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Systematic Review

Navigating Environmental Challenges through Supply Chain Quality Management 4.0 in Circular Economy: A Comprehensive Review

Kevin Nguyen [1], Mohammadreza Akbari [2,*], Huy Truong Quang [1], Scott McDonald [1], Thu-Hang Hoang [3], Teck Lee Yap [1] and Majo George [1]

1 The Business School, RMIT University, Ho Chi Minh City 700000, Vietnam; kevin.nguyen@rmit.edu.vn (K.N.); huytruong.quang@rmit.edu.vn (H.T.Q.); scott.mcdonald@rmit.edu.vn (S.M.); tecklee.yap@rmit.edu.vn (T.L.Y.); majo.george@rmit.edu.vn (M.G.)
2 College of Business, Law and Governance, James Cook University, Douglas, QLD 4811, Australia
3 School of International Business–Marketing, University of Economics, Ho Chi Minh City 700000, Vietnam; hanght@ueh.edu.vn
* Correspondence: reza.akbari@jcu.edu.au

Abstract: The infusion of circular economy (CE) principles into supply chain management has garnered significant attention from both scholars and industry professionals. Quality management and Industry 4.0 (SCQM 4.0) have emerged as central themes due to their potential to elevate supply chain efficiency and sustainability. In pursuit of this goal, a thorough literature review is conducted, with a specific focus on quality management within circular supply chains, placing a significant emphasis on Industry 4.0 (I4.0) technologies. By analyzing 126 papers spanning from 1998 to 2023, this systematic review discerns prevailing trends, identifies research gaps, and charts future avenues for investigation. These results highlight the growing academic interest in utilizing I4.0 technology to improve quality control in circular supply chains. SCQM 4.0 is thus proposed to aid in a better comprehension of Supply Chain Quality Management 4.0, which incorporates infrastructure practices rooted in various disruptive technologies and supply chain operations that link with sustainable performance with three key metrics of input management, waste handling, and preservation concentrating solely on the environmental aspect. Based on this research, we offer a four-tiered SCQM 4.0 practice path to achieve a CE.

Keywords: Industry 4.0; quality management; circular economy; supply chain; environmental impact; systematic literature review; sustainable development goals

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1. Introduction

Supply chain quality management (SCQM), a fusion of supply chain management (SCM) and quality management (QM), represents the strategic approach employed by a savvy company to harmonize its operations seamlessly with both suppliers and customers, all in pursuit of enhancing quality [1–3]. SCQM marks a shift from a mere activity-based approach to a strategy-based approach, fostering greater customer satisfaction through enhanced collaborative networks across the business ecosystem and improved execution of upstream and downstream processes [3,4] and leads to a tangible boost in the quality of products and services [3,5].

On a parallel front, Industry 4.0 (I4.0), or the Fourth Industrial Revolution, is an emerging domain experiencing a surge in research and practical applications by both scholars and industry experts. I4.0 made its debut on the global stage at the Hannover Industrial Fair in Germany in 2011 [6,7]. The Industrial Revolution 4.0 introduced a wave of cutting-edge technologies, amalgamating principles from the realms of physics, digital science, and biology, profoundly impacting all sectors, industries, and economies [2,8,9].

The industrial revolution primarily centers on disruptive technologies, including artificial intelligence (AI), the Internet of Things (IoT), robotics, Biotechnology, self-driving cars, 3D printing (3DP) or additive manufacturing (AM), nanotechnology, and big data analytics (BDA) [7,10]. These innovations collectively enable the development of intelligent factories and advanced supply chains [11].

In today's fiercely competitive and rapidly evolving corporate landscape, the repercussions of unsustainable and environmentally harmful consumption and production practices have reached an untenable level [7,12]. The shift from a conventional linear economic model to the emergence of a closed-loop supply chain, prioritizing restoration and regeneration, is propelled by the "circular economy" (CE) concept [13]. It is anticipated to provide remedies for society's sustainability, environmental, and economic challenges [14]. There is a growing belief that the incorporation of I4.0 technologies will have a constructive impact on the development of a CE-based sustainable supply chain e.g., [15–17]. Previous research has suggested that such initiatives, especially in QM, play a significant role in advancing sustainability, providing advantages to businesses through improved data visibility and transparency e.g., [3,5,8]. For instance, I4.0 is found to positively correlate with CE practices in manufacturing companies in Ecuador, as determined by Khan et al. [12]. Given the study's emphasis on 'environmental sustainability,' it is widely acknowledged that the CE, as opposed to a linear economy, is generally seen as environmentally friendly and capable of enhancing resource efficiency. Nevertheless, the environmental perspective is often overlooked, resulting in inadequately informed and occasionally incorrect decisions [18]. According to Yu et al. (2019) [19], the adoption of QM within supply chains, known as SCQM, has surfaced as a pivotal method for elevating product and process quality, thereby establishing a favorable connection with environmental performance.

The objective of this research is twofold. First, we offer to construct a conceptual framework for Supply Chain Quality Management 4.0 (SCQM 4.0), with the aim of enabling the implementation of SCQM 4.0 to propel the digital transformation of SCM which, in turn, contributes to the advancement of the CE and the resolution of environmental challenges. Second, based on a past literature review, we propose a four-stage CE-based SCQM 4.0 practice route that firms can adopt to enhance the company's overall capabilities in the supply chain sustainable performance. While most of the prior studies on SCM and environmental sustainability are centered on a company's economic, legal, and ethical obligations, our study fills the research gap by focusing on the environmental ramifications of SCQM initiatives and technologies to demonstrate the pathways of SCQM influencing environmental sustainability, which is largely unexplored [19]. This study categorizes articles by summarizing them based on their dominant industry sectors and research methods. It analyzes the evolution of published literature over the years and provides guidance for future studies, aiming to assist researchers and address practitioners' needs. In addition, this study also emphasizes the recognition of finite environmental resources and the biosphere's capacity to absorb human activities on a global scale [20]. Moreover, this study offers a comprehensive overview of the key concepts and their relationships in the literature on SCQM development. It also highlights the current perspectives on SCQM development, shows how these perspectives are related, and offers new insights into the gaps between research and practice. Additionally, the study proposes an SCQM 4.0 framework to enhance scholars' understanding of the emerging topics in SCQM. This framework will help future research to address the complex environmental challenges in SCM and to advance supply chain circularity.

In this study, we employ a Systematic Literature Review (SLR) to lay a robust knowledge base, laying the groundwork for the development of a three-phase conceptual framework for SCQM 4.0 that harmoniously blends the fields of SCM and QM within the overarching paradigm of I4.0. The SLR method contributes to the literature by providing a comprehensive review supplemented with a conceptual framework proposal that demonstrates how a sustainable SCQM 4.0 in CE can navigate environmental challenges. Furthermore, through the SLR method, our study extends practical and policy implications to the literature. It guides multiple stakeholders of firms, including suppliers, consumers, investors, and regulatory bodies, on collaborative efforts in establishing a sustainable SCQM 4.0 within a CE. Given the variations in market, institutional, and social contexts, the findings of this study are especially significant in offering a comprehensive guide for evaluating and implementing SCQM 4.0 solutions. This study lays a robust foundation for future investigations in this domain, with a specific focus on experimental and applied studies. Figure 1 illustrates how the components of I4.0, QM, and SCM combine to create SCQM 4.0.

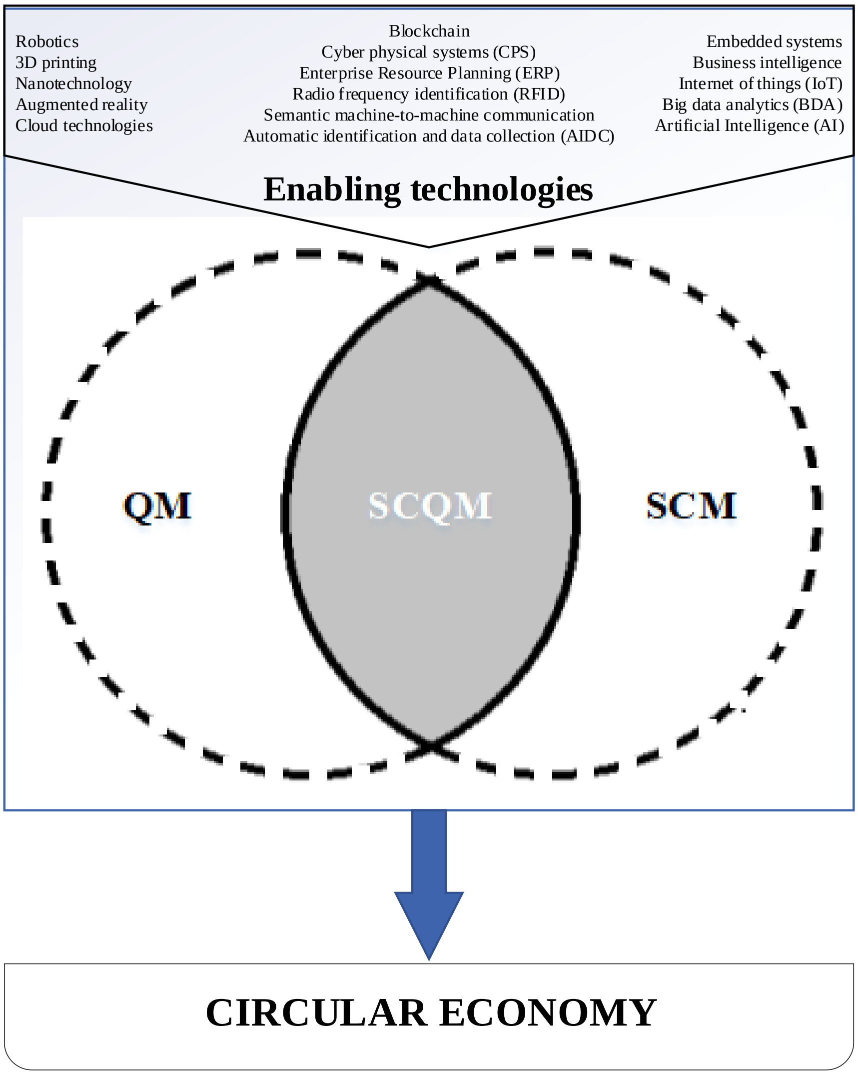

Figure 1. Integration of I4.0 of QM, SCQM and SCM.

The subsequent sections of this paper follow a structured approach. Section 2 delves into the SLR, sourcing pertinent materials concerning the fusion of I4.0, QM, and SCM. In Section 3, we unveil the outcomes of the literature review and engage in a comprehensive discussion. Section 4 introduces the conceptual framework for SCQM 4.0, while Section 5 concludes the paper and shapes directions for future research.

2. Materials and Methods

For the present study, the researchers adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA) 2020 procedure, as updated by Barnett-Page et al. (2021) [21], to perform systematic reviews, including criteria for inclusion and exclusion, as well as phases in the process, such as the initial preparation, the evaluation, and the qualification. In Supplementary Materials, Important criteria from the PRISMA checklists are used to construct our SLR. The PRISMA 2020 statement is crucial to ensure the reduction of bias in our research design. In the pursuit of improving the coordination and integration of SCQM, a suitable analytical model based on SLR has been constructed. SLR was created with the intention of laying the groundwork for robust knowledge bases, which in turn would allow for in-depth investigation and analysis [7,22]. In addition, SLR provides a thorough research approach for resolving research difficulties by means of a thorough paper scan, extensive annotations, importance assessments, and a mapping of the "known" and "unknown" for the investigated themes [2,23]. Valuable insights are garnered through thought-provoking considerations planned at future theory-building in these domains; specifically, our exploration extends into the realm of strategic management [24]. Moreover, an SLR is regarded as a robust and verifiable method that catalyzes the formulation of theories, adheres to guidelines, and culminates in well-founded conclusions [10,25]. Due to its capacity to mitigate potential bias, the SLR process ensures a centralized, transparent, and repeatable evaluation of essential research, instilling a high level of confidence in the findings [23,26,27]. The essential process for a thorough and cohesive SLR is organized into three distinct phases: planning, conducting, and reporting [27]. The PRISMA 2020 statement's identification stage is carried out, and the results are presented in Figure 2 and Table 1 for use in formulating the search strategy.

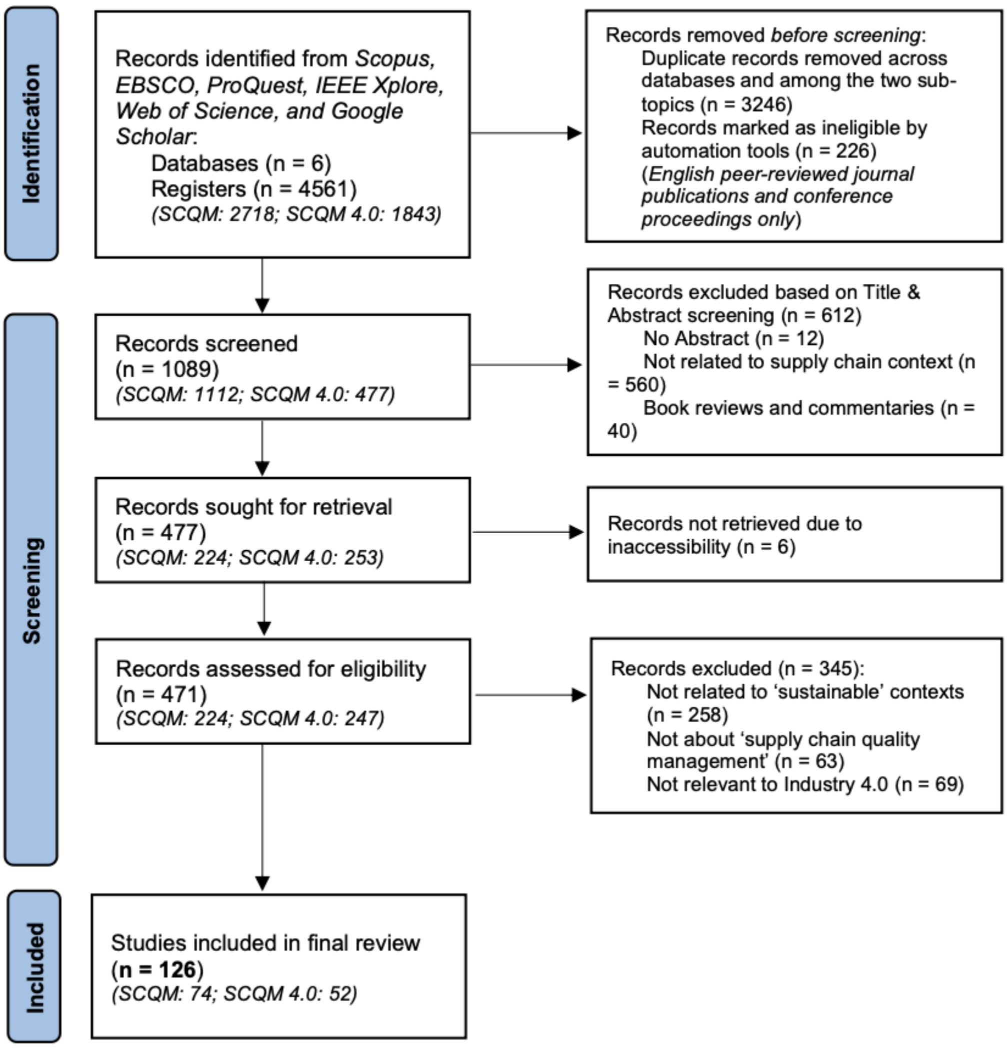

Figure 2. SLR protocol following the PRISMA 2020 statement.

Table 1. SLR protocol.

Phase 1:	
Planning	Search Strings
	SCQM: Supply Chain Quality Management, Supply Chain Management and Quality Management SCQM4.0: Industry 4.0 AND supply AND chain AND quality, Digitization AND supply AND chain AND quality, Fourth Industrial revolution AND supply AND chain AND quality, Smart Manufacturing AND supply AND chain AND quality, Smart factory AND supply AND chain AND quality, Cyber-Physical System AND supply AND chain AND quality, Internet of things AND supply AND chain AND quality, Industrial Internet AND supply AND chain AND quality, Big data AND supply AND chain AND quality, Blockchain AND supply AND chain AND quality.
	Search Period
	1998 to October 2023
Phase 2:	
Conducting	Searching Conducting searches in accordance with predetermined criteria
	Screening Identification: Confirm identity across the database and abstract Eligibility: Assess the introduction and conclusion for eligibility Included: Scrutinize the full text for inclusion
	Analysis Comprehensive examination through descriptive analysis and thematic synthesis
Phase 3:	
Reporting	Establishing Constructs for SCQM 4.0 Concept Building Conceptual Frameworks in the Context of CE

For our SLR with the PRISMA method, we have gathered relevant information from various academic databases, including Web of Science (WoS), Scopus, EBSCOhost, ProQuest, IEEE Xplore, and Google Scholar. To ensure the relevance of the selected literature, we excluded conference papers, unpublished working papers, editorial notes, and master's and doctoral theses. Employing a comprehensive approach to ensure the inclusion of crucial works, we tracked citations, verified reference lists, consulted with experienced scholars, and conducted thorough internet searches.

2.1. Planning

During the planning phase, the keywords were established to extract research topics and fundamental integration problems for these research lines. QM and SCM integration issues include but are not limited to SCQM 4.0: supply AND chain AND quality. To complement the existing literature reviews and demonstrate a general view of SCQM 4.0 consistent with the study objectives, in-depth research was conducted towards the discovery of uncharted territories with the keywords searching, as shown in Table 1. The journal and conference publications covered by the review will be located and extracted using an aggregated database including Scopus, EBSCO, ProQuest, IEEE Xplore, Web of Science, and Google Scholar. Despite the overlap in the results obtained from the concurrent usage of several databases, all relevant documents are guaranteed to be collected. However, the review exclusively incorporated peer-reviewed journal publications and conference proceedings to uphold the utmost reliability within the researched areas [2].

2.2. Conducting

In the implementation phase, the performance of a search step identifies appropriate articles based on the planned criteria. These articles are next vetted through the title, abstract, introduction, conclusion, and, if necessary, the entire manuscript. Different methods for synthesizing and analyzing qualitative data are available in the literature, including qualitative summary, qualitative meta-analysis, theoretical background, content analysis, and thematic synthesis [2,21,28]. Given its capacity to offer a structured approach to interpreting thematic information and fostering the development of a comprehensive understanding of the literature in question, this research will emphasize the thematic synthesis method. An MS Excel database was created to systematically organize, encode, and categorize the articles included in this review. The studies were grouped according to SCQM and SCQM 4.0 categories, facilitating descriptive analysis and summarization by topic. From the publications and records on the developed database, key descriptive information, including publication date (year), database, journal, survey disciplines, and applied research methods, was collected to accumulate descriptive data.

In conducting thematic analyses, primary searches focused on identified key relationships and pivotal areas of discussion, either proposed (for conceptual studies) or established (for empirical studies). These key aspects were carefully noted in each article within the category review (SCQM and SCQM 4.0). Subsequently, the essential elements of the topics are discerned, paving the way for systematic classification and coding. Ultimately, hardly any articles about SCQM 4.0 were found. Four research types were utilized in this study. Initially, the model type comprises the primary classification for each paper, drawing inspiration from the work of Sayama [29] for the classification of scientific models. After defining the model type, the SCQM (coordinated and/or integrated) goals are distinguished in the second category. The third category, "applied tools," encompasses modeling tools or techniques employed in each research. Fourth, coordination/integration mechanisms include the necessary management practices.

2.3. Reporting

The application or focus area (topic) of each research work was derived from the analysis of each paper. In this article, these areas of application/focus are referred to as "practice". Each practice was meticulously extracted through a comprehensive review and analysis of articles, drawing insights from various manuscript sections, including proposals, results, conclusions, and implications. As a result, conceptual frameworks were systematically constructed.

3. Results Analysis of the SLR

3.1. Descriptive Statistics

A total of 126 articles were systematically reviewed and classified as relevant for the lines of research graphically depicted in the preceding Figure 2. In this study, Bib Excel 1.6.4 was selected to handle extensive data sets due to its versatility and compatibility with several computer applications, such as Excel, Pajek, and Gephi [7,30]. In addition, Bib Excel assists with preparing input data for comprehensive network analysis. From the results of 52/126 articles in Figure 2, notwithstanding a more moderate quantity compared to studies on SCQM, SCQM 4.0 is indisputably fertile land for research and is of considerable interest to myriad academicians. The prominent keywords anticipated to identify SCQM 4.0 include IoT, I4.0, supply chain, and supply chain quality. Thus, based on these keywords, the proposed SCQM 4.0 will be a new research direction in this research.

Figure 3 demonstrates that the field of SCQM has increasingly captured scholars' attention since 2005. Nevertheless, it was not until 2019 that the upward trend in studies on SCMQ became apparent. From 2019 onwards, the amount of research escalated annually and peaked in 2022 and the first six months of 2023. Although SCQM 4.0 first appeared in 2005, this area of research has only piqued the interest of scholars since 2014. However, compared with the business community, the growth of research in this area is probably slower. As can be seen from the chart, studies on SCQM 4.0 are likely to increase from 2020 onwards, when multiple special issues have drawn attention from journals, especially international journals, such as The TQM Journal, Industrial Management and

Data Systems, Food Control, International Journal of Quality and Reliability Management, and International Journal of Production Economics. Undeniably, the field of SCQM 4.0 has gained momentum in recent years. From 2014 to 2020, the number of related studies has risen twofold, especially in the Digital 4.0 research line. Given the advantages that I4.0-related disruptive technologies offer organizations in response to legislative requirements, customer expectations, and the needs of contemporary society, the research focus on integrating Engineering 4.0 into business practices is expected to experience a significant upswing.

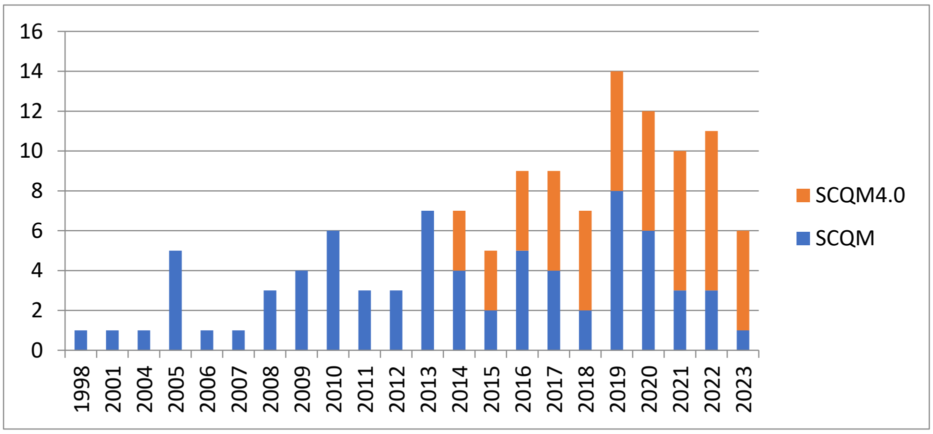

Figure 3. Distribution of papers per year.

Figure 4 illustrates the number of papers/articles per database of the antecedent literature related to SCQM. Despite the variety of databases used in the search, the articles seem to be concentrated mainly on a few key databases, notably Emerald, Elsevier, and Taylor and Francis. Figure 5 illustrates the types of surveyed industries studied in the antecedent literature related to SCQM. This data also emphasizes a limited number of empirical studies that need more attention from the academic community to evaluate the validity and reliability of conceptual models as recommended by Frederico et al. [31], Sony et al. [32], Quang, Sampaio, Carvalho, Fernandes, Binh An, and Vilhenac [4] and Fernandes, Sampaio, Sameiro, and Truong [3]. Such empirical research primarily used data from the Food (21%), Manufacturing (16%), and Multisectoral (10%) industries. Further, the proportions of the surveyed manufacturing and service industries are not much different (41–59%), which implies that the academics place a high value on service-related research.

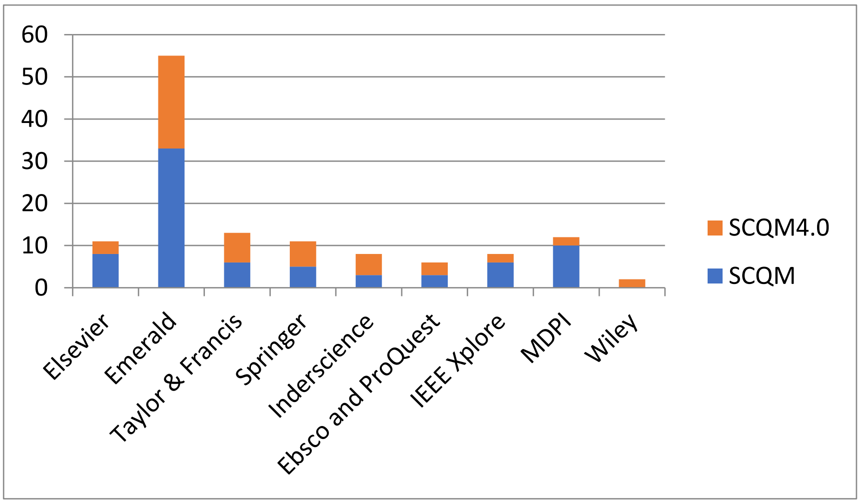

Figure 4. Distribution of articles per database.

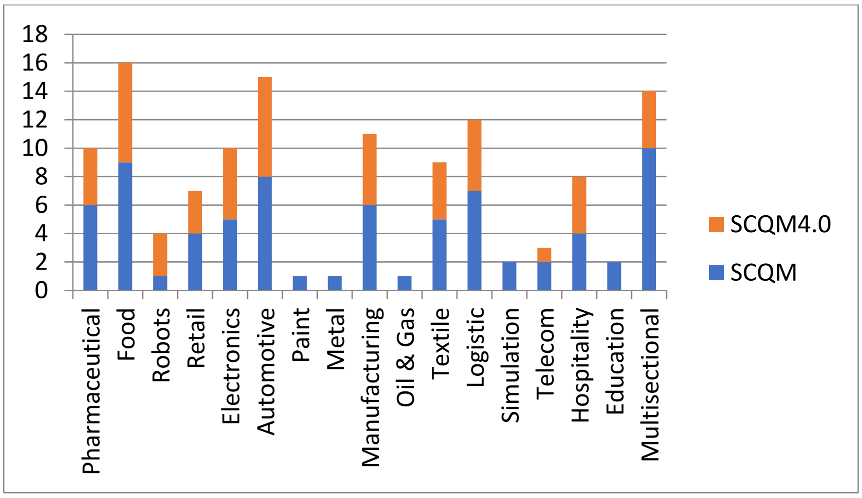

Figure 5. Surveyed sectors.

Figure 6 illustrates the distribution of papers/articles across different journals for the antecedent literature related to SCQM. Quality and supply chain-oriented journals, for example, the International Journal of Quality and Reliability Management, The TQM Journal, the International Journal of Production Economics, Supply Chain Management: An International Journal, and the International Journal of Production Research, have a wide range of publications on SCQM. Studies on SCQM 4.0 have been found in journals such as The TQM Journal, Industrial Management and Data Systems, Food Control, International Journal of Quality and Reliability Management, and International Journal of Production Economics.

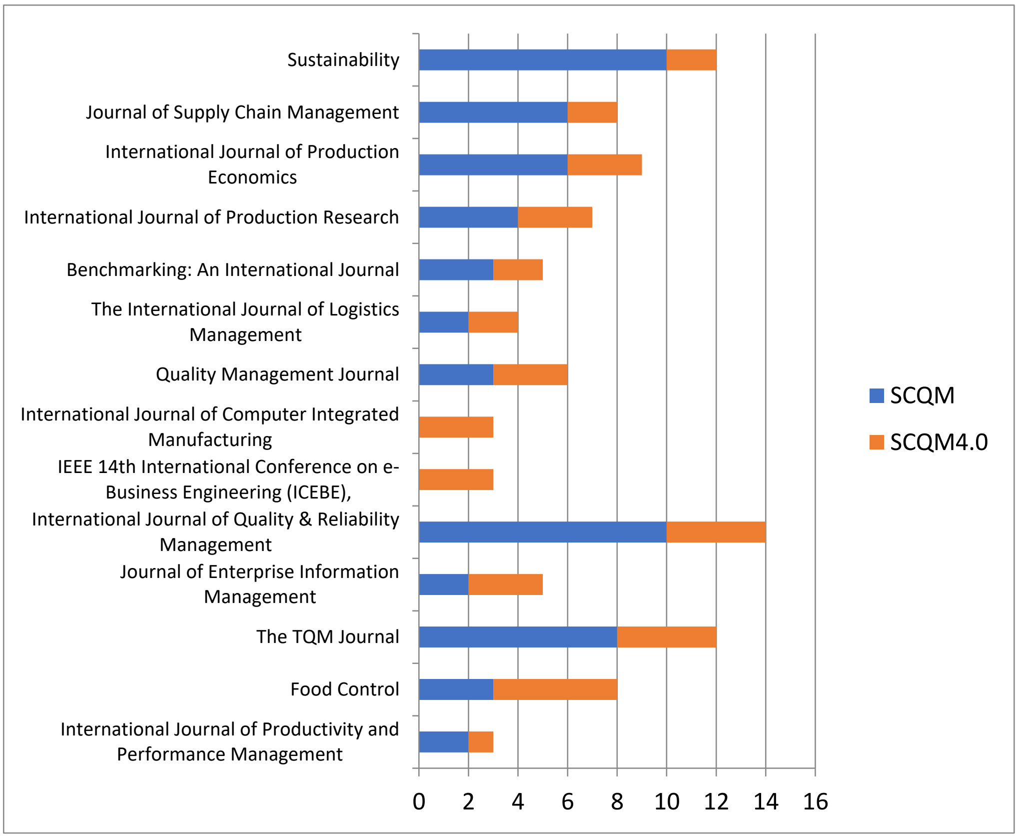

Figure 6. Number of articles by journal.

Figure 7 presents the types of research methodologies applied to antecedent literature related to SCQM. The results show that more than 53% of the publications are empirical studies, including surveys (29%) and case studies (24%). Most research methodologies are applied to lend insight into how SCM, QM, and I4.0 technologies are implemented in various industries by administering questionnaires to companies, conducting surveys with them, or analysing case studies of firms in specific sectors. The results show that 19% of conceptual papers suggest innovative frameworks for integration, including techniques, tools, and practices. Literature reviews contribute 7% of the number of publications to facilitate theory building and research directions on future directions. Empirical assessment methods, such as case studies and surveys, are quite similar at 19% and 23.5%, respectively. Only 4% of research streams apply both qualitative and quantitative methods. Carranza [33] advocated for two approaches to augment the accuracy and validity of research data results: (1) knowledge-based/directional and (2) data-based/quantitative. Future studies should apply this combination of method approach to showcase greater understanding and bolster the confidence level of integrated research paths.

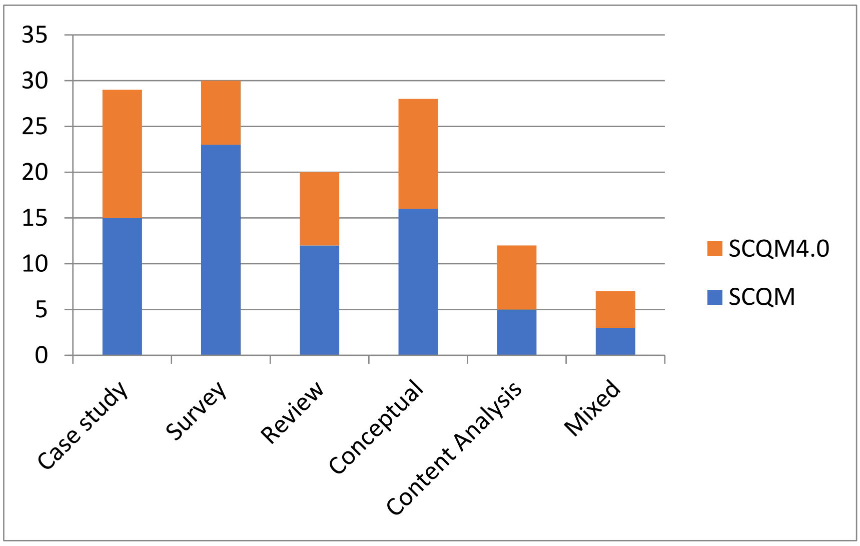

Figure 7. Research methodologies applied in prior studies.

3.2. Thematic Synthesis and Analysis

Contemporary research on SCQM 4.0 predominantly centers on the application of blockchain technology, emphasizing the mitigation of risks and advancements in SCQM, e.g., [34] blockchain as one of the emerging and disruptive technologies is driving the development of e-agriculture. The adoption of blockchain technology in various business applications has been emerging in SCM [35,36]. Due to features such as transparency, censorship resistance, distributed ledger technologies (DLT), and smart contract features, blockchain technology adoption can improve data coordination and trust between multi-stakeholder [37] and construct superior data infrastructure [38]. Existing studies suggest that the adoption of blockchain technology is a viable application for enhancing supply chain operations management [36,39–41]. Table 2 presents the summary of current traceability technologies' research trends and findings, including the uses of radio-frequency identification (RFID), Personal Data Assistant (PDA), IoT, and more. Table 3 offers a concise overview of the recent literature related to the integration of blockchain and IoT technologies.

Table 2. Traceability technology research trends and findings.

Traceability Research Issue	References
Traceability Systems Applications:	
RFIDs	Qian [42]
RFIDs with PDA and barcodes	Tian [43]
"Gapless" traceability with RFIDs	Mainetti et al. [44]
RFIDs	Barge et al. [45]
IoT, EPCglobal	Chen et al. [46]
Cold supply chain	Óskarsdóttir and Oddsson [47]
General tools	Bhatt et al. [48]; Olsen and Borit [49]
Traceability for quality	Wang et al. [50]; Xiao et al. [51]; Wang et al. [52]
Traceability for safety and security	Zhang et al. [53]; Xiao, Fu, Zhang, Peng and Zhang [51]; Liu et al. [54]
Value of traceability to consumers	Jin, et al. [55]
RFID technology management: Traceability in logistics and Traceability for anti-counterfeit operations	Aung and Chang [56]; Cuinas et al. [57]; Chen and Xiao [58]; Alfian et al. [59]; Bai et al. [60]
Implementation requirements, consistency, data security and big data expertise	Giagnocavo et al. [61]
Challenges in dealing with the heterogeneous nature of the supply chain from a technological perspective	Badia-Melis et al. [62]

Table 3. Summary of recent literature on application of blockchain technology in SCQM.

Research Topics	References
Framework for intelligent Blockchain-based SCQM	Chen, Shi, Ren, Yan, Shi and Zhang [46]
Supply chain traceability system based on Blockchain and IoT technology	Tian [63]; Lin et al. [64]; Caro et al. [65]
Supply chain traceability system based on HACCP (Hazard Analysis and Critical Control Points), Blockchain and the IoT	Tian [63]
Blockchain pilot implementation	Kamath [66]
Blockchain and smart contracts implementation challenges	Galvez et al. [67]; Tripoli and Schmidhuber [68]
Pilot implementations	Kamath [66]

There is also a growing literature that proposes the integration of blockchain systems and other disruptive technologies, including the IoT, network-physical systems, and semantic machine-to-machine communication [69–71]. The IoT represents an emerging information technology revolution, ushering in a paradigm shift across various domains, including QM. The IoT elevates supply chain communication to a new level by enabling seamless interaction between people and things. It facilitates the automatic coordination of "things" during storage within a facility or while being transported between different entities in the supply chain [11]. The IoT is experiencing exponential growth and capturing significant consideration in both academic and industrial spheres. It introduces unprecedented levels of supply chain visibility, agility, and adaptability, addressing various quality challenges [72].

However, privacy risks and security holes remain as a consequence of the inadequacy of security technology basics [73]. Current security and privacy approaches do not apply to IoT due to its decentralized topology and mobile device resource constraints [74]. The widespread implementation of IoT faces certain challenges, including the substantial investment costs associated with IoT technology [75], the management of extensive data volumes necessitating robust software, hardware, and a secure environment, and the absence of standardization in IoT systems [73], posing adoption barriers for companies. Table 4 provides an overview of recent literature on smart packaging, while Table 5 summarizes key IoT-based solutions and frameworks for the SCM.

Table 4. A concise overview of literature related to smart packaging.

Research Issues in the Domain of Smart Packaging	References
Various types of carbon dioxide sensors	Puligundla et al. [76]
Implementation of photochromic time-temperature indicators (TTI) to monitor the time-temperature history	Brizio and Prentice [77]; Tsironi et al. [78]; Zhang et al. [79]
Smart time-temperature indicator	Lorite et al. [80]; Brizio and Prentice [81]
Product tracking using IoT technology	Maksimović et al. [82]; Tsang et al. [83]
Implementation of intelligent packaging for waste reduction	Haass et al. [84]; Fang et al. [85]; Heising et al. [86]

Table 5. Primary IoT-based solutions and frameworks for enhancing the SCQM.

IoT Systems Applications and Frameworks	References
IoT systems application	
Quality and safety monitoring of agricultural products.	Liu et al. [87]; Barmpounakis et al. [88]; Yan et al. [89]; Balamurugan et al. [90]; Witjaksono et al. [91]; Wen et al. [92]
IoT-based cold supply chain monitoring.	Tsang, Choy, Wu, Ho, Lam and Koo [83]
IoT-based cargo monitoring system for product quality.	Tsang et al. [93]
IoT and cloud computing-based solutions for cold supply chain monitoring.	Lu and Wang [94]
RFID and critical Temperature Indicators sensors for real-time monitoring of supply chain temperature	Lorite, Selkälä, Sipola, Palenzuela, Jubete, Viñuales, Cabañero, Grande, Tuominen and Uusitalo [80]
IoT-based duck product traceability system	Liu, Liu, Wen, Zhang, Zhao, Yan and Yu [54]
An intelligent tracking system based on the IoT for the cold chain.	Luo et al. [95]
RFID monitoring for cold supply chains.	Ruiz-Garcia and Lunadei [96]
An optimization approach for increasing revenue from perishable product supply chain with the IoT	Yan [97]
IoT frameworks	

Table 5. *Cont.*

IoT Systems Applications and Frameworks	References
Value-centric business-technology design framework.	Pang et al. [98]
IoT-based logistic information system architecture for supply chains	Verdouw et al. [99]
IoT-based framework for supply chain planning	Accorsi et al. [100]
Supply chain virtualization	Verdouw et al. [101]; Verdouw et al. [102]
Hierarchical data architecture for sustainable SCM and planning	Accorsi et al. [103]
Green evaluation models based on IoT for agricultural products	Wang and Deng [104]

Hence, based on the findings of the SLR, we propose a definition of SCQM 4.0 as below:

"Supply Chain Quality Management 4.0 is a holistic approach in which companies leverage advanced Industry 4.0 technologies within their industry network to streamline processes, elevate product quality, cultivate resilient supply chain relationships, and proactively minimize their environmental and social footprint, with the ultimate goal of achieving stakeholder satisfaction and sustainable operations."

4. Conceptual Framework for SCQM 4.0

Since I4.0 technologies make more efficient use of resources, reducing overall energy consumption, there has been a recent uptick in scholarly interest in investigating the role that these developments play in bringing about CE practices. The difficulties of providing and maintaining quality throughout the product lifecycle and within the returned products have made SCQM a popular topic of study in the field of sustainable SCM. There has been some discussion of a link between SCQM, Industry 4.0, and CE techniques in the past, but few studies have examined this notion. According to Rathi et al. [11], small and medium-sized enterprises (SMEs) are still struggling to implement CE in Industry 4.0, and there is no roadmap for doing so. This research will fill in that information gap. In this endeavor, the paper employs an SLR to construct a pertinent analytical model for the coordination and integration of SCQM 4.0 over time. The core objective of this systematic review is to contribute to the establishment of robust knowledge bases, enabling a comprehensive and in-depth exploration and analysis. It offers a rigorous methodology to address research challenges through meticulous document scanning, detailed note-taking, significance assessments, and mapping of both the "known" and "unknown" aspects within the areas under investigation [23]. Beyond introducing the term SCQM 4.0 and offering a corresponding definition, this article attempts to propose a conceptual model of SCQM 4.0 practices to accomplish an SCQM 4.0 conceptual framework (Figure 8), as well as a four-stage practice roadmap of implementation towards a CE (Figure 9). In this paper, SCQM 4.0 is proposed to assist in a better understanding of Supply Chain 4.0 from two perspectives, which are the (1) infrastructure practices that consist of two operational components (i.e., disruptive technologies and supply chain operations), and the (2) sustainable performance that focuses solely on the environmental aspect as explained at the beginning.

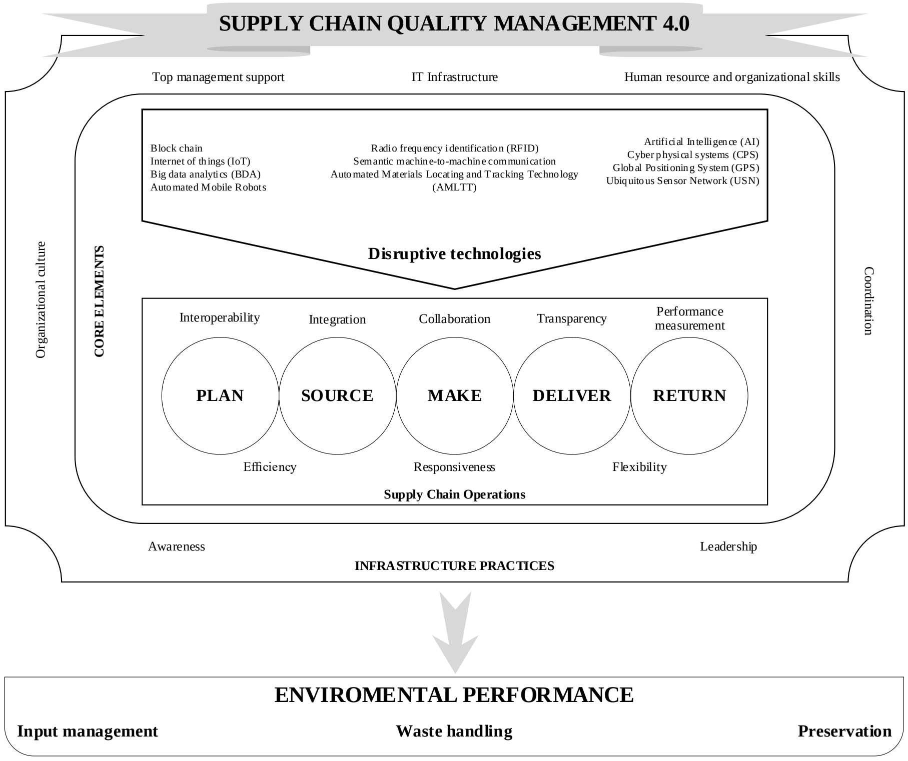

Figure 8. The SCQM 4.0 Conceptual framework in this study.

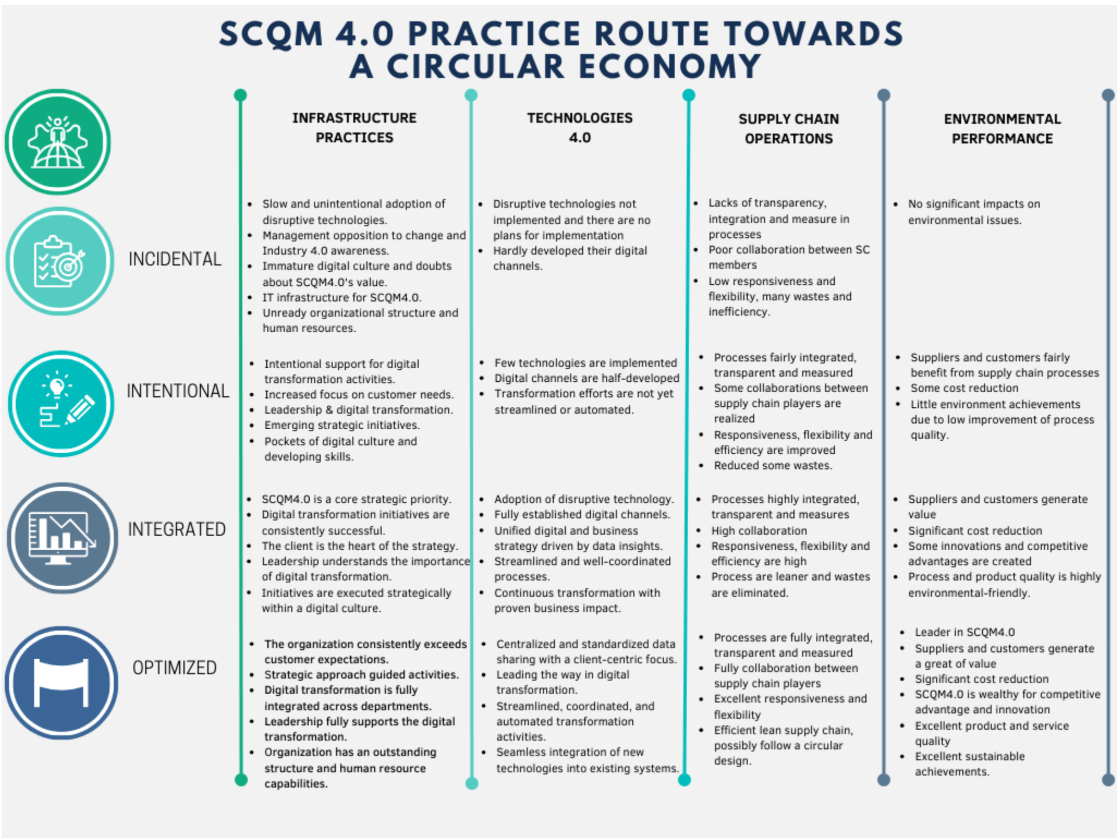

Figure 9. SCQM 4.0 practice route towards a CE.

4.1. Disruptive Technologies in SCQM 4.0

Table 6 presents the list of disruptive technologies in SCQM 4.0. The research and development of I4.0 and its relevant advanced digital technologies in diverse areas have been contributing to progressive social and economic development. The initiatives have taken place since Blockchain, IoT, BDA, RFID, GPS, USN, AMLTT, Semantic machine-to-machine communication, CPS, Robots, and AI have been gradually improving in leaps and bounds. I4.0 develops on three main pillars: digital, biotechnology, and physical, in which the core technologies of I4.0 comprise of IoT, AI, radio frequency identification (RFID), and wireless sensor networks (WSN). The advent of new technologies will impact various business domains, influencing the development of novel products and services, enhancing quality, streamlining operations management, and reshaping business models. These changes are poised to bring about significant transformations in SCQM [105,106].

Table 6. List of disruptive technologies in SCQM 4.0.

Disruptive Technologies	Authors
Semantic machine-to-machine communication	[2,106–110]
Cyber-physical systems (CPS)	[1,2,106,109,111–118]
IoT	[2,106,107,109,111,112,116–123]
Cloud technologies	[106,107,109,111,113,123–126]
BDA	[108–111,113,119,120,122,127,128]
Radio frequency identification (RFID)	[106,107,110,118,120,123,126,129]
Blockchain	[1,36,46,116,128,130]
Robotics	[2,108,109,113,119,121,122]
Enterprise Resource Planning (ERP)	[2,107,114,128,131]
3DP	[1,2,119,120,125,132,133]
Nanotechnology	[2,109,110,119,124,131]
Business intelligence	[2,108,109,134]
AI	[2,106,117,123,129,132,133]

4.2. Supply Chain Operations

Enhancing product quality across the supply chain, SCQM 4.0 makes extensive use of cutting-edge technologies; however, these innovations cannot be created, deployed, managed, or further refined without access to modern information technology infrastructures. The effective deployment of technology necessitates an ongoing commitment to training and developing personnel [135]. Moreover, the adoption of technology and the resulting difficulties in implementing SCQM 4.0 are hampered by the resistance of stakeholders to change during the implementation of technologies in organizations and business processes; therefore, the support of top management is crucial [2,40]. To further emphasize the need for top-level management's backing and a knowledge-oriented leadership style (e.g., transformational leadership style), consider that the success of SCQM 4.0 is dependent on the incorporation of technology into company strategy [136]. The absence of standardization results in a case-by-case implementation method, mainly due to the considerable product range and diversity [62]. Additionally, complicating factors arise from inadequate government regulation and deficient internet infrastructure [137]. Regarding the choice of supply chain performance assessment, according to Akyuz and Erkan [138], supply chain operations reference (SCOR) indicators have been recognized and endorsed as a suitable platform in supply-chain performance monitoring due to their importance and applicability. Numerous empirical studies were conducted based on the SCOR model to examine the connections between technological practices and sustainable supply chain performance (see also [3,13,66,81]). Table 7 provides a summary of recent SCQM 4.0 practices and indicators.

Table 7. Description of SCQM 4.0 practices.

SCQM 4.0 Practices	Description	Authors
Infrastructure Practices		
Top management support	The degree to which top management understands the importance of SCMQM 4.0 and the extent of willingness to support disruptive technologies implementation to improve quality in the supply chain. Top management is supposed to shape a proper strategy which ensures the organization's purposes are aligned with the implementation of new technology.	Sriram and Vinodh [139], Stentoft et al. [140], Nair and Adetayo [141]
IT Infrastructure	IT capabilities and resources need to be readily accessible for the initial development, implementation, and continuous management and evolution of disruptive technologies. The capability of the infrastructure enables entities to store and interpret huge volumes of data.	Sriram and Vinodh [139], Blatz et al. [142]
Human resource and organizational skills	Management structure, HR strategy, work environment, and skill development are crucial components for the successful implementation of SCWM 4.0, particularly in the context of adopting new technologies.	[2]
Coordination	Effective communication across different tiers of the supply chain is paramount, considering the evolutionary implications of SCQM 4.0. Coordination, in this context, involves active and direct cooperation achieved through transmitting accurate signals, sharing relevant information, and aligning policies. It denotes a collaborative interactive process that results in joint decisions and activities [143].	[143]
Organizational culture	A shared set of norms, beliefs, and values among members of the organization is essential for fostering a collective understanding of SCQM 4.0.	Asha et al. [144] Alamsjah and Yunus [145]
Awareness	A comprehensive understanding among all entities in the supply chain is crucial regarding the benefits and requirements of SCQM 4.0.	Fan et al. [146]
Leadership	A thorough comprehension of the evolutionary nature and strategic implications of SCQM 4.0 is essential for making informed decisions regarding budget and resource allocations.	Dhamija et al. [147] Luo et al. [148]
SCOR indicators		
Transparency	The extent of visibility and the dissemination of information, both internally and externally, depends on the desired level of disclosure. This involves the degree to which stakeholders effectively identify and gather data from all linkages in the supply chain.	Dutta et al. [149] Bui, Carvalho, Pham, Nguyen, Duong and Quang [2]

Table 7. *Cont.*

SCQM 4.0 Practices	Description	Authors
Integration	Integration, in this context, refers to the act of "making a whole" and aligning the constituent parts. It involves synchronizing the requirements, concepts, and flows among the chain members, with the ultimate goal of maximizing competitive advantages at strategic, tactical, and operative levels.	Bautista-Santos et al. [150]
Interoperability	Refers to the level of information sharing and applications; interoperability of systems and their ability to share and utilize data and features.	Sriram and Vinodh [139] Lu [151]
Collaboration	Collaboration entails working together or with someone towards a specific purpose [152]. In collaborative supply chains, all members are obligated to execute the mutually agreed-upon strategies, regardless of their size, function, or position within the chain [153].	Sriram and Vinodh [139] Faller and Feldmüller [154] Ganzarain and Errasti [155]
Performance measurement	Evaluate the efficacy of steps in the SCOR model by assessing the ratio of perfect orders to defect rates.	Basheer et al. [156] Lin et al. [157]
Efficiency	The extent to which a company's procedures optimize the use of available resources. This includes but is not limited to monetary, human, technological, and physical assets.	Lin, Chow, Madu, Kuei and Yu [157] Kuei et al. [158]
Flexibility	The business's capability to adapt to risks and shifts in consumer expectations without incurring substantial financial, temporal, or performance setbacks is known as resilience. This resilience is maintained while preserving positive relationships with critical suppliers and customers.	Duclos et al. [159] Richey et al. [160]
Responsiveness	Refers to how quickly and effectively a company's supply chain can react to new demands from customers or shifts in the marketplace.	Xu [161] Fish [162]

4.3. Environmental Performance in SCQM 4.0 towards a CE

In recent years, sustainability has surfaced as a critical concern for businesses worldwide. Sustainable performance goes beyond economic and social dimensions that are integral to its long-term viability [7]. In this context, the key characteristics of sustainable performance are environmental regard and responsible resource management. Following what Moraga et al. [13] have suggested, together with updates from Malik et al.'s [163] input-output-based sustainability assessment, we look at the indicators of (a) input management, (b) waste handling, and (c) preservation, stressing the need for ecologically responsible actions. Our goal in analyzing these metrics is to draw attention to the positive effects that businesses can have on the environment and to stress the significance of environmental concerns in sustainable performance plans towards circular supply chains.

4.3.1. Input Management

Effective input management is a key indicator of environmentally respectful sustainable performance, encompassing the responsible use and conservation of resources throughout a company's operations [164]. As mentioned previously, measuring firms' input management performance is believed to be particularly useful in understanding changes in inputs bought by sectors and by disruptive technologies over time [13]. This calls for a number of cutting-edge methods to evaluate the effects of raw material composition improvements ("efficiency"), product and raw material environmental impacts ("life cycle assessment"), and sustainable raw material and service purchases ("sustainable sourcing") [163].

- Resource Efficiency: Sustainable businesses prioritize efficient utilization of resources, such as energy, water, and raw materials. By reducing resource consumption, optimizing production processes, and minimizing waste, companies can attain substantial environmental benefits and cost savings [165].
- Sustainable Sourcing: Adopting sustainable sourcing practices involves selecting suppliers who adhere to responsible environmental standards. This ensures that the inputs and materials used in the production process are obtained in a manner that minimizes negative ecological impacts, such as deforestation or habitat destruction [163].
- Life Cycle Assessment: Businesses can perform life cycle assessments to assess the environmental effect and impact of their products/services across the entire life cycle, from raw material mining to disposal. This approach enables companies to recognize areas for improvement and make informed-decisions aimed at minimizing their overall environmental footprint [166].

4.3.2. Waste Handling

Efficient waste handling is crucial for environmentally respectful sustainable performance, as it minimizes pollution, conserves resources, and promotes CE principles [167].

- Waste Reduction: Sustainable businesses implement strategies to minimize waste generation through process optimization, product redesign, and material substitution. By reducing waste at its source, companies can decrease their environmental impact and save on waste management costs [85].
- Recycling and Reuse: Encouraging recycling and reuse initiatives helps divert waste from landfills and conserve valuable resources. By implementing efficient recycling programs and exploring innovative ways to reuse materials, companies contribute to a more sustainable and CE [168].
- Hazardous Waste Management: Environmentally respectful sustainable performance involves proper handling and disposal of hazardous materials to prevent pollution and protect ecosystems and human health. Compliance with regulations, implementing appropriate storage and treatment procedures, and promoting responsible waste management practices are essential in this regard [167].

4.3.3. Preservation

The preservation of natural resources and ecosystems is a critical aspect of environmentally respectful sustainable performance [169].

- Biodiversity Conservation: Sustainable businesses prioritize the protection and restoration of biodiversity by minimizing habitat destruction, supporting conservation efforts, and implementing sustainable land management practices. Preserving biodiversity is essential for maintaining ecosystem resilience and ensuring the long-term health of the planet [170].
- Environmental Stewardship: Engaging in environmental stewardship involves actively monitoring and mitigating negative environmental impacts caused by business activities. This includes reducing emissions, minimizing water and air pollution, and promoting sustainable land use practices [171].
- Climate Change Mitigation: Sustainable performance requires businesses to actively contribute to global efforts to mitigate climate change [138]. This entails implementing measures to curtail greenhouse gas emissions, transitioning to renewable energy sources, and implementing carbon offset strategies.

In general, emissions, waste, and inefficient use of resources are three major supply chain issues that CE tries to address. Offering goods, components, and materials with minimal or no waste is one way to accomplish these environmental aims [167]. The transition from a linear to a CE has brought about a heightened focus on enhancing supply chain reliability and QM [172]. Many existing business structures and supply networks will need substantial revision as we move toward CE. Consequently, to achieve sustainable development, businesses must adeptly navigate the challenges presented by the CE.

4.3.4. SCQM 4.0 Practice Route towards a CE

Figure 9 presents the four stages of the SCQM 4.0 practice route (i.e., incidental, intentional, integrated, and optimized) as an attempt to answer the call from Rathi et al. [11] mentioning that there has been yet a clear implementation roadmap for firms, especially SMEs, to adopt SCQM 4.0 initiatives in achieving CE. At each stage, the SCQM 4.0 practice route passes through four categories of practices (i.e., infrastructure practice, technologies 4.0, supply chain operations, and supply chain performance). This categorization is similar to what has been conceptualized by Frederico et al. [21] in the context of Supply Chain 4.0.

A rigorous methodology was employed to ensure the robustness and applicability of the SCQM 4.0 maturity model. Initially, a structured interview was conducted with academicians to gather valuable insights. These inputs were meticulously recorded and subjected to thorough analysis, focusing on aligning the maturity model with organizational goals and assessing its practical feasibility for implementation. Subsequently, a Q-sort method was implemented with the participation of eleven managers. This step was designed to conduct a preliminary assessment of the validity, reliability, and unidimensionality of SCQM 4.0 practices at each stage. The refined and validated insights gleaned from both the academicians and managers were then synthesized and integrated to form the final version of the maturity model.

As depicted in Figure 9, during the incident stage, a firm within the supply chain operations typically exhibits a low level of awareness regarding the significance of digital technologies in enhancing supply chain performance. There may be uncertainty about the concept, functionality, and the value of transitioning to business digitalization. The company, lacking technical knowledge, skills, human capital, and infrastructure investment, faces challenges in planning for the adoption of I4.0 technologies. This deficiency has resulted in a lack of openness in business dealings, limited cooperation among supply chain participants, a rigid organizational structure, and ultimately, ineffective supply chain operations [167]. In turn, the firm's stakeholders, such as its suppliers and consumers, are unable to contribute to the supply chain's performance in economically viable, socially engaged, and ecologically responsible ways [173]. Nevertheless, as a company progresses through the SCQM 4.0 practice route and attains the later phases of being "intentional," "integrated," and "optimized," the implementation of SCQM 4.0 technologies will substantially enhance the company's overall capabilities in supply chain total performance. Supply chain operations that successfully involve a wide range of interested parties will see increased investment and adoption of SCQM 4.0, increasing the likelihood of the company achieving long-term, sustainable success [1]. Concerning environmental activities, supply chain operators may reduce carbon emissions and pollution by producing market-ready goods and services with better SCQM that minimizes their impacts on the environment [131].

5. Implications and Future Research

In this paper, SCQM 4.0 is proposed as a guiding framework to improve the understanding and implementation of Supply Chain 4.0 practices within a CE, delineated through a four-stage progression from incidental awareness to optimized integration. The established cause-and-effect relationship between solutions is crucial, as highlighted by the interdependence of management and capacity infrastructure elements to support technology integration. The indispensable foundation for the successful implementation of disruptive technologies involves the establishment of infrastructure, IT infrastructure, TMS, Human Resources, organizational skills, leadership, and top management support. Without this robust foundation, the effective execution of technologies meeting process performance requirements is unlikely. The convergence of studies lies in the application of I4.0 technologies, such as Blockchain, IoT, Network Physical Systems, and Machine-to-Machine Communication, reinforcing product, and service quality in the supply chain. These technologies address supply chain trust issues, enhance resource allocation efficiency, optimize production processes, and facilitate the transition from linear to circular supply chains. CE heavily relies on innovative supply chain design and technologies for sustainability and waste reduction, especially in the environmental aspect [167]. The adoption of I4.0 technologies, including 3DP, nanotechnology, and blockchains, facilitates the realization of circular supply chain designs. The advent of I4.0 underscores disruptive technologies that empower SCQM to enhance quality and performance throughout supply chain operations. This study emphasizes the synergy between SCQM and I4.0 disruptive technologies in the manufacturing sector, showcasing their potential to maximize outputs, create high-quality products, and optimize resource utilization. [174].

This study is theoretically and practically significant. In a theoretical aspect, our SCQM 4.0 conceptual framework can be regarded as a "guideline", assisting practitioners in achieving excellence in the implementation of SCQM 4.0. In other words, the research aims to develop conceptual models that can be used as a "handbook" for measuring and implementing SCQM 4.0 solutions. Furthermore, it aims to lay the groundwork for future research in this field, with a particular focus on experimental and applied studies. Hence, this study contributes to the literature by offering a comprehensive review supplemented with a conceptual framework proposal that demonstrates how a sustainable SCQM 4.0 in CE can navigates the environmental challenges. In a practical aspect, the conceptual frameworks proposed can effectively support practitioners participating in SCQM 4.0 implementation programs. The SCQM 4.0 conceptual framework provides a complete overview of all the aspects that need meticulous consideration to achieve successful implementation and management. Subsequently, the SCQM 4.0 conceptual framework helps identify a business's position on the SCQM path. The advantages and limitations will be pointed out and analyzed to provide clear levels of progression underpinned by the structures developed. Moreover, I4.0 technologies used in SCQM are emphasized as crucial to the success of the CE. Using blockchain to enhance visibility throughout the supply chain, for instance, paves the way for easier product and resource monitoring, which in turn encourages reuse and recycling [70]. Predictive maintenance that is fed by real-time data also helps cut down on wasteful activities and move toward more circular methods of operation [10]. Selecting suppliers that adhere to sustainable procurement methods and the concepts of the CE is crucial [163]. Simply put, these managerial measures improve product quality while also promoting sustainability within the framework of a CE. In addition, our proposed SCQM 4.0 conceptual framework in CE provides references to the supply chain practitioners across the manufacturing industries on the critical success factors of SCQM establishment with I4.0 that can improve supply chain operations while navigating environmental challenges in the perspectives of input management, waste handling and preservation. The endeavours can be utilized by supply chain practitioners to gain competitive advantages in eco-friendly QM in the supply chain with I4.0 technologies. Our SCQM 4.0 framework also provides managers with some guidelines on managing the organizational factors integrated with advanced I4.0 technologies that can enhance QM outcomes in SCM. Furthermore, our study provides a reference on the application of SCQM 4.0 in CE for the researchers working in similar research domains to further research this emerging area and ultimately improve the adoption rate of SQQM 4.0 in CE for achieving environmental sustainability.

To attain that, it is vitally important that a scale of these SCQM 4.0 be developed and put on a trial. Afterwards, hypothetical models are built to examine the impact of SCQM solutions on supply chain performance based on the results from the bottom up. The bottom-up cause-and-effect relationship between constructs can be likened to a "road map" guiding SCQM 4.0 implementations towards a CE, addressing environmental issues systematically. In the pursuit of proposing new directions for further research and illuminating emerging trends in the field of Industry 4.0, future research endeavors could concentrate on conducting a Delphi study or a large-scale survey. Moreover, from the search results of 52/126 articles in Figure 2, it is noticeable that there is a limited amount of research revolving around SCQM 4.0. This burgeoning area of research is anticipated to build upon the strengths, and established relationships between supply chain, quality and digital 4.0. It aims to contribute to the development of a quality supply chain and to pioneer advancements in the field. Under the SCQM 4.0 conceptual framework, a clear development route which is underpinned by the SCQM 4.0 architecture is demonstrated. Firm owners are encouraged to conduct gap analysis and guide strategic implementation to deliver an outstanding SCQM 4.0 system that supports sustainable goals. Furthermore, the proposed SCQM 4.0 frameworks significantly contribute to the academic community. Following this, exploratory and/or experimental qualitative studies should be conducted in diverse organizations and industries to investigate any additional key structures specific to identifying critical success factors and/or barriers for SCQM 4.0 within the chosen organization and industry. Although I4.0 technologies offer limitless possibilities, more studies are needed to harness the technologies to solve current environmental challenges in SCM. Embarked from this goal, our study expects the insights provided on SCQM 4.0 in navigating environmental challenges will provide references for supply chain stakeholders to seize the next wave opportunity of moving forward to the new paradigm of Industry 5.0 in the future.

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