Collaborating with specialized firms for proper recycling and disposal of RE waste.
	Refurbishing and Reusing RE Modules	Reducing import dependency by refurbishing and reusing modules.
	Recycling and Retrofitting Initiatives	Retrofitting and recycling used RE components to extend their lifecycle.
	Logistics Incentivization and Importation Waivers	Seeking tax waivers and government incentives to reduce logistical burdens.
	Promoting Environmental Education and Awareness	Raising environmental awareness among employees, customers, and stakeholders.
Industry 4.0 Solutions	IoT for Smart Metering and Remote Monitoring	Deploying IoT-enabled smart meters for energy monitoring and remote control.
	Data Analytics for Site Identification and Planning	Using analytics for socio-economic viability assessments of project sites.
Other Solutions	Human Capital Development	Developing structured curricula and training programs for RE expertise.
	De-risking Sector through Financial Incentives	Providing subsidies and incentives to attract private sector participation.
	Supply Chain Financing Initiatives	Allowing firms to procure RE components with reduced upfront costs.
	Information Sharing Platforms	Using digital platforms like Odyssey to share RE project data and improve coordination.

GSCM Solutions

The findings show that firms in Nigerian RESCs are adopting a diverse set of GSCM practices to address sustainability and SCM challenges. At the procurement stage, companies employ Approved Vendor Lists to ensure suppliers meet ethical and environmental standards, thereby improving accountability and reducing risks of unsustainable sourcing. Complementing this, Carbon Footprint Assessments are used to monitor greenhouse gas emissions across supply chains, although limited standardisation in African contexts constrains their effectiveness (Elbaz and Iddik, 2020; Tseng et al., 2014). Financial planning measures, such as embedding decommissioning costs into project budgets, further demonstrate a proactive approach toward end-of-life management, aligning with extended producer responsibility principles (Maitre-Ekern, 2021). However, resource constraints often hinder implementation, underscoring the need for stronger policy and financial support.

Beyond planning and monitoring, firms are strengthening compliance and circularity through initiatives such as ISO certification, partnerships with waste disposal firms, and refurbishment, recycling, and retrofitting of RE modules. These practices reduce reliance on imports and extend product lifecycles, though they remain limited by weak infrastructure, inadequate expertise, and inconsistent regulatory enforcement. In addition, firms seek external support through logistics incentives and importation waivers to ease supply chain bottlenecks and invest in environmental education and awareness programmes to embed sustainability consciousness among employees and customers.

The GSCM solutions identified in this study resonate with broader GSCM and sustainability literature, while also extending it to the underexplored context of African RESCs. Practices such as supplier vetting, carbon footprint assessments, and ISO certification have been widely recognized as effective mechanisms for enhancing environmental accountability and supply chain transparency (Govindan et al., 2015;

Loaiza-Ramírez et al., 2022). Similarly, circular strategies such as refurbishment, recycling, and retrofitting echo prior studies emphasizing the role of remanufacturing and waste minimization in improving sustainability outcomes (Velenturf, 2021). However, this research contributes further by showing how these solutions are being adapted in contexts marked by infrastructural and regulatory weaknesses, where partnerships with waste firms, import waivers, and environmental education emerge as especially critical. This demonstrates that while the solutions are conceptually aligned with global GSCM best practices, their implementation in African RESCs is highly contingent on local institutional and economic conditions.

Industry 4.0 Solutions

The findings of this study indicate that the adoption of Industry 4.0 technologies in Nigerian RESCs remains at an early stage, with implementation largely confined to two areas: IoT-enabled smart metering and BDA for site identification and planning. These applications provide critical value by enabling real-time monitoring of energy use, supporting evidence-based infrastructure planning, and facilitating remote management of mini-grid systems.

Smart meters were highlighted as particularly important, not only for improving billing accuracy and financial sustainability but also for enabling remote diagnostics and system control, which reduce maintenance costs and increase flexibility in remote areas. Similarly, BDA supports site selection by analysing socio-economic and geographic variables to identify the most viable project locations, helping firms allocate resources more efficiently and mitigate investment risks. Despite these benefits, adoption is limited to a handful of firms with sufficient technical capacity and financial resources, while the majority of RESC actors remain constrained by infrastructural gaps, limited expertise, and weak digital ecosystems.

These findings resonate with the broader literature that underscores the transformative potential of Industry 4.0 in enhancing supply chain transparency, efficiency, and sustainability (Pandey et al., 2023; Wang et al., 2021; Kumar et al., 2021). However, they also extend existing knowledge by demonstrating that, in the African RESC context, uptake is restricted to narrow, operationally critical applications rather than widespread integration. This contrast highlights that while global discourse emphasizes the broad utility of Industry 4.0 for sustainability transitions, realizing such potential in African contexts requires significant investment in digital infrastructure, workforce upskilling, and enabling policy frameworks.

While GSCM practices and Industry 4.0 technologies represent the core pathways for embedding sustainability into Nigerian RESCs, interview findings revealed additional complementary interventions. These solutions, though not always directly tied to green practices or digital transformation, nonetheless play a critical role in strengthening the overall resilience, efficiency, and long-term viability of RESCs.

Broader Systemic Solutions to RESCs Issues

Beyond GSCM and digital innovations, firms and policymakers are implementing measures to address systemic gaps in human capacity, financing, and information sharing. A first set of solutions centres on human capital development, with collaborative training and certification programs designed to build technical expertise in RE installation, operations, and maintenance. Second, financial mechanisms such as subsidies, grants, and concessional schemes are being used to de-risk investments and encourage private sector participation. Complementing these are supply chain financing initiatives, which allow firms to procure RE components with reduced upfront costs, easing cash flow constraints in capital-intensive projects. Finally, information-sharing platforms such as Odyssey have emerged as digital repositories for project data, fostering transparency, improving coordination, and enhancing decision-making among stakeholders.

These findings align with literature emphasizing the importance of complementary enablers in advancing sustainable energy transitions. Prior studies highlight that human capital development is indispensable in overcoming skill shortages in developing economies (Trujillo-Gallego et al., 2022b), while financial incentives and concessional schemes are widely recognized as levers for attracting private sector investment in high-risk RE environments (Amir and Khan, 2022; Gebreslassie, 2021). Similarly, the use of supply chain financing reflects global trends toward innovative financing models in capital-intensive industries (Agrawal et al., 2023a). Finally, the emergence of digital collaboration platforms resonates with research stressing transparency and knowledge-sharing as critical for building efficient and resilient supply chains (Kunkel et al., 2022; Birkel and Müller, 2021). By situating these findings within broader debates, the study shows that African RESCs not only replicate known global challenges but also innovate through hybrid solutions tailored to their unique institutional and infrastructural realities.

8.4 Discussion of Quantitative Findings

Research Questions 2 and 3:

RQ2: How do Industry 4.0 technologies facilitate the adoption of GSCM practices in African RE firms?

RQ3: What is the combined effect of industry 4.0 technologies and GSCM practices on sustainability performance in Africa's RESCs?

The findings of this study offer important accounts on the relationship among Industry 4.0 technologies, GSCM practices, and sustainability performance in African RESCs. Through hypothesis testing, the study establishes that Industry 4.0 technologies don't possess a direct significant influence on sustainability performance but play a crucial role in enabling the adoption of GSCM practices, which in turn significantly enhance sustainability performance. These results underscore the mediating role of GSCM, demonstrating that Industry 4.0 technologies contribute to sustainability outcomes indirectly rather than directly. The following sections provide an in-depth discussion of these relationships.

Industry 4.0 Influence on GSCM Adoption (RQ2)

The study finds that Industry 4.0 technologies have a significant and positive influence on the adoption of GSCM practices, as evidenced by the hypothesis testing results (H2: β = 0.528, t = 7.543, $p < 0.05$). This confirms that the integration of digital technologies in supply chains facilitates the implementation of green practices, enabling firms to optimize resource efficiency, enhance traceability, and improve environmental performance. This finding is congruent with what Karmaker et al., (2023a) found. Industry 4.0 technologies are pivotal in improving GSCM adoption by enhancing supply chain visibility, enabling real-time monitoring, and supporting informed decision-making (Esmaeilian et al., 2020, Juszczyk and Shahzad, 2022). For instance, IoT-enabled sensors allow firms to track environmental parameters such as energy consumption and emissions, which supports sustainability efforts. Similarly, blockchain technology can improve traceability by ensuring that materials and products are sourced from ethical and sustainable suppliers. These findings align with prior research, which suggests that Industry 4.0 technologies enable the implementation of sustainable supply chain practices by improving data-driven decision-making and operational efficiency (Lerman et al., 2022, Enrique et al., 2022, Demir et al., 2022).

Despite the positive role of Industry 4.0 technologies in advancing GSCM adoption, the study also highlights that their implementation in African RESCs remains limited due to financial constraints, digital infrastructure gaps, and skill shortages. Many firms lack the technical expertise and resources needed to integrate digital solutions into their supply chain operations, limiting the widespread adoption of GSCM practices. These findings reinforce arguments in existing literature that the effectiveness of Industry 4.0 in promoting sustainability depends on firms' ability to invest in and operationalize digital transformation strategies (Trujillo-Gallego et al., 2022b, Narwane et al., 2021, Sun et al., 2022, Maisiri et al., 2021, Peter et al., 2023).

GSCM Practices as a Mediator (RQ3)

A key finding of this study is that Industry 4.0 technologies do not have a direct significant influence on sustainability performance (H1: β = -0.097, t = 1.148, $p > 0.05$), but their effect becomes positive and significant when mediated through GSCM practices (H4: β = 0.412, t = 5.202, $p < 0.05$). This result offers empirical evidence of the complete mediation role of GSCM in the relationship between Industry 4.0 and sustainability performance, suggesting that digital technologies alone are insufficient for driving sustainability improvements without structured green supply chain initiatives.

The study's mediation analysis confirms that firms leveraging Industry 4.0 technologies for GSCM implementation achieve better sustainability outcomes compared to those relying solely on digital transformation without green supply chain integration. This is because GSCM practices like green procurement, carbon footprint reduction, waste management, eco-design, and reverse logistics, serve as the actual mechanisms through which digital technologies translate into sustainability gains. These findings are consistent with prior research, which argues that Industry 4.0 technologies facilitate sustainable supply chains by enhancing green capabilities rather than directly influencing environmental and economic sustainability performance (Trujillo-Gallego et al., 2022b, Sun et al., 2022, Kumar et al., 2021).

Furthermore, the study highlights that firms that effectively integrate Industry 4.0 with GSCM strategies demonstrate superior environmental and operational performance, reinforcing the need for a dual approach that combines digital innovation with structured sustainability policies. Without GSCMPs implementation, the benefits of Industry 4.0 technologies in supply chains could be unmet, as firms fail to incorporate digital transformation efforts with sustainability objectives.

Finally, the findings of this research offer strong empirical backing regarding the enabling role of Industry 4.0 technologies in advancing GSCM adoption and the mediating role of GSCM in linking digital transformation to sustainability performance**.** While Industry 4.0 does not directly improve sustainability outcomes as found in this research**,** its adoption significantly enhances GSCM practices, thereby leading to improved sustainability performance**.** These insights highlight the importance of integrating digital transformation strategies with structured sustainability initiatives to maximize environmental, economic, and social benefits in RESCs**.** Moving forward, organizations seeking to leverage Industry 4.0 for sustainability improvements must prioritize investments in GSCM frameworks, ensuring that digital innovations are effectively aligned with sustainable supply chain goals.

8.5 Theoretical Contributions

This study offers theoretical contributions through the extension of existing frameworks and offering new insights into the interplay among sustainability performance, Industry 4.0 technologies, and GSCM practices in RESCs**.** The research refines and builds upon the RBV and NRBV respectively by demonstrating that technological resources alone do not directly enhance sustainability performance but must be embedded within structured green supply chain practices to be effective. The sections below highlight the specific theoretical contributions made by this study:

8.5.1 Extending RBV and NRBV to Industry 4.0 in sustainability contexts

RBV traditionally posits that firms acquire competitive edge by banking on VRIN resources (Barney and Arikan, 2005)**.** However, the findings of this study add nuance to traditional RBV assumption that Industry 4.0 technologies directly boost sustainability performance**.** Instead, this research suggests a more balanced view of RBV by revealing that these digital technologies only enhance sustainability performance when coupled with GSCM practices**.** This study goes beyond prior discourse (Trujillo-Gallego et al., 2022b, Narwane et al., 2021, Sun et al., 2022, Maisiri et al., 2021, Peter et al., 2023) by providing empirical evidence from African RESCs that digital resources only yield sustainability value when embedded within GSCM practices. This suggests a novel extension of RBV/NRBV to resource-constrained and institutionally weak contexts, which have been largely absent from extant studies.

While NRBV assumes that firms with strong environmental resources will outperform competitors, this study reveals that Industry 4.0 does not automatically confer environmental advantages unless it is integrated with structured sustainability mechanisms. This study not only supports prior research (Stekelorum et al., 2021b, Jell-Ojobor and Raha, 2022, Karmaker et al., 2023a, Muduli et al., 2020, Shahzad et al., 2022, Migdadi, 2022, Samad et al., 2021) which argues that the effectiveness of the NRBV varies with firm-level implementation capabilities, but also contextually extends it by showing that Industry 4.0 technologies do not generate environmental advantages in isolation, their value materialises only when embedded within structured GSCM mechanisms. By establishing the mediating role of GSCM, a more nuanced understanding of how technological advancements and environmental strategies must interact to achieve sustainability goals has been presented.

8.5.2 Establishing the mediating role of GSCM in digital sustainability

One of the most significant contributions of this study is the empirical support of GSCM as a full mediator between Industry 4.0 adoption and sustainability performance**.** While prior research has explored how digital transformation improves supply chain efficiency, this study provides suggestive empirical evidence that Industry 4.0 doesn't directly boost sustainability performance without structured GSCM initiatives. This is consistent with recent research (Esmaeilian et al., 2020, Sahebi et al., 2022, Chiappetta Jabbour et al., 2020). This study suggests that firms must proactively embed Industry 4.0 tools within GSCM practices to realize sustainability gains. This expands theoretical discussions on how firms must actively manage digitalization alongside environmental strategies to achieve long-term sustainability.

8.5.3 Bridging the research gap in emerging economy contexts

Most Industry 4.0 and GSCM studies have been conducted in developed economies, where digital infrastructure, financial resources, and regulatory frameworks are more advanced**.** This study contributes to the understudied theoretical and empirical research focusing on RESCs in Africa, a region where Industry 4.0 adoption faces significant financial, regulatory, and technical challenges (Bhagwan and Evans, 2023, Adenle, 2020, Appiah et al., 2022). By demonstrating that firms in resource-constrained environments struggle to leverage digital tools without complementary sustainability frameworks, this study therefore adds a contextual nuance to the RBV and NRBV applicability in emerging economies**,** highlighting that digital sustainability transitions require institutional support, targeted investments, and policy interventions.

8.5.4 Expanding the understanding of circular economy principles in digital supply chains

This study adds to the circular economy literature through the identification of the mechanisms through which Industry 4.0 technologies facilitate green procurement, eco-design, and internal environmental management in RESCs**.** While circular economy principles emphasize closed-loop supply chains, waste reduction, and resource efficiency (Aarikka-Stenroos et al., 2022, Agrawal et al., 2022), this study demonstrates that digital technologies alone are not enough to drive circular practices unless coupled with structured GSCM initiatives**.** This contributes to existing theoretical perspectives suggesting that the role of Industry 4.0 in supporting circular economy strategies is relative to GSCM transformations as alluded by scholars (Akkad et al., 2022, Bag and Pretorius, 2022, Bag et al., 2020)**.** The theoretical contributions are summarised in Table 8-3, which contrasts existing literature, identified gaps, and the new knowledge generated by this study.

Table 8-3: Theoretical Contributions of the Study

Theme	Current Literature Understanding	Gaps Identified	New Contribution (This Thesis)
RBV/NRBV	Industry 4.0 often treated as VRIN resources that directly enhance performance (e.g., Sun et al., 2022; Maisiri et al., 2021).	Limited empirical evidence from RESCs and neglect of contextual constraints.	Shows empirically that Industry 4.0 technologies alone don't enhance sustainability performance in African RESCs; value is realised only when technologies are embedded in GSCM. Extends RBV/NRBV to resource-constrained contexts.
Mediation of GSCM	Digitalisation linked to efficiency and sustainability, but mediation mechanisms underexplored (Chiappetta Jabbour et al., 2020).	Lack of empirical tests of mediation in RESCs.	Establishes GSCM as a full mediator between Industry 4.0 and sustainability performance advancing theoretical understanding of digital–green interplay.
Emerging Economy Contexts	Most studies based on developed economies with robust digital and regulatory infrastructure (Bhagwan and Evans, 2023).	Underrepresentation of Africa; little theorisation of institutional voids in digital–green frameworks.	Adds contextual nuance by theorising how institutional, regulatory, and infrastructural challenges condition digital sustainability transitions in RESCs.

8.6 Practical Contributions

This study contributes to practice by offering evidence-based, actionable strategies that firms, supply chain managers, and policymakers can directly implement to enhance sustainability performance in RESCs. By actionable strategies, this study refers to concrete, operational recommendations derived from empirical findings, rather than abstract prescriptions. Importantly, these contributions are contextualized within African RESCs, where financial constraints, infrastructural gaps, and institutional weaknesses limit the effectiveness of conventional approaches.

1. Integrating Industry 4.0 with GSCM practices

- *Existing knowledge:* Prior research (Ali et al., 2022a, Ali et al., 2021) has emphasized the efficiency and transparency gains of Industry 4.0 adoption.
- *New contribution:* Based on the quantitative findings, this study reveals that in African RESCs, digital adoption alone does not translate into sustainability benefits. Instead, value is realized when Industry 4.0 technologies are embedded within structured GSCM practices such as ECO, IEM, GPP, approved vendor lists, carbon footprint assessments, and recycling initiatives. The actionable recommendation is for managers to view digitalization and GSCM as mutually reinforcing strategies, not stand-alone efforts.

2. Policy and regulatory support for digital–green transitions

- *Existing knowledge:* Governments are recognized as critical enablers of green transitions through regulation and incentives (de Vries and Levinsky, 2020, Bugaje, 2006).
- *New contribution:* Based on the qualitative findings, this study shows that African RESCs require a dual policy approach: (i) *financial de-risking* through subsidies, tax incentives, and concessional loans to offset high investment costs; and (ii) *regulatory enforcement* to ensure end-of-life management of panels and batteries. Actionable guidance is for policymakers to align digital

transformation with sustainability objectives through standardized environmental regulations and structured incentive frameworks.

3. Human capital and workforce development

- *Existing knowledge:* Skills development is widely acknowledged as a general enabler of Industry 4.0 adoption (Cabral and Chiappetta Jabbour, 2020).
- *New contribution:* Based on the qualitative findings, this study identifies specific training gaps in African RESCs, including the absence of certified curricula, limited technical education, and reliance on unstructured on-the-job learning. The actionable recommendation is for firms and regulators to co-develop competency-based training programs in sustainability analytics, digital monitoring, and circular economy practices, while embedding these into technical and vocational education frameworks.

4. Leveraging digital platforms for collaboration and transparency

- *Existing knowledge:* Information-sharing platforms are known to support coordination in supply chains (Birkel and Müller, 2021).
- *New contribution:* Based on qualitative findings, this study highlights that in fragmented African markets, platforms such as Odyssey are critical for centralizing project data, improving investment decision-making, and enhancing procurement transparency. The actionable insight is for firms and industry associations to actively engage in and expand such platforms to foster collaboration, improve traceability, and reduce inefficiencies.

In sum, the practical contributions of this research lie in translating digital–green integration into context-specific, operational strategies for emerging economies. Compared with the existing literature, which has largely assumed that digital adoption or regulatory presence will independently yield sustainability outcomes, this study demonstrates that in African RESCs, these benefits only materialize when Industry 4.0, GSCM practices, and enabling policies are strategically aligned. For practitioners, this provides a roadmap of what to do differently from embedding digital adoption within sustainability practices, to lobbying for dual policy support, to building workforce capabilities, and scaling collaborative digital platforms.

8.7 Limitations and Future Research Direction

Certain limitations should be considered when interpreting the findings of this study despite its significant contributions. Firstly, the research mainly focuses on the African RES, this could make ability to generalize its findings to other geographic regions limited and weak. While the insights generated provide valuable implications for developing economies, further comparative research is timely to explore how Industry 4.0 and GSCM adoption differ across diverse economic and institutional contexts. Future studies could conduct cross-regional analyses comparing developing and developed markets to examine variations in digital sustainability adoption and regulatory effectiveness.

Furthermore, while the study involved participants from 17 countries and four RE technologies, the sample is skewed towards firms operating in the solar sector. As such, the findings are more reflective of solar-dominant RESCs in Africa, and generalisations to other technologies or more diversified energy portfolios should be made cautiously.

Moreover, the sampling approach may introduce selection bias, potentially overrepresenting firms with more advanced Industry 4.0 or GSCM maturity. While efforts were made to ensure broad sectoral and geographic coverage, the absence of country-level controls and variation in digital infrastructure may have influenced results. Future research could address this by applying stratified sampling methods or incorporating national context variables to assess heterogeneity effects more robustly.

Secondly, a cross-sectional research design is employed in this study, capturing Industry 4.0 and GSCM adoption at a particular time. However, integrating digital technologies in supply chains is an ongoing and evolving process. A longitudinal study might provide greater insights on how firms progressively implement Industry 4.0-

enabled sustainability strategies over time, allowing researchers to track long-term changes in sustainability performance and the effectiveness of policy interventions.

Another limitation of this study is the fact that the quantitative survey component was the primary source of data for hypothesis testing. While this allowed for robust statistical validation of the interplay among Industry 4.0 technologies, GSCM practices, and sustainability performance, it provided limited qualitative understandings of the practical challenges of implementation, organizational dynamics, and decision-making processes. Future research could further enhance understanding through extensive qualitative case studies to capture nuanced perspectives on firm-level sustainability transitions.

Additionally, the study highlights that Industry 4.0 adoption in African RESCs remains limited due to financial, infrastructural, and regulatory constraints. However, it does not fully explore the role of public-private partnerships and investment models in overcoming these barriers. Future research could investigate how collaborative financing mechanisms, venture capital investments, and government-industry partnerships influence the scaling of digital sustainability solutions.

Finally, while this study focuses on Industry 4.0 and GSCM practices, emerging and disruptive technological trends such as AI, blockchain-based carbon trading, and decentralized energy networks should be examined by future research. Exploring how these technologies complement existing digital sustainability initiatives could provide further insights into next-generation green supply chains.

9 Conclusion

This study has examined the relationship among Industry 4.0 technologies, GSCM practices, and sustainability performance in RESCs, with a particular focus on the African context. By integrating the RBV and the NRBV, the research sought to determine the level of influence of Industry 4.0 technologies on GSCM implementation and its subsequent impact upon sustainability outcomes. The findings elucidate empirical proof that Industry 4.0 technologies alone do not significantly improve sustainability performance but are crucial in enabling GSCM practices adoption, which in turn positively influence sustainability outcomes. This conclusion highlights the importance of structured green supply chain initiatives in translating digital transformation into tangible sustainability benefits.

The research was guided by three key questions: first, identifying the sustainability and SCM challenges confronting African RE firms; second, assessing how Industry 4.0 technologies influence the implementation of GSCM practices; and third, evaluating the combined impact of Industry 4.0 and GSCM practices on sustainability performance. The findings revealed that African RESCs face severe supply chain inefficiencies, including importation delays, logistical constraints, regulatory inconsistencies, economic volatility, and corruption-related challenges. In terms of sustainability, a lack of environmental consciousness, absence of structured End-of-Life management plans, and weak regulatory enforcement were identified as key issues. The results further confirmed that while Industry 4.0 significantly facilitates the adoption of GSCM practices, its direct impact on sustainability performance is statistically insignificant. However, when GSCM is incorporated as a mediating factor, the relationship between Industry 4.0 and sustainability performance becomes positive and significant, indicating a complete mediation effect. This finding confirms that digital technologies alone are not sufficient for improving sustainability performance unless they are embedded within structured GSCM frameworks.

The study makes several theoretical contributions by refining and extending existing theories in supply chain sustainability and digital transformation. First, it challenges the RBV assumption that technological resources inherently generate competitive advantages by demonstrating that Industry 4.0 technologies alone do not lead to sustainability improvements unless effectively integrated with GSCM strategies. This insight reinforces the importance of firms developing complementary capabilities rather than relying solely on digital transformation to drive sustainability outcomes. Second, the study empirically validates the full mediating role of GSCM practices in the relationship between Industry 4.0 and sustainability performance, reinforcing the significance of green capabilities in supply chains. Third, by linking Industry 4.0 technologies with green supply chain practices, the study provides a structured framework for integrating digital transformation with sustainability objectives, particularly in resource-constrained environments. These contributions enrich the discourse on sustainable digitalization, offering a nuanced perspective on how technological innovations can be leveraged to achieve sustainability goals in supply chain operations. Figure 9-1 presents a summary of gaps in the literature against contributions.

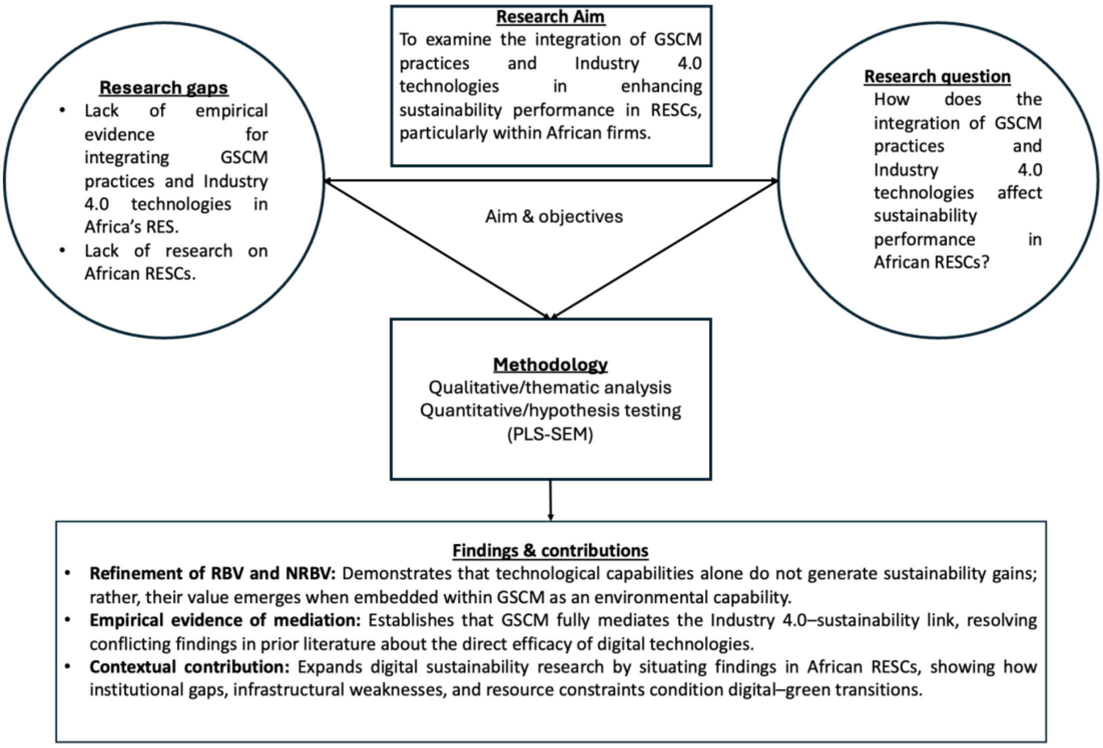

Figure 9-1 Research contributions

Beyond theoretical advancements, the study offers crucial practical implications for industry practitioners, policymakers, and supply chain managers. The findings emphasize that firms should prioritize GSCM adoption alongside Industry 4.0 implementation to maximize sustainability benefits. Investing in digital infrastructure, IoT-based monitoring, and blockchain traceability should be strategically aligned with sustainability goals to enhance responsible sourcing and waste management. Organizations should also invest in workforce training and digital skills development to address knowledge gaps in sustainability-driven digital transformation. For policymakers, the research underscores the need for financial incentives, tax breaks, and subsidies to facilitate Industry 4.0-enabled GSCM adoption. Stronger regulatory enforcement is also required to ensure responsible End-of-Life management of RE components such as solar panels, wind turbines, and batteries. Additionally, public-private partnerships should be promoted to drive investment in digital sustainability initiatives and strengthen institutional support for sustainable supply chains.

Despite its significant contributions, the study has certain limitations that need consideration when interpreting its findings. First, the research focuses on African RESCs, which may limit the generalizability of findings to other geographic contexts. While the insights generated provide valuable implications for developing economies, further comparative research is needed to explore how Industry 4.0 and GSCM adoption differ across diverse economic and institutional settings. Second, the study employed a cross-sectional research design, capturing Industry 4.0 and GSCM adoption at a single point in time. A longitudinal study could provide deeper insights into how firms progressively implement Industry 4.0-enabled sustainability strategies and their long-term effects. Third, while the study identifies financial constraints as a key barrier to Industry 4.0 adoption, it does not explore specific investment models that could overcome this challenge. Future research should investigate alternative financing mechanisms for digital sustainability adoption, including venture capital funding, government grants, and impact investment models.

Building on these limitations, several future research directions are proposed. Comparative studies should examine how Industry 4.0 and GSCM adoption contrast across dissimilar economic contexts, particularly in developed versus developing markets. Longitudinal research should track how firms gradually implement Industry 4.0-enabled GSCM strategies and assess their impact on sustainability over time. Emerging technological trends, such as AI, decentralized blockchain applications, and digital twins, should also be examined in the context of sustainable supply chains. Furthermore, policy-oriented research should focus on developing frameworks that support Industry 4.0-driven sustainability transformations, particularly in regions with weak regulatory enforcement and limited institutional capacity.

Overall, this study gives valuable insights into the role of Industry 4.0 and GSCM in enhancing sustainability performance within African RESCs. By establishing that Industry 4.0 alone is insufficient for driving sustainability improvements, the study reinforces the need for a holistic approach that integrates digital transformation with structured green supply chain frameworks. As RESCs continue to expand, the integration of digital innovation with sustainability strategies will be vital in attaining long-term environmental, economic, and social resilience. Addressing the challenges outlined in this research and implementing the proposed recommendations will enable firms, policymakers, and industry stakeholders to work collaboratively toward a more sustainable and technologically advanced RES. Through continued research, policy refinement, and industry innovation, the transition toward sustainable digital supply chains can be further accelerated, ensuring a greener and more resilient future for the global energy landscape.

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Appendix 1: Consent Form

Consent Form

Name of department: Design, Manufacturing and Engineering Management

Title of the study: Impact of Industry 4.0 on Sustainability Performance in Renewable Energy Firms: Mediating Role of Green Supply Chain Management Practices.

I confirm that I have read and understood the Participant Information Sheet for the above project and the researcher has answered any queries to my satisfaction.

- I confirm that I have read and understood the Privacy Notice for Participants in Research Projects and understand how my personal information will be used and what will happen to it (i.e. how it will be stored and for how long).
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences.
- I understand that I can request the withdrawal from the study of some personal information and that whenever possible researchers will comply with my request. This includes the following personal data:
    - Name
    - Company details
    - my personal information from responses.
- I understand that anonymised data (i.e. data that do not identify me personally) cannot be withdrawn once they have been included in the study.
- I understand that any information recorded in the research will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project.

(PRINT NAME)	
Signature of Participant:	Date:

Appendix 2: Qualitative Interview Questions

1. How would you describe the structure of renewable energy sector in Nigeria?
2. How would you describe the sector’s supply chain in Nigeria?
3. How would you describe the extent to which environmental consciousness is embedded in the management of your supply chain?
4. What would you say are the supply chain related challenges within the sector?
5. What are the sustainability related problems within the sector that you have encountered?
6. How would you describe the techniques adopted by companies to tackle such sustainability and supply chain problems?
7. How would you describe the adoption of Industry 4.0 technologies in the sector and is this something your company has considered?

Appendix 3: Constructs and Measurement Items

The measurement items presented in this appendix were adapted from established scales in the literature and further refined using insights from the qualitative phase of the study. Specifically, themes identified through interviews with practitioners in the African RES, including supply chain challenges, sustainability concerns, and the conditional role of digital technologies, informed the contextual framing and emphasis of the survey items. This approach ensured that the operationalisation of Industry 4.0 technologies adoption, GSCM practices, and sustainability performance reflects both theoretical foundations and empirically grounded realities within African RESCs.

Table A3 (1): Measurement items for industry 4.0 technologies adoption.

Second order construct	First order construct	Measurement items	Sources
Industry 4.0 technologies adoption	Digital Technology Adoption for Sustainability (DTAS)	Leverage blockchain to improve supply chain transparency and traceability (DTAS 1)	(Umar et al., 2022a, Kumar Singh et al., 2023)
		Use of IoT to enhance collaboration with suppliers on sustainability initiatives such as green procurement (DTAS 2)	(Umar et al., 2022a, Karmaker et al., 2023a)
		Leveraging AI to improve the end-of-life management of renewable energy components (DTAS 3)	(Umar et al., 2022a)
		Leveraging Industry 4.0 technologies to monitor and reduce the environmental impact of raw material sourcing (DTAS 4)	(Kumar Singh et al., 2023)
		Use of real-time data analytics and/or IoT to mitigate logistics costs and	(Rufino et al., 2022)

		reduce delays in transportation (DTAS 5)	
	Data Management (DM)	Establishment of effective data management infrastructure (DM 1)	(Karmaker et al., 2023a, Liu et al., 2023a, Eslami et al., 2023)
		Establishment of data sharing system with stakeholders to some extent (DM 2)	(Karmaker et al., 2023a)
		Establishment of strong cyber security system (DM 3)	(Eslami et al., 2023)
	Finance Planning (FP)	Management of sources of fund to implement Industry 4.0 (FP 1)	(Karmaker et al., 2023a, Umar et al., 2022c)
		Development of effective risk management system using artificial intelligence (FP 2)	(Karmaker et al., 2023a)
		Development of effective financial control system using blockchain technology (FP 3)	(Karmaker et al., 2023a)

Table A3 (2): Measurement items for the implementation of GSCMPs

Second order construct	First order construct	Measurement items	Sources
Implementation of GSCMPs	Green Purchasing/Procurement (GPP)	Collaboration with suppliers to achieve environmental goals (GPP 1)	(Umar et al., 2022a, Zhu et al., 2005)

		Evaluation of suppliers' internal environmental management through environmental auditing (GPP 2)	(Lerman et al., 2022, Karmaker et al., 2023a)
		ISO 14000 certification of suppliers for environmental management (GPP 3)	(Umar et al., 2022a)
	Eco design (ECO)	Development of products for minimized material and energy consumption (ECO 1)	(Lerman et al., 2022)
		Development of products for recycling, reuse, and recovery (ECO 2)	(Karmaker et al., 2023a, Zhu and Sarkis, 2004)
	Internal environmental management (IEM)	Leadership commitment to GSCM (IEM 1)	(Lerman et al., 2022, Khan et al., 2022b),
		Collaborative effort across departments for environmental enhancements (IEM 2)	(Green Jr et al., 2012, Karmaker et al., 2023a)
		Regulatory compliance and auditing initiatives for environmental management (IEM 3)	(Khan et al., 2022a)
		Environmental education and training programs for employees (IEM 4)	(Assumpção et al., 2022)

Table A3 (3): Measurement items for sustainability performance

Second order construct	First order construct	Survey items	Sources
Sustainability performance	Environmental performance (ENP)	Reduction of waste generation (liquid and/or solid and/or effluent) (ENP 1)	(Zhu et al., 2005, Acquaye et al., 2018)
		Minimization of usage of detrimental, hazardous, or toxic components (ENP 2)	(Karmaker et al., 2023a)
		Reduction in the number of environmental accidents (ENP 3)	(Umar et al., 2022a, Lerman et al., 2022)
	Economic performance (ECP)	Reduction of energy consumption cost (ECP 1)	(Zhu et al., 2005, Karmaker et al., 2023a)
		Improvement in return on investment (ECP 2)	(Umar et al., 2022a)
		Remarkable reduction of waste and its disposal costs (ECP 3)	(Akhmatova et al., 2022, Karmaker et al., 2023a)
	Social performance (SCP)	Improved working condition (SCP 1)	(Zhu et al., 2005, Karmaker et al., 2023a)
		Improved workplace health and safety (SCP 2)	(Umar et al., 2022a, Karmaker et al., 2023a)
		Decrease in risks to public and environmental impacts (SCP 3)	(Ahmed and Sarkar, 2019, Brenner and Hartl, 2021)

Appendix 4: Questionnaire

COMPLETING THIS SURVEY SHOULD TAKE ONLY ABOUT 5 MINUTES OF YOUR PRECIOUS TIME.

Introduction

Hello, my name is Jameel Labaran, I am a doctoral researcher at the University of Strathclyde. I am conducting a research project as part of my doctoral studies. I would like to invite you to participate in this study aimed to explore how Industry 4.0 technologies such as Artificial intelligence (AI), Blockchain, the Internet of things (IoT), cloud computing and big data analytics are used alongside green supply chain management practices to improve sustainable performance in renewable energy firms in Africa.

You are being invited to participate in this research study titled "Leveraging industry 4.0 technologies to enhance green supply chain management practices of renewable energy firms in Africa". This study is being done at the department of Design, Manufacturing and Engineering Management, University of Strathclyde.

What is the purpose of this research?

The aim of this study is to examine how Industry 4.0 technologies can be leveraged in the successful implementation of green supply chain management practices to address supply chain challenges within the African renewable energy sector firms towards achieving sustainability performance.

Do you have to take part?

Participation in this research is entirely voluntary. It is your decision whether or not to take part. If you choose not to participate or decide to withdraw at any point, it will not affect any other aspects of the way you are treated. You have the right to withdraw from the research without any detriment.

What will you do in the project?

If you agree to take part, you will be asked to participate in completing a questionnaire which is done online and takes 5 minutes. The researcher aims to get all responses between October and December 2024.

Why have you been invited to take part?

You have been invited to participate because you are an expert working in a company that operates within the African renewable energy sector.

What information is being collected in the project?

We will collect survey data regarding your operations, activities and organisational strategies based on your valuable experience.

Who will have access to the information?

Your information will be kept confidential and anonymous. Only the research team will have access to the data.

Where will the information be stored and how long will it be kept for?

Your data will be stored securely at the university of Strathclyde cloud location. Personal information will be retained only as long as necessary. Anonymous data may be retained indefinitely by depositing it in a suitable data repository. Retention periods will adhere to funder policies and guidelines. Thank you for reading this information – please ask any questions if you are unsure about what is written here.

What happens next?

If you would like to find out more about this project or wish to participate, please contact Jameel at jameel.labaran@strath.ac.uk. You will be asked to sign a consent form if you decide to participate. If you do not wish to participate, thank you for your time and attention. After the research is complete, participants will receive feedback. The results of the study may be published, and you will be informed of any publications. Researcher's contact details: Mr Muhammad Jameel Labaran (Email: jameel.labaran@strath.ac.uk) University of Strathcyde, 16 Richmond Street Glasgow G1 1XQ Chief Investigator details: Dr. Tariq Masood (Email: tariq.masood@strath.ac.uk University of Strathcyde 16 Richmond Street Glasgow G1 1XQ This research was granted ethical approval by the Ethics Committee of the Department of Design, Manufacturing and Engineering Management (DMEM), University of Strathclyde, Glasgow. If you have any questions/concerns, during or after the research, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact: Secretary to the University Ethics Committee Research and Knowledge Exchange

Services University of Strathclyde Graham Hills Building 50 George Street Glasgow G1 1QE Telephone: 0141 548 3707 Email: ethics@strath.ac.uk

If you are interested in taking part, please download a copy of the participant information sheet here: Jameel pis consent form v0.8 and retain this for your records before starting the survey. If you have any questions, please email at jameel.labaran@strath.ac.uk Your participation is entirely voluntary, and you can withdraw at any time. You are free to omit any question.

What is your role/position/designation at your organisation?

◯ Founder/Owner

◯ CEO

◯ Director

◯ Senior Manager

◯ Manager

◯ Other (Please specify)

____

How many years of experience do you have?

◯ Less than 4 years

◯ 5-10

◯ 11-16

◯ 17-22

◯ More than 22 years

What country or countries of Africa does your organisation operate in?

____

What is your company size in terms of employee number?

○ Less than 50

○ 50-200

○ 201-350

○ 351-500

○ More than 500

What type of renewable energy technology does your company deal with? Choose all that apply.

☐ Solar

☐ Wind

☐ Hydro

☐ Biofuel

☐ Others (Please specify)

____

Is your company ISO certified?

○ Yes

○ No

○ On the process of certification

On a scale of 1 to 5, rate your agreement to the statements below in relation to your organisation's implementation of Green Procurement/Purchasing.

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
We collaborate with suppliers to achieve environmental goals.	○	○	○	○	○

We conduct supplier evaluation based on supplier's internal environmental management through environmental auditing.	○	○	○	○	○
We select ISO 14000 certified suppliers for environmental management.	○	○	○	○	○

On a scale of 1 to 5, rate your agreement to the statements below in relation to your organisation's implementation of Eco-design practice.

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
Our product development process fosters minimized use of materials and energy consumption.	○	○	○	○	○
Our product design process fosters design for recycling, reuse, and recovery.	○	○	○	○	○

On a scale of 1 to 5, rate your agreement to the statements below in relation to your organisation's implementation of Internal Environmental Management practice.

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
Our top management is committed to implementing green supply chain management practices.	○	○	○	○	○

We collaborate across departments for environmental enhancements.	○	○	○	○	○
We foster regulatory compliance and auditing initiatives for environmental management.	○	○	○	○	○
We provide environmental education and training for our employees.	○	○	○	○	○

On a scale of 1 to 5, rate your agreement to the following statements in relation to your organisation's commitment towards the adoption industry 4.0 technologies for Digital Technology Adoption for Sustainability.

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
We leverage blockchain to improve our supply chain transparency and traceability.	○	○	○	○	○
We use IoT to enhance collaboration with our suppliers on sustainability initiatives such as green procurement.	○	○	○	○	○
We use AI to improve the end-of-life management of renewable energy components.	○	○	○	○	○
We incorporate Industry 4.0 technologies to monitor and reduce the environmental impact of our raw material sourcing.	○	○	○	○	○
We use real-time data analytics and/or IoT to mitigate logistics costs and reduce delays in transportation.	○	○	○	○	○

On a scale of 1 to 5, rate your agreement to the following statements in relation to your organisation's commitment towards the adoption of industry 4.0 technologies in **Data Management**.

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
We have established industry 4.0 based data management infrastructure.	○	○	○	○	○
We have established industry 4.0 powered data sharing system with stakeholders.	○	○	○	○	○
We have established a strong cyber security system.	○	○	○	○	○

On a scale of 1 to 5, rate your agreement to the following statements in relation to your organisation's commitment towards adopting industry 4.0 technologies in Financial Planning.

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
We manage sources of funds to implement Industry 4.0.	○	○	○	○	○
We have developed a risk management system using artificial intelligence.	○	○	○	○	○
We have developed a financial control system using blockchain technology.	○	○	○	○	○

On a scale of 1 to 5, what is your level of agreement to the following statements in relation to your organisation?

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
We work towards minimising our waste generation (liquid, solid and/or effluent).	○	○	○	○	○
We work towards reducing the use of hazardous/harmful/toxic components.	○	○	○	○	○
We work towards decreasing environmental accidents.	○	○	○	○	○

On a scale of 1 to 5, what is your level of agreement to the following statements in relation to your organisation?

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
We work towards reducing the cost of our energy consumption.	○	○	○	○	○
We work towards improving our return on investment.	○	○	○	○	○
We work towards considerably decreasing our waste generation and its disposal cost.	○	○	○	○	○

On a scale of 1 to 5, what is your level of agreement to the following statements in relation to your organisation?

	Totally disagree	Disagree	Neither agree nor disagree	Agree	Totally agree
We work towards improving working conditions.	○	○	○	○	○
We work towards improving workplace health and safety.	○	○	○	○	○
We work towards reducing environmental impacts and hazards to the public.	○	○	○	○	○

Appendix 5: PLS-SEM (Measurement Model) Results

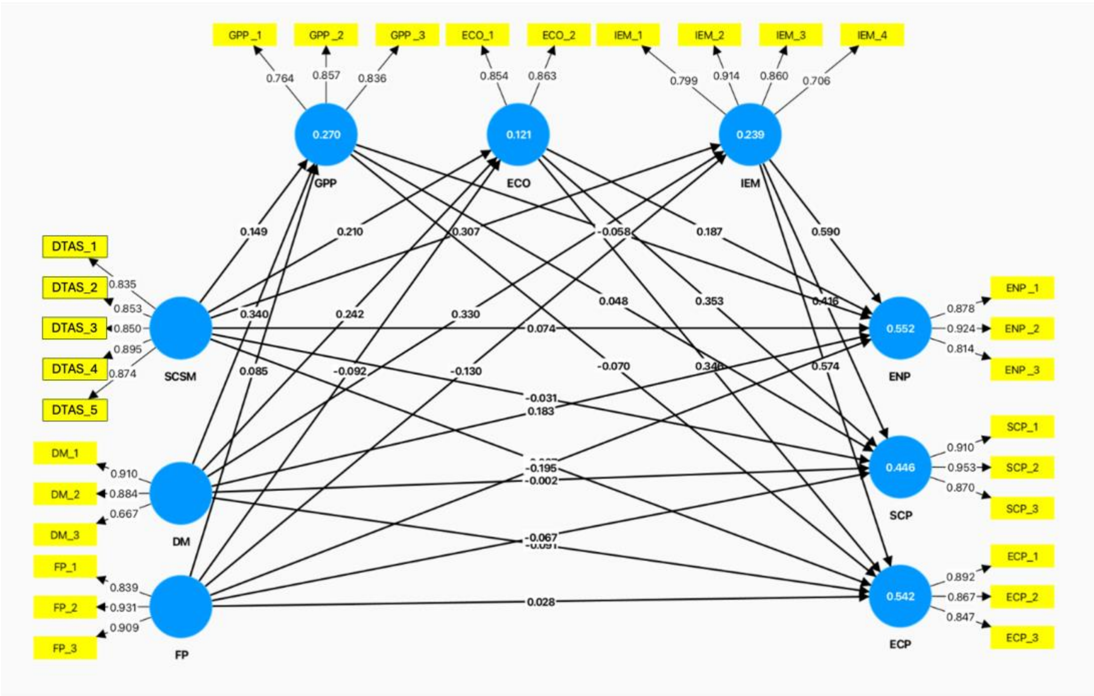

Figure A5-1: Measurement model results from SmartPLS4

Appendix 6: PLS-SEM (Structural Model) Results

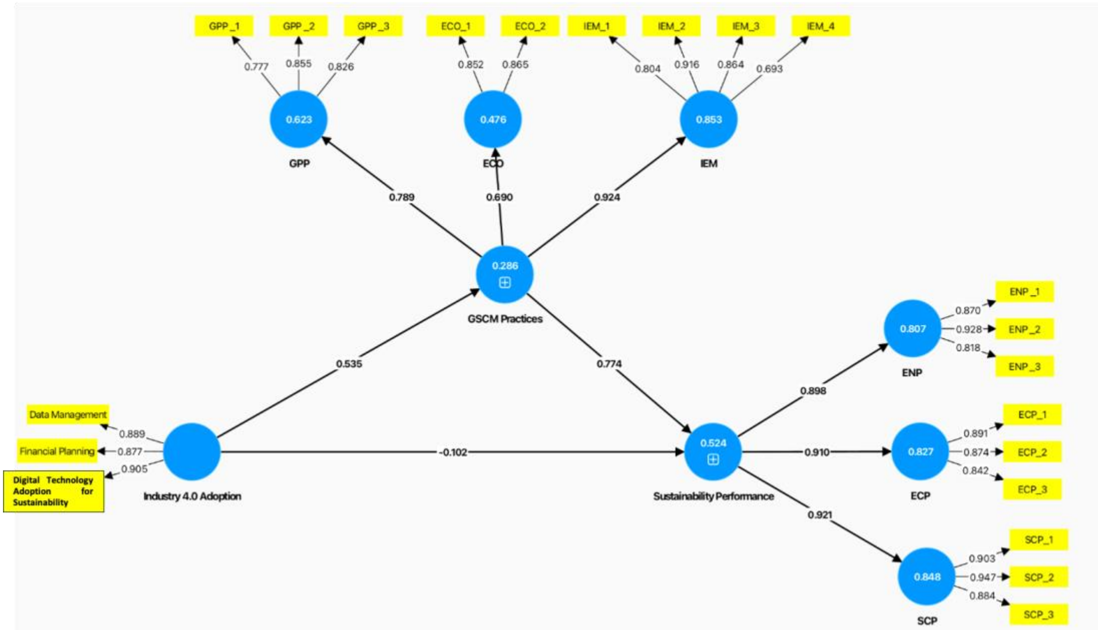

Figure A6-1: Structural model result from SmartPLS4