

Exploring the Meta-Synthesis Model of the Green Supply Chain in the Power Industry: An Industry 4.0 and Smart Sustainability Approach

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ABSTRACT

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The establishment of a green and sustainable supply chain in the power industry particularly in the manufacturing sector of electrical equipment and transmission/distribution facilities plays a vital role in supporting sustainable development and ensuring national energy security. This study aims to analyze and identify the primary and secondary variables of the green supply chain within the framework of Industry 4.0 and smart sustainability in companies producing electrical equipment and infrastructure in Mazandaran Province, Iran. The research employs a meta-synthesis technique combined with the Delphi method. Following the seven-step process of Sandelowski and Barroso (2007), theoretical foundations and prior research published between 2014–2025 (international sources) and 1393–1404 (Persian sources) were systematically reviewed. In total, 248 documents were initially identified, from which 34 core studies remained after a rigorous critical appraisal process. Through open, axial, and selective coding, five main categories and ten axial codes were extracted, including Smart Ecological Design, Digital Green Processes, Data-Driven Waste Management, AI-Based Green Marketing, and Smart Ecological Governance. The axial codes encompass Ecological Product Design, Eco-Friendly Raw Material Procurement, Ecological Production, Green Procurement, Primary and Secondary Waste Management, Ecological Information Exchange, and Green Marketing Contexts, originating from 46 open codes derived during the synthesis phase.

Keywords: *Green Supply Chain; Power Industry; Industry 4.0; Smart Sustainability; Meta-Synthesis*

1. Introduction

The power industry is one of the most strategic infrastructure sectors in any national economy because it supports industrial production, public services, technological development, urban functioning, and national

energy security. In countries where electricity generation, transmission, and distribution systems are closely connected to broader industrial value chains, the environmental performance of the power industry becomes a central issue not only for energy policy but also for sustainable development. The manufacturing of electrical equipment,

transmission facilities, distribution components, panels, transformers, cables, control systems, and related infrastructure requires substantial material input, energy consumption, logistics coordination, and supplier integration. Consequently, this industry can generate considerable environmental pressure through resource depletion, emissions, hazardous materials, industrial waste, and inefficient procurement and production processes. At the same time, because the power industry supplies critical infrastructure to other economic sectors, its transition toward greener and smarter supply chain systems can create multiplier effects across manufacturing, construction, energy, and service industries (Fouladvand et al., 2023; Shahipasand et al., 2024; Wang et al., 2025).

Green supply chain management has emerged as a comprehensive managerial and operational approach for integrating environmental considerations into supply chain activities from product design and raw material procurement to production, logistics, marketing, waste management, reverse logistics, and governance. Unlike traditional supply chain management, which has mainly emphasized cost, quality, flexibility, delivery speed, and operational efficiency, green supply chain management expands the performance logic of firms by embedding ecological responsibility into both internal and interorganizational processes. This approach requires firms to select environmentally responsible suppliers, reduce hazardous material use, improve energy efficiency, design recyclable products, optimize transportation, reduce emissions, control waste, and collaborate with customers and regulatory bodies to strengthen sustainable value creation (Madiati et al., 2018; Singh & Trivedi, 2016; Tachizawa et al., 2015; Tseng et al., 2019). In this sense, green supply chain management is not limited to environmental protection but also functions as a strategic capability that can improve organizational performance, competitive advantage, innovation capacity, market legitimacy, and long-term resilience (Fang & Zhang, 2018; Gelmez et al., 2024; Gholami & Nazari, 2018).

The importance of green supply chain management is particularly evident in energy-intensive and technology-driven industries. The power industry depends on complex networks of suppliers, manufacturers, contractors, logistics providers, regulators, and customers. Because power equipment and infrastructure projects often involve long product life cycles and high capital intensity, decisions made at the design and procurement stages can strongly influence environmental outcomes over many years. For example, the use of recyclable materials, standardized components,

energy-efficient designs, low-emission production technologies, and environmentally certified suppliers can reduce environmental risk and improve operational sustainability. Studies in the power and energy sectors have shown that environmental capabilities, green strategies, and structured sustainability practices can enhance financial, operational, and environmental performance when they are systematically embedded into managerial decision-making and supply chain coordination (Afarin-Mohammadzadeh & Hassanzadeh, 2018; Bayat & Behnia, 2020; Dhumras & Bajaj, 2024; Ding et al., 2018). Therefore, the power industry requires a model of green supply chain management that is sensitive to its technical complexity, regulatory environment, infrastructure role, and dependence on advanced materials and technologies.

Previous research has examined green supply chain management across several industrial and service contexts and has provided useful evidence about its drivers, barriers, indicators, and performance implications. Studies in the construction sector have emphasized the role of environmental regulations, project-based procurement, stakeholder pressure, and sustainable material selection in institutionalizing green supply chains (Harouache et al., 2021; Taryan et al., 2022; Yazdian & Radaei, 2019; Zarei et al., 2024). Research on the petrochemical, oil, energy, and industrial sectors has highlighted organizational structure, managerial commitment, supplier capabilities, environmental planning, human resource management, and government support as key determinants of green supply chain implementation (Alipour et al., 2022; Ghorbanpour et al., 2017; Rajabpour & Afkhami-Ardakani, 2020; Ramezani et al., 2019). Evidence from small and medium-sized enterprises and other industrial contexts further indicates that green supply chain practices can improve environmental performance when firms possess adequate internal capabilities, external collaboration mechanisms, and institutional support (Andalib & Shams, 2020; Asayesh et al., 2021; Dzikriansyah et al., 2023). These findings show that green supply chain management is multidimensional and context-dependent, and that each industry needs a tailored model reflecting its operational realities.

A review of the literature also shows that green supply chain management has been studied in relation to several important operational domains, including green product design, green procurement, clean production, ecological logistics, waste management, green marketing, and governance. Green product design focuses on reducing environmental impacts at the earliest stage of the product life

cycle through recyclable materials, modular structures, energy-efficient components, and maintenance-friendly product architecture. Green procurement emphasizes selecting suppliers that comply with environmental standards, provide eco-friendly materials, and participate in sustainability-oriented collaboration. Clean production and ecological logistics aim to reduce energy consumption, emissions, process waste, and transportation inefficiencies. Waste management and reverse logistics focus on segregation, recycling, reuse, and recovery of materials, while green marketing and ecological information exchange strengthen customer awareness, transparency, and market acceptance of environmentally responsible products (Borazon et al., 2022; Mohammadi et al., 2019; Sabzi & Karimi, 2018; Shojaei et al., 2017; Soda et al., 2017). Together, these dimensions create a systemic framework through which environmental responsibility is translated into practical supply chain routines.

Despite these advances, traditional green supply chain management models often remain reactive, fragmented, and insufficiently integrated with digital technologies. In many organizations, environmental monitoring still depends on periodic reporting, manual audits, delayed data collection, and separate departmental systems. Such limitations reduce the capacity of firms to detect environmental inefficiencies in real time, forecast waste, optimize resource consumption, verify supplier compliance, and respond rapidly to sustainability risks. This problem is especially critical in the power industry, where production and logistics processes involve complex technical specifications, large-scale equipment, multiple tiers of suppliers, and high environmental sensitivity. As a result, conventional green supply chain practices need to be reconfigured through digital transformation and Industry 4.0 technologies in order to become more intelligent, predictive, transparent, and adaptive (Hu et al., 2022; Lerman et al., 2022; Li et al., 2023).

Industry 4.0 has introduced a new technological paradigm based on the integration of cyber-physical systems, the Internet of Things, artificial intelligence, big data analytics, blockchain, cloud computing, digital platforms, and advanced manufacturing technologies. These technologies make it possible to collect, process, and exchange real-time data across the supply chain. When applied to sustainability, Industry 4.0 can transform green supply chain management from a compliance-oriented system into a smart sustainability system. IoT sensors can monitor energy consumption, emissions, equipment performance, and

material flows. Big data analytics and artificial intelligence can forecast demand, optimize production scheduling, detect inefficiencies, and support environmental decision-making. Blockchain can improve traceability and transparency in supplier evaluation, material origin, waste management, and recycling processes. Cloud-based systems can facilitate interorganizational data sharing, regulatory monitoring, and collaborative environmental governance (Haiyun et al., 2021; Karimi et al., 2023; Manavalan & Jayakrishna, 2019; Rashid et al., 2025). Therefore, the integration of Industry 4.0 with green supply chain management creates the foundation for smart green supply chain management.

Smart green supply chain management represents an advanced stage of sustainability-oriented supply chain transformation. It combines ecological objectives with intelligent technologies in order to achieve higher levels of resource efficiency, environmental visibility, operational agility, and strategic responsiveness. In such a system, ecological product design is supported by real-time product life-cycle data; procurement decisions are informed by digital supplier assessment and material traceability; production processes are optimized through intelligent monitoring and automation; logistics networks are redesigned using routing algorithms and energy-efficient transportation planning; waste flows are managed through data-driven tracking and predictive recycling systems; and green marketing is strengthened through digital customer analytics and transparent environmental communication. Recent studies have shown that digital transformation, green innovation, artificial intelligence, and big data analytics can enhance sustainable performance, green supply chain capability, and competitive advantage when they are aligned with organizational strategy and environmental goals (Borazon et al., 2022; Gelmez et al., 2024; Li et al., 2023; Rashid et al., 2025).

However, the transition toward smart green supply chains is not merely a technological issue. It also requires managerial commitment, regulatory support, organizational learning, stakeholder alignment, financial investment, and sector-specific policy frameworks. Many firms face barriers such as high implementation costs, limited digital skills, weak supplier readiness, insufficient environmental regulation, low market demand for green products, and lack of reliable sustainability data. In developing economies, these barriers may be intensified by infrastructure limitations, unstable policies, financial constraints, and fragmented institutional coordination. Studies on energy, solar companies, industrial firms, and power-related sectors

have identified stakeholder pressure, government support, environmental standards, managerial awareness, supplier collaboration, and technological capability as essential drivers of green supply chain implementation (Delshad et al., 2022; Esmaeili et al., 2020; Vanalle et al., 2017; Yassin et al., 2022). Therefore, any model of smart green supply chain management must integrate both technological enablers and organizational-institutional conditions.

In the Iranian power industry, the need for such integration is particularly important. Iran's power equipment and transmission/distribution industries operate within a context characterized by strong infrastructure needs, technological dependence, environmental pressure, and increasing demand for sustainable industrial development. Companies manufacturing electrical equipment and infrastructure components must respond to environmental concerns while maintaining cost efficiency, quality, technical reliability, and compliance with sectoral standards. Existing studies in Iran have addressed specific aspects of green supply chain management, including barriers, success factors, environmental strategies, performance indicators, and decision-making models in industries such as power, construction, petrochemicals, municipalities, industrial towns, and automotive manufacturing (Afarin-Mohammadzadeh & Hassanzadeh, 2018; Bayat & Behnia, 2020; Esmaeili et al., 2020; Ramezani et al., 2019; Sabzi & Karimi, 2018). Nevertheless, there remains a lack of an integrated conceptual framework that synthesizes previous findings and adapts them to the emerging logic of Industry 4.0 and smart sustainability in the power equipment sector.

Meta-synthesis offers a suitable methodological approach for addressing this gap because it allows researchers to systematically collect, compare, interpret, and integrate findings from prior studies in order to develop a higher-order conceptual model. Rather than merely summarizing existing evidence, meta-synthesis makes it possible to extract common concepts, identify conceptual relationships, classify dimensions, and reconstruct the field around a more comprehensive theoretical structure. This is especially useful in green supply chain research because the literature is dispersed across industries, methods, regions, and analytical levels. Prior reviews and meta-analyses have demonstrated the conceptual breadth of green supply chain management and have called for future research that links sustainability practices with digital technologies, circular economy principles, performance systems, and industry-specific implementation models (Alreahi et al., 2023; Fang & Zhang, 2018; Maditati et al., 2018; Tseng et al., 2019).

Accordingly, a meta-synthesis approach can support the development of a smart green supply chain model that is both theoretically grounded and practically applicable.

The conceptual logic of the present study is based on the assumption that smart sustainability in the power industry requires the convergence of five interrelated domains: smart ecological design, digital green processes, data-driven waste management, AI-based green marketing, and smart ecological governance. Smart ecological design emphasizes environmentally responsible and technologically informed product development. Digital green processes focus on clean production, intelligent logistics, and real-time operational optimization. Data-driven waste management integrates primary and secondary waste control with analytics, traceability, recycling, and recovery. AI-based green marketing connects environmental value creation with customer communication, market intelligence, and transparent information exchange. Smart ecological governance links managerial commitment, organizational strategy, government policy, environmental regulation, and digital monitoring systems. Together, these domains provide a comprehensive foundation for moving beyond traditional green supply chains toward proactive, intelligent, and adaptive sustainability in the power industry (Dhumras & Bajaj, 2024; Hu et al., 2022; Lerman et al., 2022; Wang et al., 2025).

Therefore, this study aims to identify and analyze the primary and secondary variables of the smart green supply chain in power transmission and distribution equipment manufacturing companies in Mazandaran Province by integrating meta-synthesis and Delphi methods within an Industry 4.0 and smart sustainability framework.

2. Methods and Materials

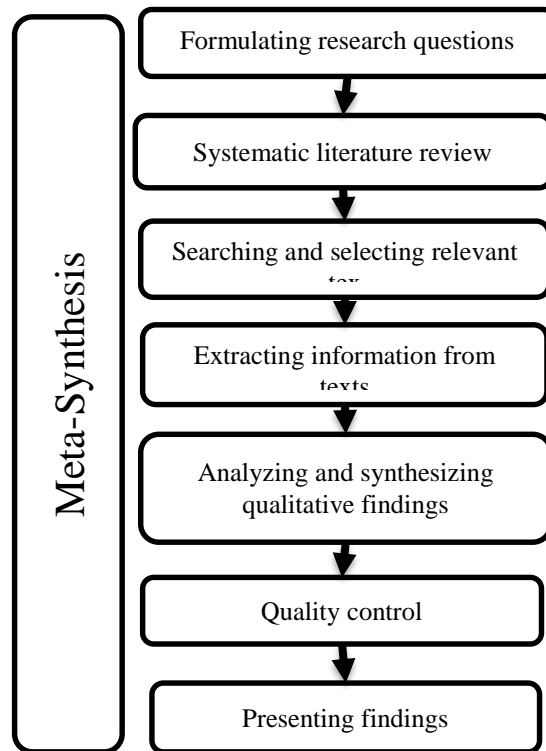
This study is qualitative in purpose and meta-synthesis in nature. The research process follows the seven-stage approach proposed by Sandelowski and Barroso (2007). The aim of this method is to extract the shared components and conceptual patterns among previous studies and integrate them systematically to develop a new conceptual model. In the initial stage, the theoretical foundations and prior research were reviewed, and key search terms including green supply chain management (GSCM), smart green supply chain, Industry 4.0 / Fourth Industrial Revolution, smart sustainability, and digital transformation (and their equivalents in Persian and international databases) were used for searching scholarly sources. The statistical

population consisted of all scientific papers related to green supply chain topics published between 2014 and 2025 (1393–1404). The selection criteria focused on studies directly linked to the main and secondary variables of GSCM and those referring to emerging dimensions of Industry 4.0 and digital sustainability. Eligible papers were analyzed using qualitative thematic analysis, whereby conceptual units were extracted, categorized, and coded through open, axial, and selective coding. The results were organized into five main categories, ten axial codes, and fifty-eight open codes. To strengthen the theoretical contribution and enhance the integrative power of the

resultant model, one additional stage titled the technological integration phase was incorporated after completing the classical meta-synthesis steps. In this stage, the previously identified categories were aligned and merged with core Industry 4.0 technologies, namely Internet of Things (IoT), cyber-physical systems (CPS), blockchain, artificial intelligence (AI), and cloud computing. This integration yielded the final conceptual framework, defined as the Smart Green Supply Chain Model for the Electric Power Industry. The overall sequence of the research process is depicted in Figure 1.

Figure 1

Research Implementation Steps



3. Findings and Results

Step 1: Formulating the Research Questions

The first step in conducting a meta-synthesis is to formulate the research questions. To organize this stage, Table 1 has been prepared.

Table 1

Formulation of Questions

Questions	Responses
What?	Inferring the primary and secondary variables within the green supply chain framework
Who? (Population studied)	Articles and theses available in scientific databases
When?	2014 to 2025
How?	Barroso and Sandelowski's method

Step 2: Systematic Review of the Smart Green Supply Chain Literature

Keywords related to the green supply chain in the electric power industry were systematically searched across several domestic and international academic databases to identify

relevant and appropriate studies for the meta-synthesis process. To enhance transparency in this stage, the databases reviewed and the search criteria applied are presented in Table 2.

Table 2

Scientific Databases Examined

Collection of Records from Domestic and International Sources		Databases
Sources	Domestic	www.sid.ir
		www.Magiran.com
		www.Noormags.com
		www.ensani.ir
		www.civilica.com
	International	www.sciencedirect.com
		www.emeraldinsight.com
		www.springer.com
		www.scholar.google.com
		www.tandfonline.com

The summary of the aforementioned content, presented as the initial criteria and indicators for screening the reviewed articles, is shown in Table 3.

Table 3

Initial Indicators and Criteria for Reviewing Records

Indicators	Acceptance Criteria	Rejection Criteria
Research Span	Records published from 2014 to 2025	Studies published before 2014
Research Language	Persian and English	Languages other than Persian and English
Type of Record	Studies published in scientific databases	Others (e.g., articles published in newspapers or blogs)
Subject	Green supply chain in the electric power industry and similar terms	Topics unrelated to green supply chain in the electric power industry
Type of Journal	Indexed in scientific databases	Others

Based on the procedures described above, the researcher ultimately identified 248 articles, which were then included in Step 3 of the meta-synthesis for further analysis and final selection.

Step 3: Searching and Selecting Relevant Articles

Among the 248 sources obtained through the specified keywords in the aforementioned databases, the studies were evaluated in terms of accuracy, credibility, and relevance. To ensure the precision of selection, three stages of assessment were conducted:

1. Title screening to verify alignment with the present study;

2. Abstract review to examine the research methods and key findings; and

3. Full-text evaluation to ensure conceptual and methodological consistency with the objectives of this research.

Following these assessments, a total of 34 studies employing qualitative, quantitative, or mixed-method (quantitative/qualitative) approaches were selected for inclusion in the research process.

The following diagram illustrates the procedure of searching, screening, and selecting the relevant literature based on the evaluation of titles, abstracts, and full texts.

Figure 2

Selected Records After Initial Screeni

Reviewed Records	Results of the Review
Total number of records: 248	
Number of records for abstract review: 197	Records rejected based on title: 51
Number of records for full content review: 124	Records rejected based on abstract: 73
Number of records for full review: 34	Records rejected based on content: 90

Step 4: Extraction of Information from Texts

The information from the records was classified based on the reference details of each record, including the author's first and last name, publication year, and the components aligned with each record. In this stage, 412 concepts were extracted.

Step 5: Analysis and Synthesis of Findings

In this stage, open codes were assigned to all extracted variables. Subsequently, the open codes were categorized based on semantic proximity, and corresponding axial codes were identified. The axial codes were further grouped to form categories. Five categories, 10 axial codes, and 58 open codes were identified and labeled for the green supply chain in the electric power industry.

Table 4

Analysis and Synthesis of Findings

Category	Axial Code	Open Code	Frequency
Smart Ecological Design	Ecological Product Design	Designing products based on customer needs and preferences (Gholami & Nazeri, 2018; Ghorbanpour et al., 2017; Borazon et al., 2022; Haiyun et al., 2021; Ding et al., 2018)	5
		Designing recyclable products (Zarei et al., 2024; Karimi et al., 2023; Bayat & Behnia, 2020; Tseng et al., 2019)	4
		Reducing waste and residues in product design (Alipour et al., 2022; Shojaei et al., 2017)	2
		Designing products with high energy efficiency (Andalib & Shams, 2020; Mohammadi et al., 2018; Gülmez et al., 2024; Madison et al., 2018)	4
		Using low-energy consumption technologies in product design (Bayat & Behnia, 2020; Shojaei et al., 2017; Gülmez et al., 2024)	3
		Designing products with standardized components and easy maintenance (Gholami & Nazeri, 2018; Shojaei et al., 2017; Bayat & Behnia, 2020; Haiyun et al., 2021)	4
		Advancing green technologies in products and services (Esmaeili & Akbarinia, 2020; Fang & Zhang, 2018; Madison et al., 2018)	3
Ecological Raw Material Procurement	Ecological Raw Material Procurement	Collaborating with suppliers of environmentally friendly products (Tarian et al., 2022; Rajabpour & Afkhami Ardakani, 2020; Gholami & Nazeri, 2018; Dzikriansyah et al., 2023; Fang & Zhang, 2018)	5
		Avoiding hazardous raw materials (Karimi et al., 2023; Delshad et al., 2022; Ghorbanpour et al., 2017; Borazon et al., 2022; Soda et al., 2017)	5
		Adhering to technical and environmental standards for raw material procurement (Delshad et al., 2022)	1
		Procuring materials with high recycled content (Tarian et al., 2022; Shojaei et al., 2017; Gholami & Nazeri, 2018; Dhumras & Bajaj, 2024)	4
		Conducting environmental audits for internal supplier management (Tarian et al., 2022; Ramezani et al., 2019; Yassin et al., 2022)	3

		Collaborating with other supply chain members to enhance sustainability (Mohammadi et al., 2018; Ding et al., 2018; Fang & Zhang, 2018)	3
Digital Green Processes	Ecological Production	Organizational capability to develop and implement green projects (Zarei et al., 2024; Karimi et al., 2023; Delshad et al., 2022)	3
		Improving product quality and variety while addressing environmental considerations (Karimi et al., 2023; Delshad et al., 2022)	2
		Using automated equipment (Esmaeili & Akbarinia, 2020; Dhumras & Bajaj, 2024)	2
		Employing clean production technologies (Alipour et al., 2022; Delshad et al., 2022; Gülmez et al., 2024)	3
		Using nanotechnology (Esmaeili & Akbarinia, 2020; Dhumras & Bajaj, 2024)	2
		Optimizing energy consumption in production processes (Alipour et al., 2022; Gülmez et al., 2024)	2
		Using low-energy consumption equipment and machinery in production (Delshad et al., 2022; Esmaeili & Akbarinia, 2020; Dhumras & Bajaj, 2024)	3
		Improving existing processes and developing new internal processes (Karimi et al., 2023; Delshad et al., 2022)	2
	Ecological Logistics	Optimizing transportation routes (Yazdian & Radaei, 2019; Sabzi & Karimi, 2018; Lerman et al., 2022)	3
		Using low-consumption transport vehicles (Zarei et al., 2024; Sabzi & Karimi, 2018; Ramezani et al., 2019; Al-Rayahi et al., 2023)	4
		Encouraging employees to use public transportation (Yassin et al., 2022)	1
		Fully loading materials and goods in trucks (Yassin et al., 2022)	1
		Designing buildings with lower material and energy consumption (Tarian et al., 2022; Dzikriansyah et al., 2023)	2
		Landscaping for temporary storage and waste segregation (Yazdian & Radaei, 2019; Sabzi & Karimi, 2018; Lerman et al., 2022)	3
Data-Driven Waste Management	Primary Waste Management	Segregation and separation of waste (Esmaeili & Akbarinia, 2020; Yazdian & Radaei, 2019; Gülmez et al., 2024; Dzikriansyah et al., 2023)	3
		Collection and transportation of waste (Alipour et al., 2022; Yazdian & Radaei, 2019; Sabzi & Karimi, 2018; Dhumras & Bajaj, 2024)	3
		Forecasting wastewater recycling (Tarian et al., 2022; Dzikriansyah et al., 2023; Dhumras & Bajaj, 2024)	3
	Secondary Waste Management	Recycling and energy recovery from waste (Zarei et al., 2024; Alipour et al., 2022; Sabzi & Karimi, 2018; Gülmez et al., 2024; Dzikriansyah et al., 2023)	5
		Recycling and reuse of components and equipment (Karimi et al., 2023; Tarian et al., 2022; Delshad et al., 2022; Dhumras & Bajaj, 2024; Madison et al., 2018; Tseng et al., 2019)	6
		Existence of markets for receiving and producing recycled materials (Ramezani et al., 2019; Yassin et al., 2022)	2
AI-Based Green Marketing	Ecological Information Exchange	Continuous customer communication regarding the green nature of products (Zarei et al., 2024; Karimi et al., 2023; Ramezani et al., 2019; Yassin et al., 2022)	4
		Providing accurate and transparent information about the environmental benefits of products (Esmaeili & Akbarinia, 2020; Ghorbanpour et al., 2017; Borazon et al., 2022; Soda et al., 2017)	4
		Introducing innovative products and services with environmental benefits (Ghorbanpour et al., 2017; Gholami & Nazeri, 2018; Haiyun et al., 2021; Ding et al., 2018; Fang & Zhang, 2018)	5
		Participating in environmental events and activities (Ghorbanpour et al., 2017; Borazon et al., 2022; Ding et al., 2018)	3
		Using recyclable materials in packaging (Zarei et al., 2024; Shojaei et al., 2017; Borazon et al., 2022; Soda et al., 2017)	4

Ecological Marketing Foundations	Pricing based on customers' financial capacity for green products (Zarei et al., 2024; Karimi et al., 2023; Delshad et al., 2022)	3	
	Green advertising (Esmaeili & Akbarinia, 2020; Dhumras & Bajaj, 2024)	2	
	Willingness to enter global markets (Haiyun et al., 2021)	1	
	Responding to customer demands for environmental compliance (Zarei et al., 2024; Karimi et al., 2023; Delshad et al., 2022)	3	
	Educating green customers (Esmaeili & Akbarinia, 2020; Dhumras & Bajaj, 2024)	2	
	Using artificial intelligence (Esmaeili & Akbarinia, 2020; Dhumras & Bajaj, 2024)	2	
Smart Ecological Governance	Top Management Actions	Managerial support systems (Zarei et al., 2024; Rajabpour & Afkhami Ardakani, 2020; Wanale et al., 2017)	3
		Accurate understanding by senior and middle managers of the importance of the green supply chain (Asayesh et al., 2021; Rajabpour & Afkhami Ardakani, 2020; Afrin Mohammadzadeh & Hasanzadeh, 2018; Yassin et al., 2022)	4
		Selecting knowledgeable and specialized managers for green production conditions (Zarei et al., 2024; Wanale et al., 2017; Singh & Trivedi, 2016)	3
		Establishing short-term and long-term strategic goals (Mohammadi et al., 2018; Andalib & Shams, 2020; Madison et al., 2018; Tachio et al., 2015)	4
		Incorporating environmental objectives into the organization's mission (Yazdian & Radaei, 2019; Sabzi & Karimi, 2018; Lerman et al., 2022; Wanale et al., 2017)	4
Government Policies	Enacting green laws, regulations, and requirements by the government (Yazdian & Radaei, 2019; Haiyun et al., 2021; Madison et al., 2018)	3	
	Mandating industries and suppliers to comply with national and international environmental standards and certifications (Tarian et al., 2022; Yassin et al., 2022; Lerman et al., 2022)	3	
	Establishing guidelines for electrical and electronic waste (Ghorbanpour et al., 2017; Borazon et al., 2022; Soda et al., 2017)	3	
	Planning for continuous monitoring and oversight by regulatory organizations (Wanale et al., 2017; Singh & Trivedi, 2016)	2	
	Providing tax incentives (Zarei et al., 2024; Yazdian & Radaei, 2019; Singh & Trivedi, 2016)	3	
	Evaluating suppliers' environmental performance indicators (Tarian et al., 2022; Alipour et al., 2022; Al-Rayahi et al., 2023)	3	
	Offering low-interest loans to green producers (Yassin et al., 2022; Lerman et al., 2022; Ding et al., 2018)	3	
Promoting environmental awareness and education at the societal and industrial levels (Rajabpour & Afkhami Ardakani, 2020; Ramezani et al., 2019; Afrin Mohammadzadeh & Hasanzadeh, 2018; Tachio et al., 2015)	4		

Step 6: Quality Control

The validity of this section was established through content validity and from two perspectives. The first involves using components and factors from previously proposed models, thereby contributing to the model's validity. The second entails conducting a focus group session and presenting the model to five experts, where the absence of changes to the model indicates its validity.

The design of the model involved the initial coding of criteria derived from existing models. Subsequently,

semantically similar codes were aggregated to develop concepts. Therefore, Cohen's Kappa (κ) was calculated to evaluate the reliability of the resulting model. A Kappa index value of 0.808 and a significance level smaller than 0.05 indicated that the extracted codes were not independent. Additionally, the code extraction demonstrated satisfactory reliability.

Step 7: Presentation of Findings

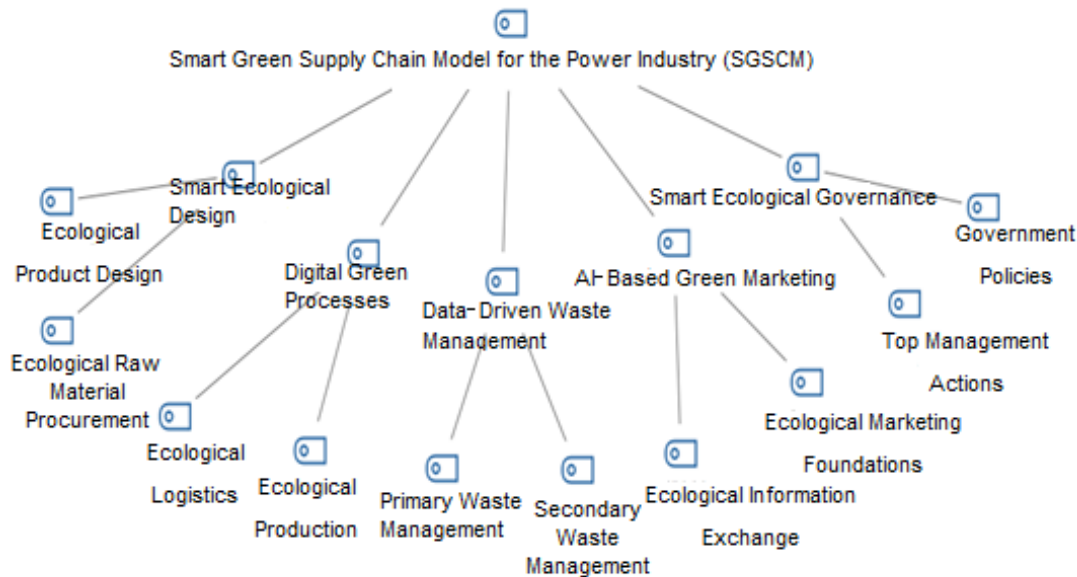
Based on the qualitative meta-synthesis analysis, a total of 58 open codes were initially extracted from the selected

articles. These codes were then organized into 10 axial codes and subsequently categorized into five main themes. In the complementary technological integration stage, these categories were aligned with Industry 4.0 technologies, leading to the development of the Smart Green Supply Chain Model for the power industry. The findings revealed that

intelligent technologies can transform conventional green activities into digital and sustainable processes. Finally, the data coding, analysis, and classification were carried out using MAXQDA 2020 software, and the conceptual model was derived and presented in Figure 3.

Figure 3

Output of MAXQDA Software Smart Green Supply Chain Model for the Power Industry (SGSCM)



3.2. Stages of the Delphi Method

First Round of the Delphi Method: In this stage, the Delphi method was applied in three rounds to localize the research indicators for companies manufacturing equipment and facilities for power transmission and distribution in Mazandaran Province. Experts were selected from companies including Maziyar Sanat, Mazandaran Electrical Paneling, Electro Lalehzar, Shah Dezh Niroo Sahel, and Talar Payeh Mazand. In the first round, 58 items derived from the qualitative method were provided to 16 experts with comprehensive knowledge of the subject. The following indicators were eliminated in the first round of the Delphi method: use of nanotechnology, recycling and energy recovery from waste, participation in environmental events and activities, pricing based on customers' financial capacity for green products, use of artificial intelligence, incorporating environmental objectives into the organization's mission, enacting green laws and regulations by the government, mandating industries and suppliers to comply with national and international environmental standards and certifications, establishing guidelines for

electrical and electronic waste, evaluating suppliers' environmental performance indicators, and promoting environmental awareness and education at societal and industrial levels. Based on expert opinions, the following indicators were added to the government policies component: enacting guidelines and regulations for green production by Tavanir, importing raw materials with a green supply chain filter, and effective and continuous monitoring and evaluation. Consequently, 50 indicators remained for further investigation.

Second Round of the Delphi Method: After evaluating the first round's output and eliminating less significant indicators, the 50 remaining indicators were presented to the experts in the second round. Based on expert suggestions, the following indicators were removed: designing products based on customer needs and preferences, using low-energy consumption equipment and machinery in production, encouraging employees to use public transportation, landscaping for temporary storage and waste segregation, using recyclable materials in packaging, and educating green customers. Additionally, the indicator "substituting hot-dip

galvanized iron" was added to the ecological raw material procurement component, and "the use of specialized foreign and European consultants in the green domain" was added to the ecological information exchange component. Ultimately, 46 indicators remained for further investigation.

Third Round of the Delphi Method: Once the second round's output was evaluated and less significant indicators were eliminated, the 46 remaining indicators were presented to the experts in the third round. Scores above 3 for all indicators suggest their effectiveness, confirming no need for further elimination.

4. Discussion and Conclusion

The findings of the present study led to the development of a Smart Green Supply Chain Management model for the power industry, structured around five main categories, ten axial codes, and forty-six final indicators after three Delphi rounds. The meta-synthesis stage initially extracted fifty-eight open codes from the selected literature, and these were organized into the five dimensions of smart ecological design, digital green processes, data-driven waste management, AI-based green marketing, and smart ecological governance. The Delphi results then localized and refined these indicators for companies producing power transmission and distribution equipment in Mazandaran Province, confirming that the transition from conventional green supply chain management to smart green supply chain management requires both environmental and digital capabilities. The reliability of the extracted coding structure was also supported by a Cohen's Kappa value of 0.808, indicating acceptable agreement and conceptual stability in the coding process. These results show that in the power industry, green supply chain management cannot be reduced to isolated environmental actions; rather, it should be understood as a multidimensional, technology-enabled, and governance-based system that integrates ecological product design, green procurement, clean production, logistics optimization, waste control, ecological marketing, managerial commitment, and regulatory support. The uploaded manuscript reports these categories, Delphi rounds, and coding outcomes as the empirical foundation of the model.

The first major finding of the study concerns smart ecological design, which included ecological product design and ecological raw material procurement. This result indicates that the environmental performance of the power industry begins before production, at the design and input-

selection stages. Designing recyclable products, reducing waste in product architecture, improving energy efficiency, using standardized and easily maintainable components, and advancing green technologies were identified as central indicators. This finding is consistent with studies arguing that green supply chain performance depends strongly on upstream design choices and supplier-related environmental capabilities (Singh & Trivedi, 2016; Tachizawa et al., 2015; Wang et al., 2025). In the power industry, product design has long-term environmental consequences because electrical equipment and transmission/distribution components remain in use for extended life cycles. Therefore, early design decisions influence energy consumption, maintenance requirements, recyclability, and waste generation across the entire life cycle. The emphasis on ecological raw material procurement also aligns with evidence showing that collaboration with green suppliers, avoidance of hazardous materials, environmental auditing, and procurement of recycled-content materials are essential prerequisites for implementing green supply chains (Afarin-Mohammadzadeh & Hassanzadeh, 2018; Shojaei et al., 2017; Soda et al., 2017). The Delphi addition of indicators such as substituting hot-dip galvanized iron further confirms that localization is necessary because green design and procurement should reflect the technical realities of the Iranian power equipment industry.

The second major finding was the identification of digital green processes as a key dimension of the model. This category covered ecological production and ecological logistics and emphasized clean production technologies, automated equipment, optimization of energy consumption, low-consumption machinery, process improvement, route optimization, low-consumption vehicles, and renewable energy systems. These results support the view that the environmental transformation of supply chains requires operational redesign rather than symbolic environmental commitments. Previous studies have shown that green production practices, process innovation, and environmental capabilities improve operational, economic, and environmental performance (Bayat & Behnia, 2020; Fang & Zhang, 2018; Gholami & Nazari, 2018). The present study extends this logic by positioning digitalization as the mechanism through which green processes become more intelligent, measurable, and adaptive. This interpretation is compatible with recent research showing that Industry 4.0 technologies, including IoT, big data analytics, cyber-physical systems, and artificial intelligence, can improve green performance by enabling real-time monitoring,

operational optimization, and evidence-based decision-making (Hu et al., 2022; Lerman et al., 2022; Li et al., 2023). In the power industry, where energy use, process reliability, and equipment precision are critical, digital green processes can reduce waste, improve process quality, and increase sustainability without weakening operational efficiency.

The third major result concerned data-driven waste management, including primary and secondary waste management. The final model emphasized waste segregation, collection and transportation, wastewater recycling forecasting, recycling and reuse of components and equipment, and the existence of markets for recycled materials. This finding confirms that waste management in the power industry should move beyond end-of-pipe disposal and become a data-supported, value-generating process. Earlier studies have emphasized the importance of recycling, reuse, waste reduction, reverse logistics, and closed-loop supply chain design in improving environmental performance and reducing resource dependency (Meditati et al., 2018; Manavalan & Jayakrishna, 2019; Mohammadi et al., 2019). The present findings are also consistent with studies showing that green supply chain management practices can significantly improve environmental performance, especially when waste reduction and resource recovery are embedded into routine operational systems (Dzikriansyah et al., 2023; Gelmez et al., 2024). In the power equipment sector, component reuse, material recovery, and recycling are particularly important because products often contain metals, electrical components, and industrial materials with both economic value and environmental risk. The exclusion of some waste-related indicators during the Delphi rounds does not weaken the importance of waste management; rather, it shows that experts prioritized indicators that were more feasible and contextually relevant for companies operating in Mazandaran Province.

The fourth dimension, AI-based green marketing, shows that smart green supply chains are not confined to production and procurement but also include market communication, ecological information exchange, and customer-oriented sustainability practices. The final model included indicators such as continuous customer communication about green product characteristics, transparent information about environmental benefits, introduction of innovative green products and services, green advertising, responding to customer demands for environmental compliance, and the use of specialized foreign and European consultants in the green domain. This finding aligns with studies demonstrating that green market orientation and green

supply chain capabilities can improve environmental and organizational performance (Borazon et al., 2022; Haiyun et al., 2021). It also supports the argument that customer expectations, market knowledge, and environmental communication are important drivers of green innovation and sustainable value creation (Alreahi et al., 2023; Harouache et al., 2021). In the power industry, green marketing may not operate in the same way as consumer-product markets; however, transparent ecological information, environmental certification, technical credibility, and communication with institutional buyers can strengthen organizational legitimacy and support entry into more demanding domestic and international markets. Therefore, AI-based green marketing should be interpreted as an intelligent interface between environmental capability and market acceptance.

The fifth and most integrative result was smart ecological governance, which included top management actions and government policies. The confirmed indicators showed that managerial support systems, accurate understanding of green supply chain importance among senior and middle managers, selection of knowledgeable managers, strategic goal-setting, tax incentives, low-interest loans, Tavanir-related green production regulations, green filters for imported raw materials, and continuous monitoring and evaluation are essential for successful implementation. This finding strongly aligns with studies that identify managerial commitment, organizational strategy, regulatory pressure, stakeholder demands, and government support as central drivers of green supply chain management (Delshad et al., 2022; Rajabpour & Afkhami-Ardakani, 2020; Vanalle et al., 2017; Yassin et al., 2022). It also supports Iranian studies showing that the establishment of green supply chain management depends on a combination of internal organizational readiness and external institutional conditions (Alipour et al., 2022; Andalib & Shams, 2020; Taryan et al., 2022; Zarei et al., 2024). In infrastructure industries, governance is especially important because firms cannot independently create all the conditions needed for green transformation. Regulations, standards, financial incentives, supplier requirements, and monitoring mechanisms are needed to reduce uncertainty and encourage investment in green and digital technologies.

Overall, the findings indicate that smart green supply chain management in the power industry is formed through the interaction of environmental design, digital operations, circular waste systems, intelligent market communication, and governance mechanisms. This integrated interpretation

is consistent with recent literature arguing that the next stage of supply chain sustainability depends on the convergence of green supply chain management and digital transformation (Dhumras & Bajaj, 2024; Karimi et al., 2023; Rashid et al., 2025). The present study contributes to this literature by showing that Industry 4.0 technologies should not be treated as external tools added to green supply chains; rather, they should be embedded within each dimension of the green supply chain model. IoT, artificial intelligence, blockchain, big data analytics, and cloud systems can support ecological design, supplier traceability, production optimization, logistics efficiency, waste forecasting, green communication, and regulatory monitoring. This conclusion is also supported by studies emphasizing that digital transformation can mediate and strengthen the relationship between organizational capabilities and green supply chain development (Lerman et al., 2022; Li et al., 2023). Therefore, the proposed model offers a conceptual pathway for transforming reactive environmental management into proactive smart sustainability in the power industry.

From a theoretical perspective, the study confirms that green supply chain management should be understood as a dynamic and systemic capability rather than a set of disconnected environmental practices. The five-category structure of the model corresponds with prior frameworks that have identified product design, procurement, production, logistics, waste management, marketing, and governance as recurring components of green supply chain management (Fang & Zhang, 2018; Maditati et al., 2018; Tseng et al., 2019). However, the present study advances these frameworks by integrating Industry 4.0 and smart sustainability into the conceptual structure of the model. This integration is particularly important because many earlier studies were developed before the full expansion of digital transformation in supply chain management. By synthesizing previous studies and validating the results through Delphi analysis, the study provides a localized and technologically updated framework for the power equipment industry. It also complements sectoral studies in construction, municipalities, petrochemicals, automotive industries, and energy by demonstrating that each industry requires its own implementation model based on technological intensity, regulatory structure, and supply chain complexity (Esmaili et al., 2020; Fouladvand et al., 2023; Sabzi & Karimi, 2018; Yazdian & Radaei, 2019).

The practical meaning of the findings is that companies in the power transmission and distribution equipment sector should adopt a staged but integrated approach to smart green

supply chain implementation. The results suggest that isolated investments in clean production or recycling will not be sufficient unless they are connected to green design, supplier management, digital monitoring, market communication, and governance support. For example, ecological product design requires supplier collaboration; supplier collaboration requires regulatory and managerial support; waste management requires data infrastructure; and green marketing requires credible information generated from actual environmental performance. This interdependence supports the argument that green supply chain capability is built through alignment among strategy, technology, process, and stakeholder management (Borazon et al., 2022; Ding et al., 2018; Haiyun et al., 2021). Accordingly, the model developed in this study can guide power industry managers in identifying priority areas for intervention and can help policymakers design supportive instruments for accelerating the transition to smart sustainability.

The limitations of this study should be acknowledged. First, although the meta-synthesis method enabled systematic integration of previous findings, the final model depends on the quality, scope, and availability of the selected studies. Second, the Delphi stage was conducted with experts from companies producing equipment and facilities for power transmission and distribution in Mazandaran Province; therefore, the localized results may not fully represent all regions of Iran or all segments of the national power industry. Third, the study developed and refined a conceptual model but did not empirically test the causal relationships among the identified components. Fourth, some indicators were removed during the Delphi process because of contextual relevance or feasibility considerations, but these indicators may still be important in other industrial, regional, or technological contexts.

Future research should quantitatively test the proposed smart green supply chain model using structural equation modeling, partial least squares, or other causal modeling techniques. Such studies can examine the relationships among smart ecological design, digital green processes, data-driven waste management, AI-based green marketing, smart ecological governance, and outcomes such as environmental performance, operational efficiency, competitive advantage, and energy consumption intensity. Future studies should also compare the model across different provinces, energy subsectors, and industrial contexts to determine which indicators are generalizable and which are context-specific. In addition, longitudinal research

can investigate how firms move from conventional green supply chain practices toward smart sustainability over time and what organizational capabilities are required at each stage of this transition.

Further research should also apply multi-criteria decision-making methods to prioritize the identified indicators and determine their relative importance for strategic implementation. Techniques such as fuzzy AHP, fuzzy TOPSIS, DEMATEL, ANP, BWM, and WASPAS can be used to rank the components, identify causal relationships, and develop implementation roadmaps for power industry firms. Future studies may also investigate the role of specific Industry 4.0 technologies separately, including IoT-based supplier monitoring, blockchain-based material traceability, AI-based waste forecasting, big-data-driven energy optimization, and cloud-based regulatory dashboards. Such research would deepen understanding of how each technology contributes to environmental, operational, and economic performance in smart green supply chains.

For practice, managers of power equipment and transmission/distribution companies should treat smart green supply chain management as a strategic transformation program rather than an environmental compliance project. They should begin by assessing current practices in product design, procurement, production, logistics, waste management, marketing, and governance, and then develop an integrated roadmap for digital and ecological improvement. Priority should be given to supplier environmental assessment, energy-efficient product design, clean production technologies, digital waste tracking, transparent environmental reporting, and training programs for managers and employees. Firms should also invest in digital infrastructure, including IoT sensors, data analytics platforms, traceability systems, and integrated dashboards that allow managers to monitor sustainability indicators in real time.

At the policy and industry level, regulatory bodies and supporting institutions should create practical incentives for firms that invest in smart green supply chain capabilities. These incentives may include tax benefits, low-interest loans, green import filters for raw materials, technical standards for power equipment, continuous environmental monitoring, and specialized guidelines for green production. Industry associations and large public-sector buyers can also accelerate adoption by requiring environmental documentation, supplier sustainability evidence, and measurable performance indicators in procurement

contracts. In addition, collaboration with universities, technology firms, and international consultants can help companies access specialized knowledge and reduce the implementation risks associated with digital green transformation.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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