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Review

Review of Uncertainty, Carbon Emissions, Greenness Index, and Quality Issues in Green Supply Chains

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Abstract: The ability of closed-loop supply chains (CLSC) and reverse logistics (RL) to improve the triple bottom line (economic, social and environmental values) has increased the development of design and management models for CLSCs and RL. Consequently, there exists an extensive body of literature dedicated to exploring these supply and logistics issues. This paper reviews recent and relevant literature on CLSC and RL with an emphasis on uncertainty, carbon emissions, greenness index, return product quality and reliability considerations. The selected references are organized, reviewed, and analyzed to establish valuable mapping to highlight major findings. Finally, the outcomes are synthesized, and the primary research gaps are emphasized, pointing toward potential avenues for future investigation. These findings reveal that research efforts must be directed towards the development of multi-criteria greenness indices and multi-objective robust optimization models for uncertain quality and reliability of returns.

Keywords: closed-loop supply chain; reverse logistics; uncertainty; return product quality and reliability; carbon emissions; greenness index

Citation: Ghayebloo, S.; Venkatadri, U.; Diallo, C.; Samuel, C.N.; Pishvaee, M.S. Review of Uncertainty, Carbon Emissions, Greenness Index, and Quality Issues in Green Supply Chains. *Sustainability* **2024**, *16*, 9580. https://doi.org/10.3390/su16219580

Academic Editors: Marc A. Rosen and Giada La Scalia

Received: 3 August 2024
Revised: 15 October 2024
Accepted: 29 October 2024
Published: 4 November 2024

1. Introduction

The combination of forward and reverse supply chain (SC) operations constitutes a closed-loop supply chain (CLSC) [1]. CLSC management covers processes such as recycling, reconditioning, refurbishing, repairing, and remanufacturing. Annually, in the United States, the recycling industry supports more than 500,000 direct jobs and contributes a substantial USD 117 billion in economic benefits [2,3]. The same source reports that the global recycling sector has an estimated annual turnover of around USD 500 billion. The substantial revenue and employment potential stemming from recycling and remanufacturing have become compelling reasons for industry and governments to prioritize sustainable manufacturing. Furthermore, consumers are inclined to back CLSC initiatives due to their role in conserving Earth's limited resources, ensuring environmental cleanliness, and preserving the planet and its resources for current and future generations. In essence, monetary, socio-economic, and environmental advantages motivate participation from consumers, companies, and policy-makers.

Prominent industry players, including Caterpillar in construction equipment, Toyota and Volvo in the automotive industry, as well as Apple Inc. in consumer electronics, actively pursue remanufacturing. These companies sell remanufactured parts and products at reduced prices compared to new, while still providing service support. Volkswagen, for instance, asserts that remanufactured parts are often priced at half the cost of new equivalents. This commitment to remanufacturing has yielded substantial benefits. The business case for remanufacturing is clear, as evidenced by its adoption by leading brands across multiple sectors. Remanufacturing represents a major profit opportunity, as evidenced by Caterpillar remanufacturing products for other companies like Ford [4]. World renowned logistics providers such as FedEx, DHL, and UPS have established dedicated reverse logistics divisions to manage product returns. Industry organizations like the "Remanufacturing Industries Council" actively promote remanufacturing through lobbying, consumer education, and engagement with companies [5]. With the demonstrated cost savings and environmental benefits, remanufactured products are gaining wider acceptance among both businesses and consumers. The remanufacturing movement is gaining momentum across sectors, driven by the compelling business case and rising awareness of its advantages.

The International Organization for Standardization (ISO) and its partner, the American National Standards Institute (ANSI), have developed guidelines for advancing the remanufacturing of products. Indeed, ISO 10987-2:2017 [6] outlines standards for remanufacturing heavy machinery. Countries are also acting by implementing policies that enhance producer responsibility (EPR). Notable examples include Canada with its Electronics Product Stewardship and the European Union with the WEEE (Waste Electrical and Electronic Equipment) directive. These directives set benchmarks to direct organizations in recovering and reusing End-of-Use (EOU) or End-of-Life (EOL) products. Similar regulatory initiatives have been introduced by various other countries as well.

In a CLSC/RL, products (cores) are recovered from the market and processed in several different ways at inspection, disassembly, repair, and refurbishment centers (IDRRCs). The typical options at IDRRCs are disposal, reuse, refurbishing, and remanufacturing in increasing order of energy required [7] The latter three options result in some form of the product going back to the market, as shown in Figure 1.

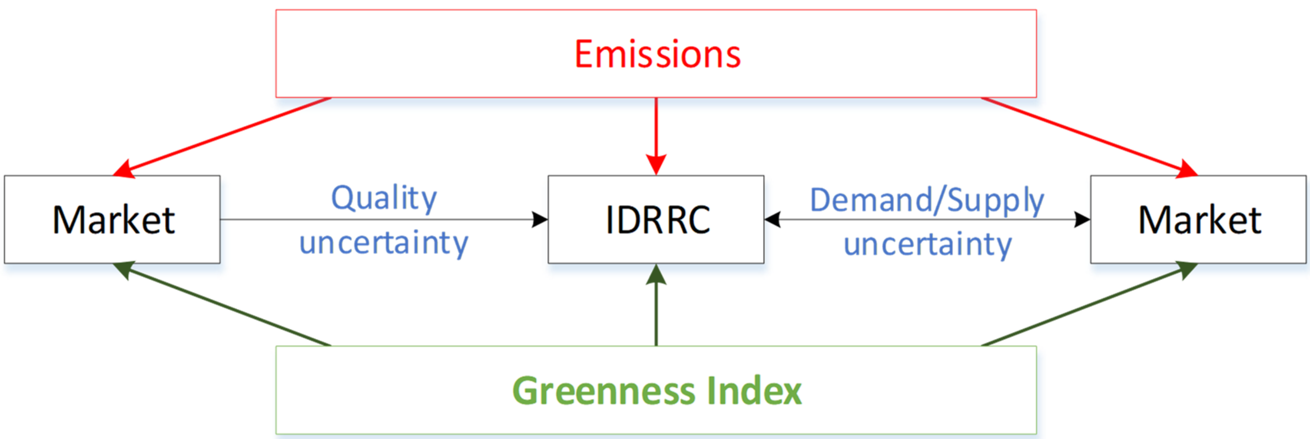

Figure 1. The focus areas of this literature review.

The goal of this paper is to explore the treatment of uncertainty in return quantity and product quality and reliability, which are key to planning IDRRC operations. Since these activities are carried out to minimize carbon emissions, this aspect is also covered in this literature review. The final aspect covered in this paper is the greenness index of a supply chain. For many sourcing decisions, companies are interested in greenness measures of their supplier supply chains. Thus, it is desirable to identify the measures of greenness used in the literature dedicated to CLSC/RL problems. Although there is an abundance of literature reviews on CLSCs, the main contributions of this review are in its critical analysis of specific quality, reliability, greenness and uncertainty aspects, which are important to decision-making but seldom addressed in the extant literature.

The four areas of focus in this literature review depicted in Figure 1 are uncertainty in quality and demand or supply, emissions, and greenness index.

Uncertainty: CLSCs involve significant uncertainty compared to forward supply chains. Returned cores have unpredictable quality and reliability due to varied customer usage. Cores range from unused to destroyed beyond repair. Uncertainty also stems from fluctuating supply and demand in the market for refurbished goods. Most research on CLSC underestimates this uncertainty by using deterministic models [8]. Another reason for the uncertainty in demand for refurbished products is customer trust. For this reason, developing models for warranty policies for new and reconditioned parts is important [9]. Incorporating quality, reliability, and variability in supply and demand would greatly benefit reverse logistics planning. More accurate predictions would help decision-makers in properly scaling facilities and assigning sufficient resources to remanufacturing processes. Managing uncertainty is key to optimizing CLSCs.

Emissions: Given the harmful environmental impact of carbon emissions, environmental advocates and government regulators have pressured companies to cut emissions. Various carbon reduction policies have been implemented globally. Accounting for these emission regulations can further increase the benefits of CLSCs.

Greenness Index: The greenness index is a tool for evaluating the environmental sustainability of different supply chain options. Assessing green supply chain performance is critical yet challenging, especially for closed-loop models. An effective evaluation requires a standardized system that combines financial and non-financial metrics across all supply chain aspects. With the ability to quantify eco-friendliness, companies can make better decisions when selecting environmentally sustainable supply chain alternatives. The greenness index enables scientifically grounded comparisons to identify the most informed eco-conscious decisions [10].

The rest of the article is organized as follows: In Section 2, we present a survey of surveys on CLSC and green supply chain management (GSCM) to present a high-level perspective. Section 3 presents the research methodology followed. Section 4 reviews articles that fall within the categorical themes. Finally in Sections 5 and 6, we discuss potential avenues for future research and provide concluding remarks.

2. Review of Literature Reviews on CLSC and GSCM

Over the years, a substantial body of literature on CLSC and GSCM has developed. Thus, we have analyzed, categorized, and drawn conclusions based on many literature review articles to identify future research opportunities. Using multiple factors, including application area, scope of study, time horizon covered, and number of articles evaluated, a total of 17 current and pertinent review papers are found and categorized. In Table 1, some critical studies grouped according to the defined characteristics are provided to clarify the need for this research.

Based on their focus, these papers can be classified into two groups. One group (eight papers) covers critical reviews exploring key references with a broad focus [11,13,20,25–29]. Among these papers, only two of them provide broad coverage of CLSC and RL [11,20]. However, their limitation is the coverage period of the studies, which were published in 2012 and 2016, respectively.

The second group of 11 papers consists of review articles focused on a particular research area within CLSC/RL. The scope of the reviews includes the following: modeling of reverse logistics inventory systems [21]; distributed decision-making [12]; developing decision support models for the management of returnable transport item [22]; remanufacturing with emphasis on the acquisition/collection and reprocessing of returned products [23]; integration between the industrial production of materials and CLSC research [14]; value creation in a CLSC [19]; green procurement in the private sector [16]; green supply chain management [17,18,30]; green-VRP [15]; quality, reliability, maintenance, and warranty issues in second-hand products [24].

Based on our analysis of these literature review papers, we have determined that there is still a notable absence of thorough research in the specific areas of greenness index, carbon emissions, uncertainty, as well as quality and reliability of returned products, since the reviews covering these areas are lacking. Only one review [26] discusses uncertainty in detail. As for return product quality and reliability, Diallo et al. [24] conducted a review of 104 articles on closed-loop supply chains published after 1985, focused specifically on remanufactured and second-hand products. The authors categorized the papers under six topics—quality, reliability, maintenance, and remanufacturing, warranty, and risk/safety models. They also classified the papers by methodology, mathematical tools, and techniques. The review found the lowest number of papers examining risks, safety, and hazards. However, a limitation is that this review covers articles only through 2016, missing more recent publications. Updated reviews could build on this framework to assess new advances and continuing research needs related to second-hand and remanufactured products in CLSCs.

Table 1. Characteristics of recent review papers.

Paper	Area	Scope	Coverage	Papers
[11]	CLSC/RL	Production and operation management and logistics	Until 2012	74
[12]	RL	Distributed decision making	Until 2012	47
[13]	CLSC	Classified the papers into strategic, tactical and operational issues	Until 2013	98
[14]	CLSC	Process industry defined as the production of materials	Until 2014	167
[15]	CLSC/RL	Green-VRP	1959–2012	267
[16]	CLSC/RL	Green procurement in the private sector	1996–2013	86
[17]	CLSC/RL	Green supply chain management	Until 2014	–
[18]	CLSC/RL	Application of swarm intelligence in green logistics	1995–2014	115
[19]	CLSC	Value creation in a CLSC	1998–2014	144
[20]	CLSC/RL	Papers were classified into RL activities such as remanufacturing and recycling	Until 2014	382
[21]	RL	Modeling of reverse logistics inventory systems	Until 2016	–
[22]	CLSC	Develop decision support models for the management of returnable transport item	Until 2016	33
[23]	RL	Remanufacturing with the focus on acquisition management of returned products	2000–2014	90
[24]	CLSC	Quality, reliability, maintenance and warranty issues regarding second-hand products	1985–2015	104
[25]	CLSC	drivers, barriers, and practices towards circular economy	2000–2016	60
[26]	CLSC	Uncertainty factors, methods, and solutions of closed-loop supply chain	2004–2018	302
[27]	CLSC	Factors affecting CLSC models based on game theory	2004–2018	215
Our study	CLSC/RL	Progress on CLSC/RL with a focus on greenness index, uncertainty, carbon emissions, and return product quality and reliability	Until 2022	190

We did not find a review paper covering the issue of carbon emissions at the time of initial submission. As for greenness index, Peng, Shen et al. [26] combed through the CLSC literature, focusing on uncertainty factors, techniques, and solution methods. Here, 302 articles published between 2004 and 2018 were included in the study. They examined the origins of uncertainties across various SC stages and identified suitable techniques for quantifying the effects of these uncertainties on production processes. The greenness index is a tool for assessing an organization's performance on greenness aspects. Only in four review papers [15–17,19] is the concept of greenness explored. Lin et al. [15] reviewed the literature on GVRP that is classified into green-VRP, VRP in reverse logistics, and pollution routing problems. Traditional variants of VRP have been classified into different categories based on the type of problem addressed. Appolloni et al. [16] reviewed 86 papers on green procurement in the private sector published from 1996 to 2013. They categorized the research into drivers, barriers, and performance outcomes of green procurement, and developed a conceptual framework to guide future research. Wang [17] reviewed definitions and developments in GSCM, classifying the literature into topics like green design, procurement, manufacturing, reverse logistics, and recycling. Schenkel et al. [19] analyzed 144 papers from 1998 to 2014 on value creation in CLSCs, identifying four types of value (economic, environmental, information, customer) and six value-adding concepts (partnerships, product design, services, IT, processes, organization). These reviews structure the literature on green and CLSCs using conceptual frameworks spanning key focus areas, research themes, and value creation mechanisms. However, the reviewed papers did not mention greenness index.

This study can help scholars and practitioners identify the key variables (characteristics) in CLSC, particularly in the context of modern global trade, which involves uncertainties in CLSC, adherence to carbon emission regulations, the use of a greenness index to evaluate CLSC performance, and the assurance of quality and reliability in returned products. The study reveals the interrelationships between these factors/characteristics, helping to highlight research gaps. As described in Section 3, content analysis of the references enables a detailed comparison of the literature concerning the features in question. A categorization scheme is implemented, leading to subcategories for the main features (i.e., return product quality and reliability, greenness index, carbon emissions, and uncertainty).

3. Research Methodology

Content analysis, systematic reviews, and bibliographic reviews are popular research approaches for examining the literature, with each serving a unique purpose. When comparing them in terms of applicability, reliability, validity, and adaptability, it is important to assess how they work in various situations.

Content analysis (CA) is a method for systematically categorizing and quantifying qualitative data to identify patterns, themes, or trends. CA is applicable when the research involves large volumes of textual data, media content, or qualitative data. Its reliability depends on the coding scheme and the consistency of the coders. The choices of coding categories and the operationalization of variables are crucial. There is a risk of researcher bias in selecting coding categories or interpreting results [31].

Systematic reviews (SRs) are a method for synthesizing research findings by critically appraising and summarizing the results of all relevant studies on a specific research question. SRs are most applicable in fields where research questions require synthesizing evidence from multiple sources. Predefined protocols (e.g., PRISMA guidelines) help ensure consistent and unbiased data collection and analysis. The validity of systematic reviews depends on the rigor of the included studies, the comprehensiveness of the search strategy, and the critical appraisal of studies [32].

Bibliographic reviews (BRs) or narrative reviews involve synthesizing research findings by summarizing and discussing the literature on a particular topic without the formal rigor of a systematic review. BRs are often used for providing an overview of a broad research field or identifying gaps in the literature during exploratory research and theory development. BRs may lack the rigor and comprehensiveness of SRs as they do not typically follow strict protocols, which can result in inconsistent or selective data inclusion. The validity of BRs depends on the author's expertise and ability to critically appraise and synthesize the literature. There is a greater risk of bias, as the selection of studies may not be comprehensive or systematically justified [33].

In this research, the Qualitative Content Analysis (QCA) methodology suggested by Mayring [34] is used within a BR to reduce its bias. Mayring [34] suggests that content analysis and the description of research methodology should include four stages: material collection, descriptive analysis, category selection and material evaluation. This article answers the following main research questions:

Q1. What studies incorporate the main characteristics of CLSC (uncertainty, quality and reliability, carbon emission, or greenness index) in their modeling?

Q2. What are the methods and approaches in modeling the aforementioned characteristics?

Q3. What parameters of the models are assumed to be uncertain?

Q4. What are the modeled research gaps that would contribute the most the academic knowledge and judicious decision-making in the design and operations of CLSCs?

3.1. Material Collection

This literature review covers peer-reviewed articles published in English between 2003 and 2022, retrieved through comprehensive searches using Engineering Village (Compendex) and Google Scholar. Relevant papers were obtained from key publishers including IEEE, Elsevier, Springer, Taylor & Francis, and Emerald Group. The focus was on identifying pertinent journal articles, conference proceedings, and other literature from these databases and publishers to conduct a thorough review. The research procedure was performed in three stages, as follows:

Initially, the keywords "reverse logistics", "closed loop supply chain", "uncertainty", "quality and reliability", "carbon emission", "robust optimization (RO)", "stochastic programming", "performance measurement", "performance evaluation" and "green supply chain management" were searched for, and this resulted in 445 matches.

In the second stage (i.e., filtering stage), the abstracts and keywords of the resulting papers were examined and reviewed concerning the concept of CLSC and RL, resulting in a total of 190 papers.

Finally, the full text of the identified papers was scrutinized to determine which of them would be categorized as per the predefined categories (uncertainty, quality and reliability, carbon emission, or greenness index).

3.2. Descriptive Analysis

This study analyzes 190 scientific papers published between 2003 and 2022. An initial examination unveiled the prevailing research trends pertaining to CLSC and RL as depicted by Figure 2, which shows the yearly publication count. Here, 40 articles appeared between 2003 and 2010, while 150 (79%) papers were published from 2011 to 2022, which highlights the importance of this field in recent years. A spike is evident in 2015, with the publication of 25 articles, followed by a decline to 15 articles in 2016.

The distribution of journals where the selected references appear shows the growing interest in the CLSC and RL issues. Figure 3 shows the distribution of the reviewed references by journal of publication, with only venues having 3 or more papers included (13 journals overall). J Clean Prod (JCLPRO) has the largest number of research articles (approximately 26%), followed by Int J Prod Res (IJPR) (13%), Int J Prod Econ (IJPE) (13%), Comput Ind Eng (CAIE) (9%), Oper Res (8%), Sustainability (4%), and Eur J Oper Res (EJOR) (4%).

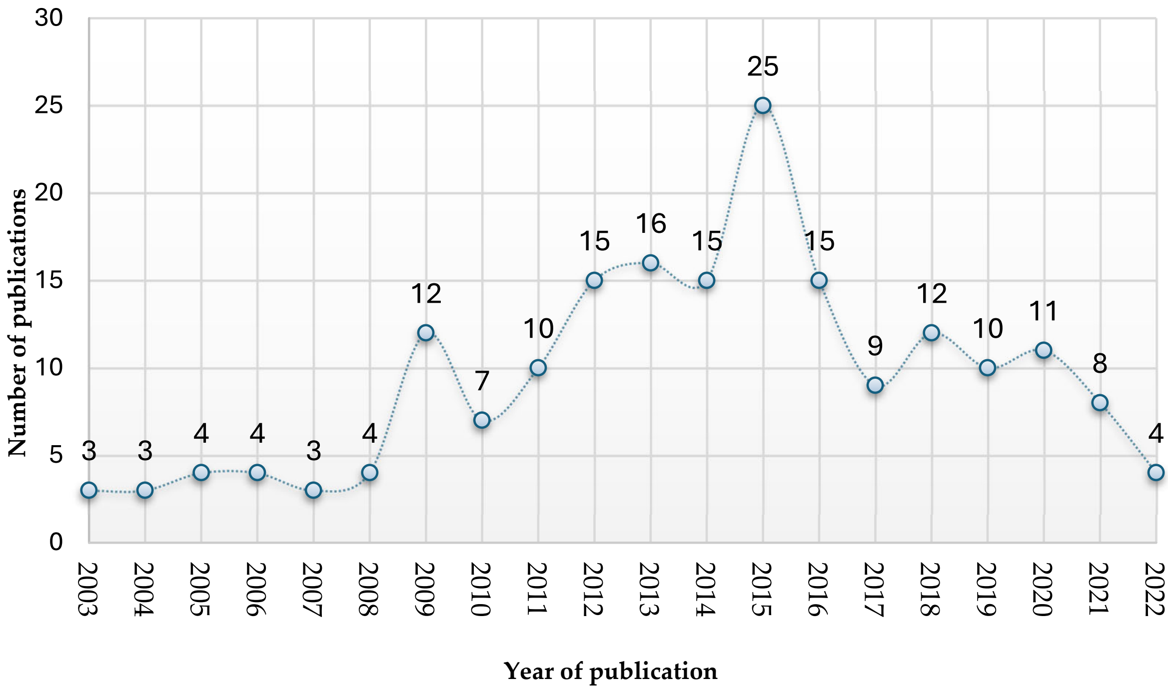

Figure 2. Distribution of publications per year across the period of the study (190 papers: 2003–2022).

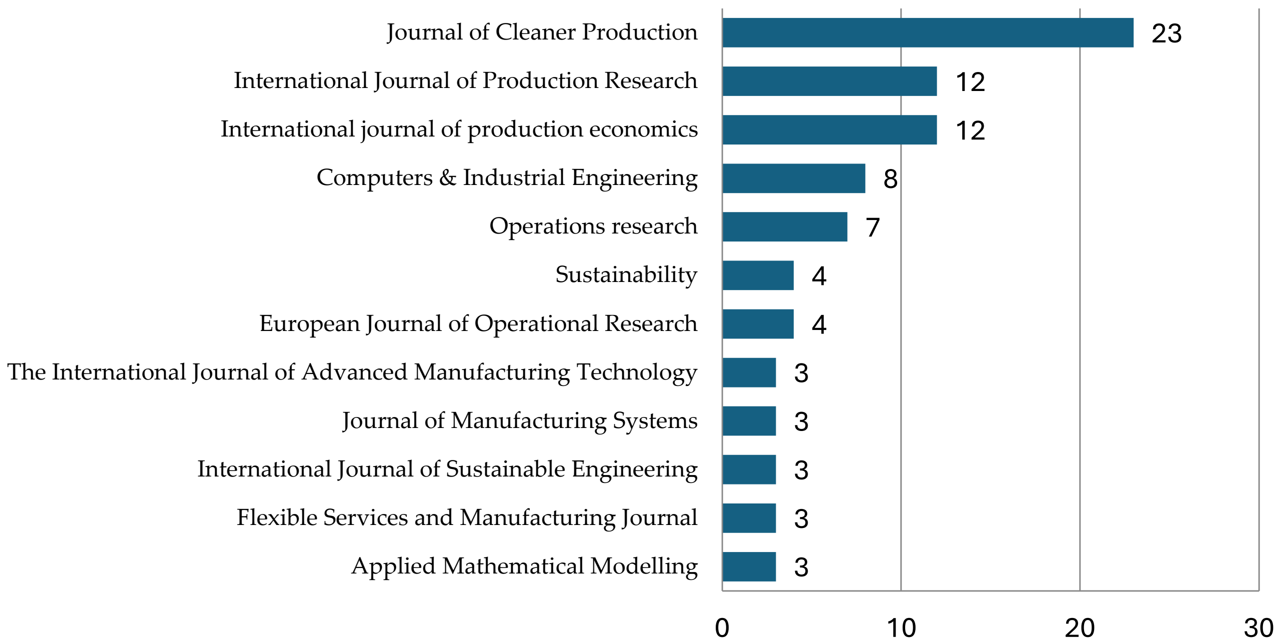

Figure 3. Distribution of publications based on different journals (190 papers: 2003–2022).

3.3. Category Selection

Figure 4 shows the categorization of the main formulation characteristics. The literature on uncertainty is categorized by the sources of uncertainty examined and industry applications. Papers addressing the quality and reliability of returned cores are grouped based on similarities in modeling features (e.g., periods, products, components) and quality attributes considered (e.g., price, grade). Articles on carbon emissions are classified by the type of carbon policy studied. Research papers dealing with greenness index are organized according to the methodologies employed in creating metrics for supply chain sustainability.

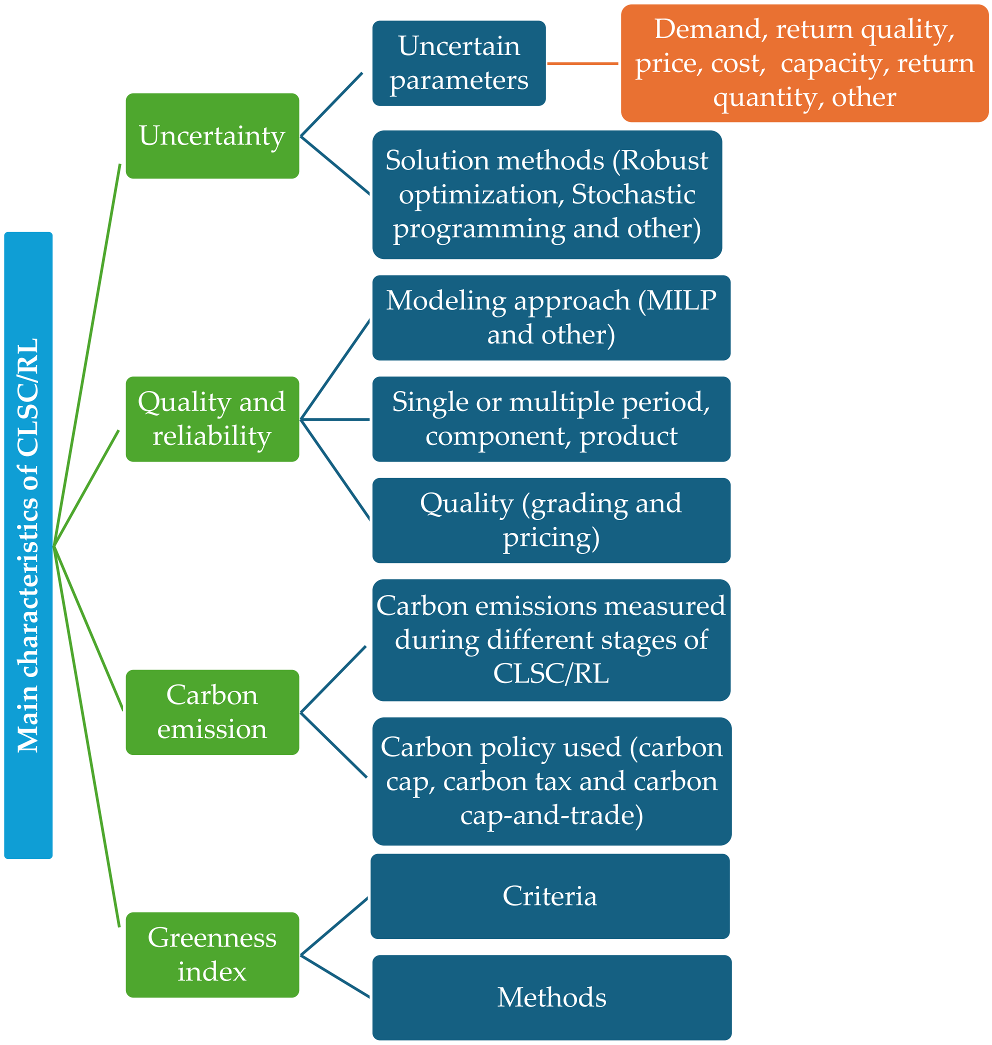

Figure 4. Categorization of the papers based on the main characteristics of CLSC/RL.

3.4. Material Evaluation

The literature surveyed was entered into a spreadsheet and cross-validated by the authors. The electronic versions of the papers were downloaded on a cloud service and hyperlinks were created to the original papers in the spreadsheet. The author downloading the paper made notes on which aspects of the categories in Figure 4 were relevant and why. The papers were cross-checked for Authority (were the papers peer-reviewed, how often were they cited, and the affiliations of the authors), Usefulness (how did the paper contribute to the themes of interest), and Reliability (quality of the journal, its impact factor, reputation in the field, etc.) As mentioned in Section 3.2, a total of 76 journal and 24 conference proceedings papers were searched. Most journal papers fell in higher quartiles. Conference papers were included because even though they often present early-stage results, they indicate what the most recent development in the field is. The conferences were checked for their reputation. Most of the papers were presented at IEEE conferences. A few papers were presented at other conferences but published by notable publishing houses such as Springer. There was one paper in the International Conference on Production Research, which is well known in the field. Through the material evaluation process, we were able to vouch for the sources of the materials gathered.

4. Analysis of the References

In the following, a summary of surveys is used to identify the main subjects of the RL/CLSC research. The selected references are grouped in the following four main classifications: uncertainty (Tables A1 and A2 in the Appendix A), return product quality and reliability (Table A3 in the Appendix A), carbon emissions (Tables A4 and A5 in the Appendix A), and greenness index (Tables A6–A8 in the Appendix A). In the following subsections, the characteristics of the Tables are explained in detail.

4.1. Surveys on Uncertainty

The observation by Pliny the Elder that "the only certainty is that nothing is certain" rings true for many organizations operating in unpredictable conditions today. In a CLSC and RL, uncertainties in procurement, end-of-life collection, (re)processing, market dynamics, and other SC stages have significantly contributed to the intricate nature of reverse logistics operations, leading to diminished process efficiency. A vast number of recent publications have focused on the uncertainty analysis of CLSC [26]. Papers dealing with uncertainty are grouped based on the uncertain factor under consideration (e.g., uncertainty in demand, cost uncertainty, uncertainty in return quality, price and capacity). Table A1 in the Appendix A provides a summary of the published articles incorporating uncertainty in different forms. This table also shows the main characteristics of the paper, including the method of modeling, the solution method applied in encountering the uncertainty (robust optimization (RO) and fuzzy method), settings and uncertain parameters. Table A2 in the Appendix A summarizes the publications based on the type of industry.

Regarding uncertainty in demand, while Khorshidvand et al. [35], Wang and Huang [36], Zhen, Huang et al. [37], and Prakash et al. [38] examined demand uncertainty in isolation, other studies have explored demand uncertainty in conjunction with additional sources of uncertainty. Khorshidvand et al. [35] proposed a new hybrid method, in which supply chain cooperation decisions and closed-loop supply chain network design (CLSCND) objectives are simultaneously involved. In the proposed approach, first, price, greenness, and advertisement decisions are made, and then maximizing the profit and minimizing CO_2 emission is considered. Prakash et al. [38] proposed a model for developing robust and dependable SC networks in the face of risks and uncertainty. Some papers combine demand uncertainty with other uncertainties. For example, demand uncertainty is combined with uncertainty in used product return ratio [39–49], uncertainties in the supply and collection of products [50], uncertainties in the demand of products and purchasing costs [51,52], product pricing [53], uncertainty caused by external disturbances [54], uncertainties in demand, transportation costs and return rate of products [55], variations in demand, transportation and processing costs [8], demand and quality uncertainty [56], uncertainties in returned goods, demand for recovered goods and transportation costs [57], uncertainties in variable costs and demand rate [58], and uncertainty surrounding the demand and supply of products [59]. Others, such as [41–44,46,47,50,54,55,57,60–65] and [49,59,66] have considered uncertainty in return quantity. Some publications have provided insights on return quantity uncertainty. Nikbakhsh et al. [62] used a robust bi-objective MILP model to optimize a third-party reverse logistics provider facing uncertain defective product returns. Piplani and Saraswat [63] minimize costs under uncertain return quantities, defective rates, warranty coverage, demand growth, and return supply using RO. Their model identified facility locations and traced product flows. It was determined that the supply of faulty modules played a pivotal role in influencing the network. Realff et al. [64] designed a reverse manufacturing network robust to all uncertainty scenarios using ideas from Kouvelis et al. [67]. Their model identified the optimal raw materials for recovery, determined recycling tasks, established facility locations and capacities, and chose transportation modes between facilities while maximizing profit. Zeballos et al. [66] proposed a two-stage stochastic optimization model accounting for uncertainty in return quality and quantity when planning closed-loop supply chain activities across time periods. Common sources of uncertainty include return volumes, defect rates, demand fluctuations, and return quality. RO and stochastic programming are utilized to hedge against uncertainty and identify strategies feasible across scenarios [68,69]. Optimal infrastructure design and product flows are determined under uncertainty to maximize profitability and cost-efficiency.

Another extensively addressed uncertainty is cost uncertainty. Various costs are considered uncertain in the literature. Vahdani and Mohammadi [70] tackle the challenges of overall costs uncertainty in a CLSC network (CLSCN) and product waiting times within the iron and steel industry. Xu and Zhu [71] modeled a CLSC with remanufacturing, where returned parts can be refurbished to substitute for new parts in manufacturing. The manufacturer handles the recovery and disposal of returns. The model incorporates uncertainty in three cost parameters: (1) disassembly costs for returned products, (2) refurbishing costs for disassembled parts, and (3) disposal costs for unrecoverable components. There are fewer models dealing with uncertainty in quality, price, and capacity for returned cores. Studies examining uncertainty in return quality include Hatefi and Jolai [54], Mukhopadhyay and Ma [56], and Zeballos et al. [66]. Realff et al. [64] addressed uncertainty in price, while Vahdani and Mohammadi [70] focused on uncertain capacity. Nahr et al. [72] incorporated uncertainty in quantity, quality, cost, and capacity using the approach of Torabi and Hasani [73].

Incorporating uncertainty in the modeling of CLSC for different industries is important. In the following, papers dealing with uncertainty are classified based on their application area or industry.

Automotive Industry: Small and large automotive industry case studies with varying demand levels are presented in Cui et al. [41]. Hatefi and Jolai [54] proposed a model to handle uncertain supply, demand, and disasters in the automotive industry. Mahmoudzadeh et al. [46] addressed production and pricing decisions for automotive (re)manufacturing facilities. Mukhopadhyay and Ma [56] derived scenarios based on uncertain remanufacturing yield rates and demand for car engine remanufacturing with sizable part inventories. Shahedi [74] developed a sustainable CLSC network model for a modular automotive product in Iran. Stochastic programming is used to handle the uncertainties in demand and the number of unusable end-of-life vehicles.

Iron and steel Industry: CLSC models for the iron and steel industry were investigated by Vahdani et al. [49,70,75]. The models included forward supply chain activities like ore suppliers, steel manufacturers, and metal product facilities. Reverse supply chain elements such as scrap collection and processing were also incorporated. Their case study exemplifies an integrated closed-loop network encompassing both forward and reverse flows, tailored to the metals industry.

Electronics Industry: A model for the recovery of post-sales consumer electronics such as cell phones and televisions was proposed by Nikbakhsh et al. [62]. Piplani and Saraswat [63] proposed a model for the repair and refurbishment network of electronic products with an application to computers. Substantial cost benefits are achieved by locating distribution centers near Original Equipment Manufacturers (OEMs) and repair/retailers. Talaei et al. [58] addressed copier remanufacturing. Ramezani et al. [47] formulated a CLSC model with four layers in the forward direction (suppliers, distributors, plants, and customer zones) and four layers in the reverse direction (repair, disposal centers, etc.). Their model finds applications in the automotive and electronics industries. These industries are also covered by [8]. The food and high-tech electronics manufacturing industries were the focus of [52]. Their models took time-dependent factors such as product cost and warehouse lifecycle into account.

Other industries: Altmann and Bogaschewsky [40] leveraged data from a leading mechanical and plant engineering firm to test their model. They found that SC design choices around facilities, logistics, suppliers, planning, and inventory can greatly benefit environmental performance. Dubey et al. [42] applied their model to an industrial air conditioner manufacturing company. Their work focused on critical aspects in the CLSCND literature, including addressing uncertainty, social considerations, environmental benefits, and methods for quantifying uncertainty. Hasani et al. [53] worked with a major medical device company expanding internationally to adapt to trade agreements and import/export policies under uncertain demand and costs. Stochastic models yielded more accurate profit estimates than deterministic approaches. Kara and Onut [44] optimized a reverse supply chain for a large paper recycling company to locate facilities and determine product flows. Realff et al. [64] addressed challenges for carpet recycling by building robust models to handle variations in carpet volume and price variability of a valuable raw material. RO performed well due to the significant costs associated with system changes, elevated uncertainties, and the scarcity of historical data. A Portuguese glass company was investigated by Zeballos et al. [66]. They classified returned products by quality (good, medium, or bad) before disposal or inclusion in the new product stream. Improving the quality of returns enhanced network performance and profitability by reducing reliance on raw materials. Prakash et al. [38] applied sustainable network design to an Indian e-commerce firm to mitigate risk. Shafieeroudbari et al. [76] proposed a model for an exhaustive multi-echelon CLSC network with three objectives, maximizing network profit, minimizing network emissions and maximizing job positions created by the network. The proposed model is applied to the garment industry in Montreal, Canada. Based on the important role of the mining industry in the economic growth of developing countries, Arabi and Gholamian [77] proposed a multi-period multi-product mixed-integer quadratic programming problem to optimize the design of a CLSC. Their study considers the specific condition of this industry, such as disruptions and quality of products. To demonstrate the efficiency and applicability of the proposed model, a real case study on stone quarries in Iran is analyzed and some useful managerial insights are presented. Abdolazimi et al. [78] developed a multi-objective mathematical model to design a construction supply chain to address challenges and enhance the viability and competitiveness of the construction sector. The proposed model is implemented in a real case study for validation. The tire industry is one of the applications of online-to-offline (O2O) commerce, which will help the decision-makers to operate online and offline businesses. Along with this new way of commerce in the tire industry, Fathollahi-Fard et al. [79] proposed a dual-channel, multi-product, multi-period, multi-echelon CLSCND under uncertainty for the tire industry to balance online and offline sales. Besides this, a fuzzy approach is applied to tackle the uncertain parameters of the problem. Fattahi et al. [80] developed a model for a supply chain system for power generation from biomass by using various technologies. The proposed model is implemented on a real case study in Iran to demonstrate the applicability of the model in evaluating the economic potential, the sustainability aspects, and the required infrastructure in planning the supply chain.

Summary of the Uncertainty Literature

The literature on closed-loop supply chain optimization under uncertainty has primarily focused on demand, return quantity, and cost parameters. As summarized in Table 2, most papers (76%) incorporate uncertain demand in their models. Return quantity uncertainty has also received substantial attention, and is featured in 53% of articles. Cost uncertainty is addressed in 32% of the papers. However, other parameters like return quality, pricing, and capacity have received relatively less focus, suggesting gaps for further research. While progress has been made in modeling key sources of uncertainty like demand and returns, additional work is needed to capture the full range of uncertainties faced in real-world closed-loop supply chains.

Studies addressing cost uncertainty in closed-loop supply chains have modeled uncertainties in total network costs, queue waiting times, transportation, demand rates, return rates, processing, pricing, purchasing, defective products, warranty coverage, carbon regulations, and disassembly/refurbishing/disposal costs. Cost uncertainties also encompass potential disruptions from natural disasters, accidents, or attacks.

The automotive, iron/steel, and electronics sectors have seen significant applications of uncertainty modeling. Other industries addressed include mechanical/plant engineering, air conditioners, medical devices, paper/carpet recycling, and glass manufacturing. Overall, cost uncertainty research covers a wide range of factors across manufacturing, remanufacturing, and recycling supply chains. Automotive and electronics are common application areas, but opportunities exist to expand modeling to more industries.

Table 2. Summary table, uncertainty in the modeling.

Citation	Methods				Robust Methods						Settings						Uncertain Parameters						
	Queuing	MILP	MINLP	Heuristics	Ben-Tal & Nemirovski	Soyster's	Bertsimas and Sim	Mulvey/Yu & Li	Other	Stochastic Methods	Single Period	Multi Period	Single Product	Multi Product	Capacitated	Uncapacitated	Demand	Return Quality	Price	Cost	Capacity	Return Quantity	Other
Total articles	2	20	3	2	7	1	7	4	11	7	17	14	14	16	25	5	26	5	2	11	2	18	6
% of total articles	6	59	9	6	21	3	21	12	32	21	50	41	41	47	74	15	76	15	6	32	6	53	18

Regarding the solution approach used to counter uncertainty, RO and fuzzy approaches are applied more than the others [81–85]. Most RO models in the literature are built on the foundational work by Soyster [86]; Mulvey et al. [84]; Yu and Li [87]; Ben-Tal et al. [81,88–90]; Bertsimas and Sim [82,91]. These models generate solutions that are feasible across all potential realizations of uncertain parameters. However, robust solutions come at a higher cost compared to deterministic ones. The robust optimization methods provide a way to handle uncertainty sets, but at the expense of higher-priced solutions than deterministic approaches that do not account for variability.

4.2. Surveys on Quality and Reliability

The decision-making process in remanufacturing is significantly influenced by the quality and dependability of the recovered items. After being upgraded or refreshed, these products should deliver satisfactory performance to consumers throughout their subsequent life cycles [24]. The capacity to forecast the quality and reliability of reclaimed products empowers decision-makers to adequately plan for facilities and allocate the necessary resources for reverse logistics operations. In this subsection, the articles considering product quality and reliability, quality (grading and pricing) and settings (number of periods/components/products) are classified. The quality pricing refers to the acquisition or selling price as a function of the quality of the cores, and quality grading considers different quality grades/bins/levels.

Behret and Korugan [92]; Dwicahyani et al. [93]; Teunter and Flapper [94]; Zou and Ye [95]; Masoudipour et al. [96,97] and Hassanpour et al. [98] developed one-period mono-component product models with quality grading and quality pricing considerations. Hassanpour et al. [98] is the only study that considered government regulations by developing a bi-level programming model. Radhi and Zhang [99] provided a multi-product extension. Their work is one of the few studies to address discounted pricing for remanufactured goods compared to new products. One-period mono-component and multi-component product models dealing with quality grading and quality pricing considerations can be found in Bhattacharya and Kaur [100]; Chen et al. [101]; Krikke [102]; Li [103]; Örsdemir et al. [104]; Jiang et al. [105] and Biçe [106]. Among these studies, Li [103] and Jiang et al. [105] studied the concept of reliability in CLSC. The use of multiple products is seen in Das and Chowdhury [107]; Giglio and Paolucci [108] and Ghayebloo et al. [109]. In Ghayebloo et al. [109], the concept of reliability is incorporated along with a greenness score, which accounts for part/material reliability and environmental friendliness. Denizel [110] and Nenes and Nikolaidis [111] considered multiple periods, single components and single products settings in their modeling. Nenes and Nikolaidis [111] develop a practical and quantitative tool to support the assessment of returned cores/products. Multiple periods, multiple components and multiple products considerations are incorporated in Jayaraman [112]; Ramezani et al. [113], Sheriff et al. [114]; Yamzon et al. [115] and Jeihoonian et al. [116]. The work by Ramezani et al. [113] stands out for its multi-objective approach combining profit maximization, customer service level improvements, and quality enhancements. Specifically, their model concurrently optimizes total supply chain profit, minimizes product delivery times in forward and reverse logistics, and reduces defective part procurement to maximize six-sigma quality levels. Sheriff et al. [114] provides an early look at incorporating clustering into reverse logistics optimization. Their model uniquely addresses location, allocation, and routing decisions simultaneously, while grouping facilities into clusters. Table A3 in the Appendix A provides a summary of the mentioned articles within their setting.

Additional articles consider other modeling methods, quality considerations and settings [117]. Guide et al. [118]; Huang et al. [119]; Jin et al. [60]; Li et al. [120]; Östlin et al. [121]; Robotis et al. [122] and Samuel et al. [123]. Among these studies, the study of Li et al. [120] is the one that developed the concept of product effectiveness based on reliability and the time utility value of a product. Also, Masoudipour et al. [97] considered location and routing decisions simultaneously. Since low return quality decreases a CLSC's usable core count, Samuel et al. [124] considered presorting centers in the CLSC network. Presorting facilities have the potential to segregate lower-quality items at the onset of the reverse logistics cycle, thereby reducing transportation expenses and emissions. Table A3 in the Appendix A provides a summary of the articles in detail, including the characteristics of method, quality, settings, the problem solved and the industry example.

Summary of the Literature Considering Reliability and Quality Issues

Studies on CLSC optimization have explored diverse decision problems, including modular product design, determining production quantities for new and remanufactured items, procuring new parts, salvaging old components from returns, managing inventory levels, routing logistics, locating and allocating facilities, modeling entity relationships, maximizing quality levels, product recovery design, production planning, control in remanufacturing, and competition between original equipment manufacturers and independent remanufacturers. The breadth of research spans key strategic, tactical, and operational decisions facing CLSCs, from procurement and production to quality management and network design.

As summarized in Tables 3 and 4, the existing literature has strongly focused on modeling quality grading and pricing in closed-loop supply chains, while the concept of return product reliability has received limited attention. Strategies like leasing, trade-in credits, and other manufacturer incentives aim to secure higher-quality returns. Mixed integer linear programming, scenario analysis, genetic algorithms, stochastic programming, and heuristics represent dominant modeling techniques. Application contexts include remanufacturing construction equipment, electronics, glass, automotive parts, household items, printer cartridges, plastics, tires, cell phones, mailing systems, and electric vehicle batteries, among others.

Table 3. Final grouping of papers dealing with reliability and quality.

	Method		Quality		Settings					
	MILP	**Other**	**Grading**	**Pricing**	**Single Period**	**Multi Period**	**Single Component**	**Multi-Component**	**Single Product**	**Multiple Product**
Nb. of articles	7	28	31	27	21	8	8	15	18	11
%of articles	21	85	94	82	64	24	24	45	55	33

Table 4. Papers with reliability modeling.

Article	Reliability	
	Assessment Method	**Failure Modeling**
[103]	Reliability function of new, repaired	Components fail independently and failure rate is used
[120]	Reliability function of new, repaired	Failure rate is used
[105]	Failure rate of remanufacturing operations represents reliability	
[109]	Two reliability levels have been defined	
[123]		Failure rate of parts is used

However, opportunities remain to advance multi-period, multi-product models and to develop enhanced ways to predict return reliability. Expanding optimization frameworks across planning horizons and product portfolios could help to better represent real-world complexity.

4.3. Literature on Carbon Emissions

The following studies incorporate carbon emission constraints into CLSC models using common policy approaches. The literature is categorized based on three primary carbon regulation policies—carbon caps, carbon taxes, and carbon cap-and-trade systems. Under a carbon cap, firms face a hard limit on their total allowable emissions. With a carbon tax, firms are charged based on their carbon output. Cap-and-trade combines an emission cap with a trading system where firms that stay under the cap can sell unused allowances, while those exceeding it must purchase extra allowances [125]. Zhang et al. [126] conducted a review examining the repercussions of carbon policies on supply chains.

Regarding articles implementing the carbon cap policy, Darbari et al. [127]; Kafa et al. [128]; Poursoltan et al. [129] and Xu et al. [130,131] consider the carbon cap. Poursoltan et al. [129] proposed a green CLSC framework for ventilators during the COVID-19 pandemic. Carbon cap is combined with other emission schemes in additional studies, as follows: a combination of carbon cap and carbon cap-and-trade [124,132,133]; a combination of carbon cap, carbon tax and carbon cap-and-trade [125,131,134]; a combination of carbon cap and carbon tax [135,136]. Kannegiesser and Günther [137,138], Alinezhad et al. [39], Saxena et al. [139], Dou and Cao [140], and Tong et al. [141] considered carbon tax emission policy. Incorporating the carbon cap-and-trade policy in the modeling was done by Abdallah et al. [142]; Chaabane et al. [143]; Fahimnia et al. [144]; Zhou et al. [145] and Kazancoglu et al. [146]. Table A4 in Appendix A summarizes the articles considering different carbon policies in their formulations.

Some articles have considered emissions at all stages of the CLSC [37,146–157]. All these studies consider carbon emissions in the objective function of the proposed model. Among these studies, Setiawan et al. [155] is notable for its study of the corona virus pandemic by designing a CLSC network for different types of masks. Table A5 in Appendix A classifies the reviewed references based on the stages of CLSC where carbon emissions are measured, and according to the application area.

4.3.1. Governmental Policies on Carbon Emissions

Governmental policy affects carbon emissions at a macro level. While most of this paper deals with sustainability issues in the supply chain at a more micro level, governmental policies do impact how these supply chains are designed and operated. The same can be said about the reverse. A fundamental approach to understanding the economic development of a nation and its environmental state is the Kuznets curve [158]. The idea is that initially, the degradation of the environment increases as income rises. China is a good example of this principle. However, once a threshold in income is reached, the degradation begins to subside (as seen with stricter controls in China on carbon emissions).

According to Qin et al. [159], significant reductions in carbon emissions in the G7 can be attributed to environmental policy, green innovation, and renewable energy research and development. The authors found bidirectional causality between carbon emissions and environmental policy, composite risk index, and green innovation. However, they observed unidirectional causality between GDP and renewable energy research and development in relation to carbon emissions.

Zhou et al. [160] found evidence that carbon emissions trading could be a fruitful long-term strategy to ensure green and sustainable development in the Chinese manufacturing industry. This viewpoint seems to be supported by many studies, including that of Chen et al. [161], who used a model-based approach to conclude that while both carbon tax and the cap-and-trade system stimulate green innovation, cap-and-trade is more effective on climate change.

Earlier, in this section, we presented three policy mechanisms: carbon cap, carbon taxes, and carbon cap-and-trade systems. When an entire supply chain is considered, carbon cap impacts each player in the supply chain through a constraint mechanism (which can be seen as the least flexible of options), carbon tax works through pricing (at each level in the supply chain), while cap-and-trade gives the supply chain and industry more flexibility in reducing emissions.

4.3.2. Summary of CLSC Articles Considering Carbon Emissions

Research in this field has concentrated on curbing emissions at every phase of the CLSC, spanning from suppliers and manufacturers to recyclers and transportation. The overarching goals have been two-fold: maximizing profits, while minimizing carbon emissions or reducing the number of distribution vehicles, or CLSC costs, and the time required to attain sustainability. Various topics explored include carbon pricing/trading, consumer behavior regarding carbon emissions, taxes, and government subsidies.

Furthermore, since the implications of these policies for supply chain management are substantial, Liu and Hu [162] studied the interaction between supply chain cooperation and the carbon tax problem in a two-echelon supply chain under consumer's preference behavior. They also investigated the impacts of consumers' preferences and the carbon tax on supply chain coordination, which yields a decision-support tool for pricing and green product design in the real world.

Numerous illustrations and case studies from a diverse array of industries, such as solar energy, semiconductor manufacturing, electrical appliance production, the retail sector, refrigeration, personal computer manufacturing, welding, and printer production, are detailed in this research.

As summarized in Table 5, scholars have extensively examined emissions stemming from the manufacturing of final or recyclable products, as well as those occurring during transportation, remanufacturing, recycling, and product recovery. Please note that the sum of percentages exceeds 100% as some references use more than one criterion. For future research endeavors, attention could focus on emissions related to product storage/handling, emissions throughout sales and product usage, carbon pricing dependent on energy source used, and emissions arising from disposal activities. Given that these categories have received comparatively less attention (about 34% of references did not incorporate carbon emission policies), it is worthwhile to incorporate new policies and regulations introduced by governments globally aimed at curbing carbon emissions.

Table 5. Carbon emission-based papers summary.

	Carbon Emissions Measured During									Carbon Policy Used		
	Extraction of Raw Material, Sourcing	**Manufacturing of Product**	**Storage and Handling**	**Retailing and Usage**	**Energy/Power Consumption**	**Recovery/Remanufacturing**	**EOL/Disposing**	**Logistics (Forward/Reverse)**	**Total Emissions**	**Carbon Cap**	**Carbon Tax**	**Carbon Cap and Trade and Other**
Nb. of articles	6	24	6	5	4	17	5	21	8	14	13	12
% of total articles	16	63	16	13	11	45	13	55	21	37	34	32

4.4. Surveys on Greenness Index

To construct a greenness index, first the criteria and then the method should be defined. Within the literature, various authors have put forth a range of criteria for assessing supply chains, and multiple methods have been suggested to construct a greenness index. These papers are categorized based on the approach employed to establish the index system. The subsequent subsections delve into these primary topics, providing detailed explanations.

4.4.1. The Applied Criteria in the Literature

This subsection summarizes the diverse evaluation criteria proposed across studies for assessing and rating supply chain sustainability as depicted in Table A6 in the Appendix A. As we examine the data in Table 6, it becomes evident that SCs have been evaluated at each pivotal stage, starting from the design phase and extending to the end-of-life (EOL) of products. Please note that the sum of percentages exceeds 100% as some references use more than one criterion. Notably, processes such as recycling and remanufacturing, as well as the societal consequences linked to manufacturing organizations, have received particular attention. While most authors have incorporated environmental and economic factors into their assessments, only a small minority have included elements such as strategy development, inter-entity relationships, and political and regulatory considerations in their index systems. Obtaining a global view of greenness implementation in organizations, multiple factors and their assessments should be comprehensively incorporated to lead to the promotion of greenness drivers [163,164]. Khan et al. [165] developed a comprehensive and empirically validated scale based on interviews and survey results in the UAE service industry. The results of their study indicate that greenness in a service supply chain has six underlying dimensions: "managing operations", "reducing resource requirements", "building eco-friendly infrastructures", "green computing", "avoiding risks and uncertainties", and "monitoring utilities".

Table 6. Summary of criteria used for assessing SCs.

	Criteria														
	Design & Planning	**Manufacturing**	**Purchasing and Warehousing**	**Business Process and Operational Flexibility**	**Logistics**	**Returns**	**Recovery/Remanufacturing**	**Waste Disposal**	**Environmental Impact & Pollution**	**Economical (Cost and Profit)**	**Social Attributes & Customer Satisfaction**	**Information Value & Sharing**	**Innovation/Technology/Certifications**	**Strategy Formulation & Nodes Relationship**	**Political & Regulatory Attributes**
Nb. of articles	15	14	13	17	10	9	23	13	31	27	25	10	14	7	3
% of all articles	43	40	37	49	29	26	66	37	89	77	71	29	40	20	9

4.4.2. Methods to Construct the Greenness Index

In this subsection, a variety of methods used by different authors to develop a greenness index for supply chains are extracted from the review papers. The methods are grouped in two parts: fuzzy methods and other methods. Tables A7 and A8 in the Appendix A show the fuzzy methods and other methods (e.g., Delphi method, analytical hierarchy process, Grey relational analysis, balanced score card) used to develop the greenness index.

In reviewing the articles regarding the applied method for greenness index, we see that nearly half of them combine the fuzzy concept with another method (see Table A7 in the Appendix A). The combination of fuzzy and other approaches such as TOPSIS in Rostamzadeh et al., [166]; DEMATEL and TOPSIS in Uygun and Dede [167]; a data-driven approach in Tseng et al. [48]; a group decision-making model in Deng et al. [168] and DEMATEL in Nozari et al. [169] are proposed. Nozari et al. [169] applied their model in the fast customer moving consumer goods (FMCG) domain.

Cao et al. [170]; Jun [171]; Liang et al. [172]; Liu and Wang [173] and Yang et al. [174] have used AHP with fuzzy concepts. The studies that have developed the index system using AHP and techniques apart from fuzzy logic are Chen et al. [175]; Nie [176]; Sellitto et al. [177] and Sellitto et al. [178]. The Delphi method was used in the development of the greenness index system [171,176,179–181]. Cao et al. [170]; Wenhai et al. [182] and Chen et al. [175] used Grey relational analysis. Sellitto et al. [177]; Genchev et al. [183] and Hervani et al. [184] used the qualitative research methodology. The balanced scorecard approach aims to create equilibrium across multiple indicators, including short- versus long-term goals, financial versus non-financial objectives, leading versus lagging indicators, and stock versus flow metrics. Studies employing balanced scorecards for greenness index development include Yao and Zhang [185]; Tseng et al. [179] and Yang et al. [174]. The Analytic Network Process (ANP) is a multi-criteria decision-making technique that can model interdependence among factors. ANP has been applied for green supply chain analysis by Sarkis [186] and Tseng et al. [179]. However, limitations of ANP include large data requirements and difficult sensitivity analyses. While ANP can capture interrelationships, the extensive data inputs and computational intensity can restrict its practical application.

Some studies have taken unique approaches to developing greenness indices, diverging from the common methods. These include Liberatore scoring by Gopal and Thakkar [187], the Decision-Making Trial and Evaluation Laboratory method by Lin [188], Information Entropy [175], and Likert Scaling by Sellitto et al. [178]. Other alternative techniques include Membership Conversion Algorithms [189], Meta-Analysis [190] and Data Envelopment Analysis [191]. While less prevalent, these innovative methods contribute additional modeling perspectives for building comprehensive greenness indices to evaluate supply chain sustainability. More research is needed on applying and comparing alternative modeling approaches as this area matures. Wilson [192] developed a decision support system towards supply chain performance assessment. The development of the relationship between total and partial performance in mathematical formulation is the novelty of this study. Izadikhah [193] used a chance constraint-based data envelopment analysis to measure the performance of sustainable supply chains under uncertainty.

4.4.3. Governmental Policy Implications on Greenness Index

The greenness index is much broader than carbon emissions. Since environmental degradation affects land, air, and water, the measure of greenness should ideally encapsulate any form of pollution, not just relating to carbon and air. Not surprisingly, governmental policy does have an impact on the promotion of greenness in the supply chain. This is a vast area of research, and space limitations prohibit us from getting into the whole body of literature. Naruetharadhol et al. [194] looked at public policy and what they termed eco-innovation, which is closer to our interpretation of greenness. The viewpoint taken here is that eco-innovation must happen with several levels of the supply chain. However, the government has several policy tools at its disposal, such as research and development investments, regulation, incentives, and infrastructure development. The authors explore the impacts of these tools on promoting sustainability in small and medium enterprises.

Yikun et al. [195] investigated "green growth" in G7 economies through the sustainable development goals (SDGs) lens. They looked at 2000–2019 data with yearly observations for advanced panel estimations and used a cross-sectional autoregressive distributed lag

(CS-ARDL) model to shown that technological innovations and green growth encourage environmental sustainability. Since the question that arises is how technological innovation and green growth occur, they show that governments have a significant role in promoting SDGs

Sun et al. [196] empirically examined the impact on green innovation of government subsidies, research and development investment and public participatory environmental regulation in manufacturing enterprises, based on a study of 1308 manufacturing firms in the Chinese A-share list from 2010–2019. They concluded that that government subsidies can significantly promote green innovation, especially in private enterprises. According to the authors, research and development investment has a mediating role in green innovation, while public participatory environmental regulation has a negative impact.

In conclusion, through these and numerous studies not cited here, it appears that government policy has a significant role to play in green innovation and sustainability.

4.4.4. Summary of Literature on Greenness Index

Greenness index models primarily assess economic, social, and environmental dimensions of SCs. Index development techniques include fuzzy methods, AHP, Delphi, Grey relational analysis, balanced scorecard, ANP, and qualitative approaches.

Evaluation combines subjective qualitative factors with objective quantitative parameters. Fuzzy AHP is a key methodology used to address subjectivity in assessments. Other techniques include membership conversion algorithms, AHP with information entropy or uniform distribution, Liberatore scoring, and signal-to-noise ratios. Case studies come from sectors like automotive, air conditioning, construction, food, footwear, metals, and appliances.

As summarized in Table 7, fuzzy methods are predominant, followed by AHP and other methods. Specific fuzzy techniques include fuzzy AHP, fuzzy comprehensive evaluation, and fuzzy multi-attribute decision-making. While fuzzy set theory has seen significant application, opportunities exist to refine current techniques and explore new approaches as greenness index research evolves. Please note that the sum of percentages exceeds 100% as some references use more than one method.

Table 7. Summary of methods used to assess greenness index.

	Fuzzy Methods	Analytic Hierarchy Process (AHP)	Delphi Method	Grey Relational Analysis	Qualitative Research Methodology	Balanced Score Card	Analytical Network Process	Other
# of articles	28	11	5	3	3	4	3	15
% of all articles	68	27	12	7	7	10	7	37

5. Future Research Directions

The preceding literature review highlights several potential avenues for future research, as listed hereafter.

For the uncertainty aspects of CLSC using stochastic and robust programming, further examination of uncertainty in the areas of return quality, pricing, and facility capacity is badly needed. It is recommended to expand modeling approaches beyond mixed integer linear programming, which dominates the current literature, to encompass other methods such as queuing, MINLP, simulation optimization, and heuristics so as to better handle the stochastic processes underlying the uncertain factors. Shifting from predominantly single or bi-objective functions (profit maximization, cost minimization) to multi-objective formulations with diverse foci should be prioritized to yield practical solutions. Industry applications must go beyond automotive, iron/steel, and electronics, which are well represented in the extant literature.

A significant amount of research exists on return quality and grading, but reliability of returns is an understudied area. Examining return reliability could better inform remanufacturing and recycling decisions. Most models involve single components and products over limited time periods. Developing multi-component, multi-product, multi-period models would enhance real-world applicability. Although such models would be more complex and difficult to solve, the use of decomposition techniques could still yield high-quality solutions to better inform design and operational decisions.

For carbon emission-based aspects, future research could explore carbon emissions from additional supply chain stages, including raw material sourcing, warehousing and logistics, retailing, consumption, energy sources, and disposal. Studies could also incorporate new and evolving carbon emission policies being implemented globally. Currently, emissions from manufacturing, transportation, remanufacturing, and recycling are well-studied, but other sources and emerging regulations have received limited focus. Broadening the scope of emissions modeling and covered policies would provide a more complete and up-to-date understanding of carbon footprints and tradeoffs in sustainable CLSC design.

For greenness index-based studies, fuzzy methods are predominantly used to develop greenness indices, but it would be innovative to explore alternative techniques like preference function modeling [197]. In future studies involving greenness indices, there could be an amplified emphasis on enhancing information sharing and understanding the dynamics of relationships among various entities within the supply chain. Given the pivotal role of political and regulatory policies in shaping supply chain design, it would be advantageous for researchers to prioritize this criterion when developing greenness indices. Recent advances in multi criteria decision-making (MCDM) should be leveraged and combined with insights from supply chain resilience to develop novel greenness indices that can help stakeholders perform the internal and external auditing or assessment of their CLSCs.

Another interesting and promising research avenue would be the combination of several of the features investigated above. For example, the integration of the quality and reliability of returned cores within the context of uncertain remanufacturing costs or uncertain demand for remanufactured products would help decision-makers in their selection of remanufacturing options. A distributionally robust chance-constrained optimization framework can be used to formulate and solve such a problem. The combination of carbon emission policies along with the design of remanufacturing facilities is another interesting research question. Regulations around carbon emissions are constantly changing due to unstable political commitments. How can a firm commit to a specific design of its CLSC if emission reduction targets and carbon pricing are uncertain? Strategic and tactical design decisions as well as operational (re)manufacturing decisions must be robustified in such a context.

One final area of investigation is the use of artificial intelligence (e.g., machine learning, deep learning) to develop data-driven models for the various stages of the CLSC. AI and learning techniques can be leveraged to assess the quality and reliability of cores before they are returned, and/or predict the quantity of returns. This would allow for proactively planning the logistics of collection and remanufacturing decisions. Research must be conducted to assess how AI can be used for predictive remanufacturing in agile CLSCs.

6. Conclusions

This article has presented a literature review focused on four key aspects in the context of closed-loop supply chains (CLSC) and reverse logistics (RL)—return product quality and reliability, uncertainty, greenness indices, and carbon emissions. The reviewed articles have been categorized based on their contributions to addressing uncertainty, industry applications, compliance with emission policies, and similarities in settings and methodologies. Finally, the outcomes were synthesized, and the primary research gaps were highlighted, pointing toward potential avenues for future investigation. These findings reveal that research efforts must be directed towards the development of multi-criteria greenness indices, multi-objective robust optimization models for uncertain quality and reliability of returns, and the development of data-driven remanufacturing frameworks and models for agile CLSCs.

Author Contributions: All authors S.G., U.V., C.D., C.N.S. and M.S.P. contributed to the study conception and design. The focus areas of the literature review were developed by authors C.D., U.V. and M.S.P. Material preparation, data collection and analysis were performed by authors S.G., C.N.S. and C.D. The manuscript was written by authors S.G., U.V., C.D. and C.N.S. and revised based on comments from author M.S.P. All authors have read and agreed to the published version of the manuscript.

Funding: Authors C.D. and U.V. would like to acknowledge the funding made possible by NSERC Canada through its Discovery grants program.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix A

Table A1. Summary of papers incorporating uncertainty in modeling. (*) marks coverage of topic by article.

	Methods				Robust Methods						Settings						Uncertain Parameters						
Citation	Queuing	MILP	MINLP	Heuristics	Ben-Tal & Nemirovski	Soyster	Bertsimas & Sim	Mulvey/Yu & Li	Other	Stochastic Methods	Single Period	Multi Period	Single Product	Multi Product	Capacitated	Uncapacitated	Demand	Return Quality	Price	Cost	Capacity	Return Quantity	Other
[64]		*							*			*	*		*					*		*	Collection volume and price of recycled material
[56]										*	*		*		*		*	*					
[71]									*			*		*	*					*			
[44]								*		*	*		*		*		*					*	
[57]		*			*						*		*		*		*			*		*	
[63]		*							*	*	*			*	*							*	% of faulty products, warranty fraction
[66]		*								*		*		*	*			*				*	
[75]	*	*			*				*		*			*	*	*							Environmental and system uncertainty
[52]					*							*		*	*		*			*			
[62]		*					*					*		*	*							*	
[49]		*									*			*	*		*			*		*	
[47]		*							*		*			*	*		*					*	
[46]							*				*	*		*			*			*		*	
[36]									*			*		*	*		*						
[50]		*						*				*	*		*		*					*	

Table A1. *Cont.*

Citation	Methods				Robust Methods					Stochastic Methods	Settings						Uncertain Parameters						
	Queuing	MILP	MINLP	Heuristics	Ben-Tal & Nemirovski	Soyster	Bertsimas & Sim	Mulvey/Yu & Li	Other		Single Period	Multi Period	Single Product	Multi Product	Capacitated	Uncapacitated	Demand	Return Quality	Price	Cost	Capacity	Return Quantity	Other
[54]			*					*	*		*		*		*		*	*				*	
[43]					*					*		*	*		*		*					*	Carbon emissions
[40]								*				*	*		*		*						Return ratio
[70]	*			*					*	*	*			*	*	*				*	*		
[59]		*								*	*			*			*					*	
[53]			*	*				*				*		*	*		*			*			
[42]		*			*	*	*					*		*	*		*					*	
[58]		*							*		*			*	*		*			*			
[65]									*		*		*		*		*			*		*	Facility availability, average disposal fraction
[8]		*			*						*			*	*		*			*			
[55]		*					*			*	*		*		*		*					*	
[41]				*							*		*		*		*					*	
[45]		*					*				*		*			*	*						Uncertainty of recycled products
[38]		*			*						*		*			*	*						Considered risk and uncertainty simultaneously
[72]			*						*			*		*	*		*	*		*	*	*	
[35]		*						*				*		*			*						
[51]		*							*		*			*	*		*	*	*				
[74]		*							*	*		*	*			*	*					*	
[37]		*								*	*			*	*		*						

Table A2. Summary of papers incorporating uncertainty in different industries.

Citation	Industry	Problems	Single/Multi-Objective Approaches
[75]	Iron and steel	Designing a CLSC network under uncertainty	Bi-obj.—min total costs and backup transportation costs
[50]		Sustainable capacitated facility location problem for two-way product flows	Min cost
[49]	Iron and steel	Designing a CLSC network under uncertainty	Multi obj.—min total costs, min expected failure costs
[46]	Automotive	Dynamic production/pricing problem	Max profit
[36]		Demand-driven disassembly planning problem in CLSC	Recycling volume, timing and recovery strategy
[53]	Medical devices	Designing a robust closed-loop global supply chain network	One objective—max profit
[70]	Iron and steel	CLSCND under uncertainty	Multi-objective—Min total costs and waiting time
[65]		CLSCND with partial and complete facility disruptions	Single objective—min total costs (facilities + disruptions)
[58]	Copiers	Carbon efficient CLSCND under uncertainty	Multi-objective—Min total costs and CO_2 emissions
[55]	Computer/laptop manufacturers designing a CLSC network under uncertainty	Single objective—max profit	One objective—max profit
[8]	Electronics, digital manufacturing, automobile, food industry and others	Supply chain configuration and supplier selection	One obj.—min total costs
[41]	Automotive	CLSCND under uncertainty	One obj.—min cost
[38]	e-commerce	CLSCND under risk and uncertainty	One obj.—min cost
[74]	Automotive	Sustainable CLSCND	Multi-obj.—max profit, min emissions and max employment

Table A3. Reliability and quality papers summary. (*) marks coverage of topic by article.

Citation	Method		Quality		Settings						Problem Solved	Industry Examples
	MILP	**Other**	**Grading**	**Pricing**	**Single Period**	**Multi-Period**	**Single Component**	**Multi-Component**	**Single Product**	**Multi-Product**		
[118]		Case study approach									Contingency planning in CLSC	Kodak, Xerox and US navy depots
[117]		Linear programming	*			*			*		Production planning for remanufacturing	Mailing equipment
[112]		Linear programming	*	*		*		*		*	Production planning and inventory control	Cell phone
[121]		Qualitative approach	*	*							The advantages and disadvantages of 7 closed-loop relationships for collecting cores for remanufacturing	Automotive, toner cartridges
[92]		Multi stage inventory control model	*	*	*		*		*		Modeling and analysis of a hybrid manufacturing–remanufacturing system	
[110]		Stochastic programming	*	*		*	*		*		Remanufacturing production planning under conditions of returned product quality uncertainty	Mailing equipment
[102]			*	*	*			*	*		Decision framework for optimizing CLSCs, includes location-transportation and disposition decisions	Copiers
[94]		Simple closed form expression and newsboy-type solutions									Acquisition and remanufacturing decisions under quality uncertainty	Mobile phone
[122]		Two-period model framework	*	*	*		*		*		Study the effects of used product quality uncertainty on investment decisions related to product reusability and used goods collection efforts	Cell phones
[111]			*	*		*					Optimization of decisions related to procurement, remanufacturing, salvaging and stocking	Cell phones
[107]		Mixed integer programming	*	*		*	*		*		Reverse logistics planning with modular product design	
[103]		Quantitative method for evaluating economic, product quality and ecological parameters	*	*	*			*		*	Evaluating the production system in CLSC	Soy milk machines manufacturing company
[60]		Markov decision process	*	*	*			*	*		Policy-making considering modular product reassembly in remanufacturing	Batteries of electric vehicles

Table A4. Carbon emission based papers summary (carbon policy). (*) marks coverage of topic by article.

Citation	Carbon Emissions Measured During									Carbon Policy Used			Industry
	Manufact. of Raw Material/Sourcing	Manufact. of Final/Recyclable Product	Product Storage and Handling	Sales and Product Usage	Energy Mix Used/Power Consumption	Remanufacturing/Recycling/Recovery	EOL/Disposing Product/Land Filling	Transportation (Forward/Reverse)	Total Emissions for the CLSC	Carbon cap	Carbon Tax	Carbon Cap and Trade, and Other Policies	
[145]									*		*		
[142]											*		
[143]		*			*		*				*		Aluminum production
[132]		*	*		*			*	*	*		*	
[135]									*	*	*		Notebook computer manufacturing
[144]		*			*		*				*		Company providing fibrous material used in car seats carriers, sofas, dining chairs filling material, and seat covers
[137]		*		*	*			*			*		Automotive
[138]		*		*	*			*			*		Automotive
[128]	*								*	*			Washing machine manufacturer
[136]		*				*				*		*	
[133]		*								*		*	
[125]	*	*	*			*		*		*	*	*	
[127]								*		*			Printers
[129]		*	*			*		*		*			Ventilator logistics network

Table A4. *Cont.*

Citation	Carbon Emissions Measured During									Carbon Policy Used			Industry
	Manufact. of Raw Material/Sourcing	Manufact. of Final/Recyclable Product	Product Storage and Handling	Sales and Product Usage	Energy Mix Used/Power Consumption	Remanufacturing/Recycling/Recovery	EOL/Disposing Product/Land Filling	Transportation (Forward/Reverse)	Total Emissions for the CLSC	Carbon cap	Carbon Tax	Carbon Cap and Trade, and Other Policies	
[146]									*			*	Home appliances industry
[39]								*			*		Dairy
[124]						*		*		*		*	
[139]	*							*			*		

Table A5. Carbon emission-based papers summary (absence of carbon policy). (*) marks coverage of topic by article.

Citation	Carbon Emissions Measured During									
	Manufact. of Raw Material/Sourcing	**Manufact. of Final/Recyclable Product**	**Product Storage and Handling**	**Sales and Product Usage**	**Energy Mix Used/Power Consumption**	**Remanufacturing/Recycling/Recovery**	**EOL/Disposing Product/Landfilling**	**Transportation (Forward/Reverse)**	**Total Emissions for the CLSC**	
[150]		*				*		*		Refrigerators
[147]		*				*		*		Solar energy
[149]	*	*		*	*	*			*	
[148]	*	*				*		*		
[151]								*		Geyser manufacturing
[153]		*		*		*	*			Traditional retailers and online e-tailers
[156]	*	*				*	*	*		Semiconductor industries
[152]								*		Perishable products
[155]								*		Mask production
[146]	*	*	*	*			*	*	*	Home appliances
[157]		*				*	*	*		
[154]		*				*		*		
[37]								*		

Table A6. Criteria for evaluating supply chains. (*) marks coverage of topic by article.

Citation	Criteria to Evaluate the Supply Chain													
	Design and Planning	**Manufacturing**	**Purchasing, Packaging and Inventory Control**	**Business Process and Operational Flexibility**	**Returns**	**Reuse/Recycle/Remanufacturing/Refurbishing**	**Waste Disposal**	**Environmental and Pollution**	**Economical (Cost and Profit)**	**Social Attributes and Customer Satisfaction**	**Information Value and Sharing**	**Innovation/Technology/Certifications**	**Strategy Formulation and Nodes Relationship**	**Political and Regulatory Attributes**
[186]	*	*	*	*		*	*	*	*			*		
[184]		*	*		*	*	*	*	*	*				*
[18]				*				*	*	*	*			
[198]	*					*		*		*		*		
[147]				*		*		*	*	*				
[174]				*		*	*	*	*	*	*	*		
[199]						*		*	*	*	*			
[200]						*		*	*	*		*		
[189]					*	*		*	*	*	*			
[182]						*		*	*	*	*		*	
[171]	*	*		*	*	*		*	*	*	*			
[191]	*			*	*		*	*	*	*				
[180]							*	*	*	*				
[201]						*		*	*	*				
[172]								*	*					

Table A6. *Cont.*

Citation	Criteria to Evaluate the Supply Chain													
	Design and Planning	Manufacturing	Purchasing, Packaging and Inventory Control	Business Process and Operational Flexibility	Returns	Reuse/Recycle/Remanufacturing/Refurbishing	Waste Disposal	Environmental and Pollution	Economical (Cost and Profit)	Social Attributes and Customer Satisfaction	Information Value and Sharing	Innovation/Technology/Certifications	Strategy Formulation and Nodes Relationship	Political and Regulatory Attributes
[202]		*		*		*		*	*	*		*		
[173]						*	*	*	*	*				
[170]	*	*	*		*	*								
[185]				*		*		*	*	*	*	*		
[183]					*	*	*		*	*	*			
[203]	*		*			*		*				*	*	
[190]				*		*	*	*	*	*	*	*		
[188]	*	*	*			*		*	*				*	*
[204]	*	*	*	*										
[177]	*	*	*	*		*	*	*				*	*	
[205]				*	*			*	*	*		*		
[178]	*	*	*	*		*	*	*				*	*	
[179]	*		*	*			*	*	*	*	*	*	*	*
[187]							*	*	*	*		*		*
[176]					*	*			*	*	*			*

Table A6. *Cont.*

Citation	Criteria to Evaluate the Supply Chain													
	Design and Planning	Manufacturing	Purchasing, Packaging and Inventory Control	Business Process and Operational Flexibility	Returns	Reuse/Recycle/Remanufacturing/Refurbishing	Waste Disposal	Environmental and Pollution	Economical (Cost and Profit)	Social Attributes and Customer Satisfaction	Information Value and Sharing	Innovation/Technology/Certifications	Strategy Formulation and Nodes Relationship	Political and Regulatory Attributes
[168]	*	*	*							*				
[169]	*	*	*	*	*	*	*	*	*	*	*	*	*	*
[206]		*						*	*	*				
[207]	*	*	*	*		*		*	*	*		*		
[167]	*	*	*	*	*	*		*						

Table A7. Greenness index—fuzzy methods focus. (*) marks coverage of topic by article.

Citation	Aggregate Methods								Industry Examples
	Fuzzy Methods	Analytic Hierarchy Process (AHP)	Delphi Method	Grey Relational Analysis	Qualitative Research Methodology	Balanced Score Card	Analytical Network Process	Other	
[18]	*								
[198]	*								
[182]	*			*					
[199]	*								Household electrical appliance manufacturer
[174]	*	*				*			
[200]	*								Automotive
[171]	*	*	*						
[201]	*								Air conditioning
[180]	*		*						
[202]	*								Iron and steel
[173]	*	*							Automotive
[172]	*	*							Construction
[170]	*								Produce (Fresh food)
[203]	*	*		*					Automotive
[188]	*							Decision-making trial and evaluation laboratory method	
[204]	*								

Table A7. *Cont.*

Citation	Aggregate Methods								Industry Examples
	Fuzzy Methods	**Analytic Hierarchy Process (AHP)**	**Delphi Method**	**Grey Relational Analysis**	**Qualitative Research Methodology**	**Balanced Score Card**	**Analytical Network Process**	**Other**	
[205]	*								
[179]	*		*			*	*		Printed circuit board (PCB)
[187]	*							Liberatore score and signal to noise ratio	Automotive
[168]	*							Group decision making model	
[169]	*							Dematel	Fast moving customer goods
[166]	*							Fuzzy CRITIC approach	Oil industry
[167]	*						*	DEMATEL and TOPSIS	
[207]	*					*			Automotive
[48]	*							Data-driven sustainable supply chain management performance	
[208]	*							Fuzzy Hamacher averaging operator	Wireless network
[181]	*	*	*						Garment manufacturing firms

Table A8. Greenness index—other methods. (*) marks coverage of topic by article.

Citation	Aggregate Methods								Industry Examples
	Fuzzy Methods	Analytic Hierarchy Process (AHP)	Delphi Method	Grey Relational Analysis	Qualitative Research Methodology	Balanced Score Card	Analytical Network Process	Other	
[186]							*		
[184]					*				
[189]								Membership conversion algorithm	
[147]		*		*				Information entropy method	Electronics
[191]								Data envelopment analysis (DEA)	
[185]						*			
[183]					*				Electronics and other industries
[177]		*			*				Footwear
[190]								Meta analysis	
[178]		*						Five point Likert scale	Automotive
[176]		*	*						
[206]		*						LMBP and DEMATEL	
[192]								Decision support system	
[193]								Network DEA	soft drinks industry

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