

Article

Circular Economy Practices, Green Value Co-Creation, and Sustainable Supply Chain Integration: The Moderating Role of Digital Maturity

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Abstract

This research investigates how CE initiatives, interpreted as manifestations of corporate social responsibility, shape green value co-creation, green collaborative culture, and green supply chain integration across both supplier and customer contexts. The proposed conceptual framework also explores the possibility that digital maturity can moderate these interrelations, based on signaling theory. Empirical results, obtained through PLS SEM and NCA on a data sample of 493 suppliers and customers, confirm that CE practices have a significant positive impact on green value co-creation, which, in turn, influences the green collaborative behavior of the actors and the integration of the supply chain. The moderating role of digital maturity is reinforced in the linkages between green value co-creation, collaboration, and integration. Thereby, their effectiveness is strengthened. This study adds to the literature by proposing an integrative relationship between CE practices and outcomes within the supply chain dyad, offering a rare empirical study of relationships between suppliers and organizations in an emerging economy, and shedding light on the boundary condition of digital maturity within these relationships. The results have significant implications for managers seeking to maximize their sustainability performance through circular practices and digital capabilities.

Keywords: circular economy; green supply chain integration; green value co-creation; digital maturity

1. Introduction

The ongoing discourse on sustainability is reshaping organizations' perceptions of their social, economic, and environmental responsibilities [1]. Central to this transition is corporate social responsibility (CSR), which has evolved into a strategic instrument for harmonizing diverse stakeholder interests and fostering ethical business conduct that addresses contemporary societal demands. In the realm of the circular economy (CE), CE itself is increasingly viewed as a tangible expression of CSR, particularly as it addresses mounting social and regulatory pressures. With its core logic rooted in reducing, reusing, and regenerating resources, the CE model not only boosts operational performance but also unlocks fresh pathways for co-creating value across multiple supply chain participants [2].

Existing research has established that the CE plays a pivotal role in reshaping production systems, with primary emphasis on its advantages in resource optimization, waste minimization, and sustainability-driven innovation [3]. Simultaneously, it helps organizations reposition themselves strategically. This has primarily facilitated and transformed



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the relationship among stakeholders and business models [4]. However, the existing literature has mainly focused on internal organizational factors, with little attention paid to the relational dimension of the supplier–customer relationship, particularly regarding green value co-creation and sustainable supply chain integration. While an increasing number of studies discuss CE as a manifestation of CSR, empirical evidence on the impact of CE on green value co-creation remains limited, particularly regarding the upstream–downstream interactions that enable sustainable supply chain integration [5]. Moreover, previous studies have not provided a full picture of how these processes function. This creates a significant research gap in understanding the relationship between different degrees of interdependence between suppliers and customers and responsible adoption and the co-creation of value [6].

Supplier and customer relationships play an important role in organizations to attain long-term competitive advantage and environmental sustainability. The importance of signaling theory in this context lies in its explanation of how organizations convey trustworthy information to stakeholders about their intentions regarding the environment and social issues. In this way, organizations minimize information distance and develop trust, thereby enhancing closer cooperation between partners [7]. Organizations can demonstrate their genuine commitment to sustainability by adopting consistent, reliable practices, including CE initiatives. This motivates suppliers and customers to be actively involved, thereby encouraging green value co-creation and long-term integration in the supply chain [8].

Despite the growing body of literature examining the CE as a manifestation of CSR [9], limited empirical evidence exists regarding its influence on green value co-creation, particularly among upstream and downstream partners [10] that support sustainable supply chain integration. Moreover, prior research has not yet fully explained the mediation factors underlying these relationships holistically, nor has it adequately examined how varying degrees of dependence in supplier and customer relationships affect the implementation of responsible practices and joint value development. Furthermore, the role of digital maturity in moderating these relationships remains underexplored, particularly in emerging-economy contexts where technological infrastructure varies significantly [11]. This study addresses these critical gaps by proposing an integrative framework that examines how CE practices, as a strategic embodiment of CSR, foster green value co-creation and, in turn, enable green collaborative practices and sustainable supply chain integration, while considering the boundary condition of digital maturity in these relationships.

To address these gaps, the current study analyzes how CE, as a viable application of CSR initiatives, fosters the creation of green values among suppliers and customers. Furthermore, it examines how this co-creation will result in green collaborative activities and contribute to the sustainability of supply chain integration. Based on signaling theory, this research examines the relationships between CE practices and green value co-creation, and between green collaborative practices and sustainable supply chain integration, as well as the conditional moderating effect of digital maturity on these relationships. By doing so, the study clarifies not only whether CE practices support sustainable supply chain outcomes but also how and under what digital conditions these effects occur. The constructs in the proposed framework are based on the prior literature. Green value co-creation and green collaborative practices are integrated, serving as relational mechanisms that enable sustainability practices to produce shared outcomes [12,13]. Incorporated as a moderator is digital maturity, which affects the visibility and credibility of sustainability signals.

In the current study, a dual-source data collection approach is employed to minimize potential bias due to common method variance. It gathers data from suppliers and customers, who are significant stakeholders in the supply chain, and incorporates their views into its research. The dataset comprises 493 supplier–customer relationships from organizations across Pakistan’s industrial and service sectors. Hypotheses were tested using structural equation modeling. The study’s primary contribution to existing scholarship lies in its empirical validation of an integrated theoretical model that positions CE practices as a strategic CSR instrument. In doing so, it advances current understanding of how CE initiatives shape green value co-creation and foster collaborative dynamics within supply chain networks. Theoretically, the research enriches the extant literature by providing a nuanced articulation of CE’s role in embedding sustainability principles throughout supply chain operations [14]. This occurs particularly via the co-creation of green value and the perceived credibility of sustainability-oriented signals [15]. Placing co-creation as a relationship mechanism and as a boundary condition, the model identifies significant dynamics that have not been previously considered in the study of the CE and supply chain sustainability. This is a multilevel relational view that extends beyond the traditional focus on operational or practice-based views of circularity and demonstrates that its effects can be determined by how stakeholders socially construct and assess the validity of environmental signals, an area that remains underexplored despite its growing significance [16].

This research makes an empirical contribution by testing the suggested integrative framework through dual-source supplier and customer data. It provides high-quality quantitative data on customers’ perceptions, evaluations, and reactions to the Suppliers’ circular initiatives. The methodology provides a more detailed understanding of how circular practices contribute to joint sustainability outcomes, addressing a long-standing research gap. This is especially important because most previous studies have focused on individual firms or respondents.

Section 2 of this research contributes to the theoretical standpoint and hypothesis development; Section 3 represents the methodological procedures; Section 4 represents the results and discussion; Sections 5 and 6 represent the implications and conclusions of the research.

2. Theoretical Perspective, Hypothesis Development, and Model Building

2.1. Green Relationships: Towards CE

CE has become one of the key methods for transforming consumption and production systems by reducing the environmental footprint, optimizing resources, and restructuring value creation and generation through regenerative and restorative processes [17]. It is shifting away from linear traditional models to systems that store and reuse resources over time. Practices such as material reuse, resource regeneration, eco-design, and reverse logistics aim to close resource loops and help supply chains move toward more sustainable and circular forms [18]. This shift has become more of a systemic change requiring integrated efforts across actors, sectors, and value chain stages [19]. In this transformation, green relationships are paramount to achieving sustainability by fostering partnerships among supply chain members. Such relations are not limited to transactions but entail long-term relationships with a strong emphasis on environmental responsibility, resource optimization, and value co-creation [20]. Inter-organizational cooperation enables firms to transfer knowledge, minimize waste, coordinate operational processes towards circularity, and jointly create innovative solutions to facilitate circularity [21]. Such collaboration, enhanced by trust, information sharing, and digital technologies, can overcome barriers to circular adoption and create sustainable competitive advantage by enabling

continuous learning and more effective resource management. While project-based collaboration formats are well-established mechanisms for organizing interorganizational cooperation, our focus centers on the ongoing relational dynamics of trust, transparency, and co-creation that enable sustained implementation of the circular economy across supply chain relationships.

2.2. Signaling Theory

Signaling theory, proposed by [22], describes how organizations decrease information asymmetry in uncertain environments. Signals in business relations, particularly in B2B relationships, are expressed in various ways, including sustainability certifications, environmental friendliness, customer feedback, and financial performance. Their success is determined by their credibility, by whether they meet stakeholders' expectations [23]. While formal certifications provide baseline legitimacy in developed economies, they remain insufficient for building deep collaborative value chains as they are static signals that lack the relational and interpretative richness required for sustained trust and co-creation; signaling theory addresses this gap by illuminating the dynamic processes through which firms transmit and validate sustainability intentions in ongoing B2B relationships. Recent research points out that stakeholders do not assess signals individually. Instead, they take into account various signals and interpret them through complex cognitive processes despite certain signals possibly appearing inconsistent [24]. Such understanding relies not only on the perceived authenticity of the signals but also on how they implement the values and objectives of the stakeholders to whom they are directed [8]. Building on this perspective, CE practices meet the conditions for quality signals as they require high cost and effort, making them difficult for low-capability firms to credibly mimic; thus, accumulating CE capabilities reinforces signal authenticity and strengthens partner trust [25,26].

The signaling theory provides an important lens for understanding how companies can communicate their circular economy efforts to their customers and supply chain. Environmentally friendly practice signals may stimulate green value co-creation by fostering trust and commitment, thereby promoting collaboration and more complete implementation of green supply chain practices [8]. These signals, however, may be affected by a firm's degree of digital maturity, as they determine the clarity and transparency of a firm's sustainability. Increased digital maturity facilitates data sharing, traceability, and communication, enabling stakeholders to better interpret these signals. Conversely, lower digital maturity can diminish the visibility and transparency of such information, thereby reducing its influence on stakeholders' perceptions. Thus, signaling theory is twofold: first, it sheds light on the relationships among CE, customer green collaborative behaviors, and green supply chain integration; second, it points to the role of digital maturity as a moderating variable that strengthens these links [27]. We acknowledge the potential risk of signal mimicry, in which low-quality firms may imitate sustainability signals without genuine commitment; however, our framework mitigates this concern by emphasizing digital maturity as a transparency-enhancing mechanism and by using dyadic data, in which partners validate the credibility of signals through their collaborative responses.

2.3. Ce and Green Value Co-Creation

Green value co-creation is a framework for the collective integration of organizations and their various stakeholders, with their respective assets, expertise, and operating strengths. This synergy aims to deliver results that yield simultaneous gains to the environment and the economy [28]. Unlike traditional, firm-based methods of value

creation, this model is social and collaborative. Consumers, suppliers, and external partners are participants in this paradigm and actively contribute to the design and implementation of the eco-friendly offering and business operations [29]. Moreover, modern studies of CE indicate a gradual trend towards decentralized value generation processes. In such configurations, multiple actors collaborate to develop restorative solutions and synchronize their contributions within a multi-layered circular system to ensure system-wide sustainability.

The central concept of the CE is co-creation, as circularity requires coordinated exchanges and operations among different organizations, involving the transfer of information, the mutual adjustment of processes, and the integration of diverse competencies throughout the product life cycle [30]. The current studies reveal that green value co-creation occurs when organizations co-develop solutions based on restorative practices, reduced waste production, or reuse and remanufacturing initiatives, integrating environmental considerations across all design stages, from product conception to end-of-life [31]. Taken together, the results indicate that the cooperative nature of CE creates the necessary environment for the growth of green value co-creation between suppliers and their buyers [32]. Therefore, we proposed the following hypothesis:

H1. *CE has a strong influence on Green Value Co-Creation.*

2.4. Green Value Co-Creation and Green Collaborative

Green value co-creation is an interactive process in which suppliers, clients, and strategic partners across the supply chain collaborate to foster eco-innovation, drawing on their integrated resources and shared expertise [29]. This collaborative model is key to realizing environmental and financial gains, as it instills a sense of shared responsibility and ensures that all parties are well-coordinated to work towards sustainability [30]. Green collaborative practices, as opposed to the general process of co-creation, are the functional implementation of these alliances. These are the individual, combined actions and concerted efforts that transform collaborative intent into quantifiable outcomes. Some examples are shared capital investments in environmentally friendly technologies, joint projects to reduce environmental footprints, and the creation of shared knowledge-exchange systems [33]. There is also evidence that adopting such practices delivers meaningful operational benefits, including better demand forecasting, reduced inventory shortages, increased transparency and financial health, and greater environmental integrity of the supply chain.

Signaling theory provides a valuable additional prism through which green collaborative practices serve as a strategic signal to network partners. Through such collaborative efforts, organizations demonstrate a reasonable degree of sustainability that fosters beneficial attitudes, builds mutual trust, and drives enhanced collaboration throughout the entire supply chain [23]. The interaction between green value co-creation and practice-based collaborative programs, in turn, is inherent in the alignment of stakeholder interests and the successful implementation of systemic sustainability agendas [34]. Thus, we defined the following hypothesis:

H2. *Green Value Co-Creation is positively associated with the green collaborative.*

2.5. Green Value Co-Creation and Green Supply Chain Integration

GSCI is a form of strategic alignment between an organization and its network partners, which is aimed at aligning internal operations with external partnerships. The focal point of this integration is efficiency optimization and increased customer value, while ensuring a triple-bottom-line approach with economic, social, and environmental bene-

fits [35]. GSCI reduces an organization's ecological footprint while amplifying its positive environmental impact by systematically embedding environmental considerations into supply chain design, operational oversight, and process optimization [36]. Internally, this kind of integration fosters consumer-driven innovation. On the outside, it helps engage more with regulatory bodies, suppliers, and the end market, thus expanding the impact and effectiveness of sustainable initiatives on the entire value chain [35].

In this conceptual architecture, green supply chain integration goes beyond mere process coordination; it requires highly collaborative interactions with stakeholders at the extremes of the spectrum. Green value co-creation is a catalyst that manifests at this intersection. It enriches the power of GSCI by organizing mutual forces among companies and their affiliates to generate sustainable value [28]. While the direct relationships among co-creation, collaboration, and integration may seem intuitive, their simultaneous empirical testing within a dyadic supplier–customer framework, particularly in an emerging economy, is critical, as prior research has not comprehensively validated these interconnected mechanisms. In this light, signaling theory would help explain the logic behind such interactions: these joint efforts are strategic signals. These messages can rebrand and entrench sustainable compatibility across the entire supply chain network by fostering transparency and genuine intent to be environmental stewards [7].

In B2B business, active engagement with both suppliers and customers is a major motivator for adopting environmentally friendly projects. Such extensive collaboration not only accelerates sustainable innovation and cost-cutting measures but also strengthens the organization's competitive positioning in the marketplace [37]. Therefore, we develop the below hypothesis:

H3. *Green Value Co-Creation is positively associated with the green supply chain integration.*

2.6. Green Collaborative and Green Supply Chain Integration

GSCI requires the strategic alignment of business functions and inter-organizational relationships to diminish costs, facilitate value creation, and entrench sustainability within the supply chain network. This incorporation is also supported by green-oriented inter-organizational cooperation to create synergies and enhance coordination. This configuration helps achieve a balance among environmental, social, and economic performance [35]. Further, green collaborative practices are critical in addressing complex socio-environmental challenges. These practices are more than just sustainable; they provide tangible benefits, including improved demand estimation, increased profits, and transparency [33]. Collaboration is a means of enhancing supply chain performance by creating shared value, allowing companies to keep pace with increasing sustainability demands and to foster stronger supplier and customer relationships. However, the success of these collaborative initiatives can sometimes be dependent on institutional distance.

Moreover, collaborations build bridges to GSCI by optimizing operations and enriching communication to attain the environmental goals. Singling theory also demonstrates that collaborative actions work as a strategic indicator that mitigates information asymmetry. These signals reduce uncertainty and build trust between suppliers and customers to attain GSCI [7]. When coordinated with existing industry standards and environmental demands, these collective efforts lead to greater innovation, efficiency, and co-creation of value [38]. Thus, we proposed the following hypothesis:

H4. *Green Collaborative positively influences green supply chain integration.*

2.7. Moderating Mechanism of Digital Maturity

Digital maturity in the supply chain industry is the multifaceted ability of an organization to employ sophisticated digital processes to organize complex manufacturing and logistical operations [39]. The notion of digital maturity is presented as a critical moderator that determines the effectiveness with which green collaborative practices, namely, the upstream suppliers and downstream customers, can be translated into full GSCI. For these firms, high digital maturity becomes a precondition for continued innovation performance and competition [40]. Nevertheless, the technology gap has been a challenge for many supply chains in the developing world, where their ability to integrate green efforts with suppliers is limited by limited access to advanced technological infrastructure and constrained organizational resource bases.

However, digital maturity is not simply about acquiring new equipment, but a fundamental adjustment to the unceasing technological transformation [41]. Organizations that attain higher levels of digital maturity have a unique opportunity to leverage these technologies across their business architecture to deliver operational efficiency, innovation, and greater market competitiveness [42]. This maturity in a B2B supply chain serves as the digital glue between a supplier and its partners. Signaling theory to create the trust and transparency required to minimize information asymmetry between the B2B partners. Although these practices are meant to deliver a complete GSCI move towards collaborative purpose, structural alignment is strictly dependent on the level of digital maturity, not merely the uptake of such technologies as big data or cloud computing, but the ability to institutionalize them into its main workflows. Within the realm of green manufacturing, the lack of digital maturity creates significant operational gaps, hindering the realization of shared ecological objectives within integrated systems and the latter effects. Digital maturity can achieve this by closing the gap between partnership and performance and enabling collaborative green initiatives to deliver a robust, competitively advantaged, and fully integrated green supply chain. Therefore, we present the following hypotheses:

H5a. *Digital maturity moderates the association between green value co-creation and green collaborative.*

H5b. *Digital maturity moderates the association between green value co-creation and green supply chain integration.*

Figure 1 represents the conceptual framework of this research.

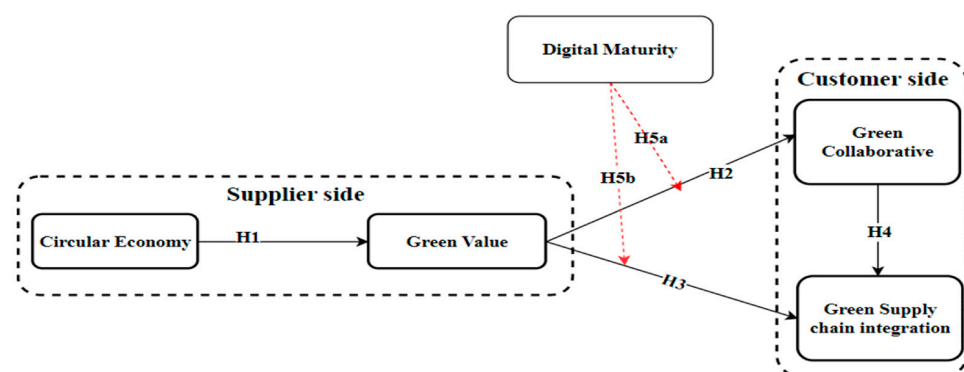


Figure 1. Conceptual framework.

3. Research Methodology

3.1. Selection of Context

The choice of an appropriate methodology is a complex yet essential step in research on supply chain and information systems because it defines how raw data is converted

into actionable insights. In accordance with the principles of quantitative research, this study aimed to identify the most effective data collection tools and to determine the specific parameters for data collection. A survey-based study using structured questionnaires was considered the most suitable. This technique is especially useful in studying the behavior of large groups of users. To evaluate the proposed research model, the survey instrument was organized into three distinct sections, beginning with an introductory segment that outlined the study's objectives and affirmed the confidentiality of participant responses, a demographic section, and a concluding section that incorporated the main variables that were assessed as per the technology and supply chain integration.

The present study aims to examine industrial and service firms operating in Pakistan, a theoretically important and internationally applicable context for studying the dynamics of the dyadic CE. To ensure the sample's relevance to this study's objectives, firms were selected grounded on several inclusion criteria. First, the firms had to be operating in the industrial or service sectors and have identifiable supply chain activities, such as procurement, production, logistics, distribution, customer relationship management, or supplier coordination. Second, the firms were required to have direct or indirect involvement in sustainability-related practices, including resource efficiency, waste reduction, recycling, CE initiatives, green collaboration, or environmentally responsible supply chain activities. Third, only firms with active supplier–customer interactions were considered suitable, as the study examines CE practices and green value creation on the supplier side, and green collaboration and green supply chain integration on the customer side. Finally, firms with fewer than 50 employees or without relevant supply chain-related operations were excluded to confirm that respondents could provide expressive information about organizational-level practices.

As a developing economy with growing global sustainability requirements, Pakistan provides a distinct institutional setting in which the introduction of circular practices is only starting to shift the informal routines of the supply chain to formal supply chain strategies. The country's industrial environment, characterized by high-tech SMEs and a high rate of long-term, trust-based relationships between suppliers and customers, provides an ideal setting for leveraging relational processes, including co-creation and credibility signaling. While Pakistan occupies a strategically significant position within worldwide manufacturing domains, including textiles and surgical equipment, the area remains conspicuously under-examined in empirical studies adopting a dyadic perspective on circular economy dynamics. The investigation on such dyads, therefore, provides important insights into the co-construction of circularity in emerging markets and can contribute to a more comprehensive understanding of global green supply chain transitions. Data collection began in July 2025 through personally and professional networks from both suppliers and customers. In October, a preliminary collection of 367 responses was obtained. A more practical methodology was adopted to ensure the findings were reliable; it was followed by a phone call and an on-site visit. Using convenience sampling method, 539 responses were obtained by December 2025. Convenience sampling was used because no comprehensive, publicly available sampling frame exists for identifying firms and respondents engaged in CE practices, green collaboration, and supply chain integration in Pakistan. Moreover, the study required access to knowledgeable respondents from both the supplier and customer sides, which made probability-based sampling difficult. Therefore, respondents were approached through personal and professional networks, followed by telephone follow-ups and site visits to improve participation and data quality.

Respondents were selected based on their professional relevance to the constructs examined in this study. The target respondents included individuals working in management, operations, administration, finance, procurement, logistics, sustainability, supply chain, and

related functional areas. These respondents were considered appropriate because they were expected to possess knowledge of their firms' CE practices, green value creation, customer collaboration, supply chain integration, and digital capabilities. Therefore, the respondent selection process focused not merely on general employees but on individuals whose roles provided sufficient exposure to organizational processes and supply chain decision-making. Responses from individuals who were not associated with the target sectors, had limited organizational knowledge, or provided incomplete information were excluded during the screening process. After a preliminary screening process that eliminated 47 incomplete or ineligible responses, a conclusive sample of 493 valid responses was determined. This sample size exceeds the minimum required for Structural Equation Modeling [43] and is sufficient to conduct advanced analyses, such as NCA, to address the study's research questions. To address non-response bias, we compared key characteristics of early and late respondents using the extrapolation method and found no significant differences ($p > 0.05$), indicating that non-response bias is not a serious concern.

To capture insights from both sides of the supply chain, the measurement of constructs adopted a dyadic approach. CE practices and green value co-creation were evaluated from the supplier's standpoint, whereas GSCI and green collaboration were measured from the customer's perspective. We clarify that our design is dual-source rather than formally dyadic; data were collected from both supplier and customer representatives to capture complementary perspectives on the supply chain relationship, though individual observations were not linked through explicit matched-pair identifiers.

3.2. Measures

The questions were also streamlined linguistically to make the survey easy to comprehend and to be culturally acceptable. This study employed a 5-point Likert scale, in line with [44], which is among the most reliable and widely used measurement tools in academic research. The answers were given on a scale of 1 (Strongly Disagree) to 5 (Strongly Agree). Quantitative research must use well-designed questionnaires, as they provide a strong foundation for data analysis, but they require considerable preparation to be effective and valid. The study aimed to obtain more specific information and higher-quality data by making the survey shorter. A 5-point scale, as noted by [45], is especially effective in online surveys because it captures a wider range of opinions and reduces the risk of response bias.

The CE scale constructs were adapted from the prior study by [46]. Under these constructs, we assess the CE engagement and practices, raw material, input, and output. Discriminant validity confirmed that CE is statistically distinct from other constructs through HTMT and Fornell-Larcker tests. The scale's internal consistency was also verified, achieving a high Cronbach's alpha of 0.832. We measure green value co-creation using three-item scales adapted from prior research and tailored to the current research purpose [28]. The value of Cronbach's alpha is 0.828, which is above the threshold of reliability and consistency. Considering that the Green collaborative items scale was adapted from [38], and the scale's internal consistency is also proven with the Cronbach's alpha value of 0.876. GSCI was measured using a six-item scale adapted from [35]. Lastly, digital maturity was assessed using a 5-item scale [47], and its reliability and validity were evaluated using Cronbach's alpha, which was 0.903. For questions, please visit Appendix A.

3.3. Respondents Demographic Information

The demographic composition of the respondents was reported to establish the suitability and credibility of the sample. Since the study relies on survey responses to measure organizational-level constructs, information on respondents' gender, age, education, pro-

professional background, functional area, and firm size helps assess whether participants had sufficient experience and knowledge to complete the questionnaire. In particular, education level, job function, and professional background are important because the constructs examined in this study, circular economy, green value co-creation, green collaboration, green supply chain integration, and digital maturity require respondents who are familiar with organizational practices and supply chain-related activities. Therefore, the demographic profile was included not merely for description, but to demonstrate the appropriateness and reliability of the respondent group. The survey used closed-ended questions to collect demographic data, including gender, age, education, and professional background. The demographic characteristics of the respondents are as follows. Of the 493 respondents, 321 were male, and 172 were female, indicating that males comprised the majority (around 65.1%). The respondents were fairly diverse in age, with 66 over 25 years old, 100 between 23 and 30 years of age, 117 aged 31–35 years, and the largest number, 209. This implies that a high percentage of the respondents were highly mature and experienced in their professions.

In terms of academic qualifications, the results show that 247 respondents held postgraduate degrees, 193 held undergraduate degrees, and 53 had other educational backgrounds, indicating that the respondents were fairly well educated. Organization-wise, the allocation by firm size shows that 186 respondents represented firms with 50–100 employees, 153 represented firms with 101–150 employees, and 154 represented firms with 150+ employees, which is a good representation of small, medium, and large enterprises. The respondents were distributed across the major functional areas by professional expertise, with the largest numbers in management (130), operations (147), administration (81), finance (79), and other positions (56). This wide dispersion shows that the data were gathered from individuals with an in-depth understanding of the organizational processes. Lastly, the sample was selected from both the supplier and the customer with about 55% and 45%, respectively, to represent the supply chain.

3.4. Common Method Bias and Full Collinearity

CMB is evaluated in this research as the difference attributable to the measurement method rather than to the underlying constructs the measures aim to assess. This problem typically occurs when the information is gleaned from a single source at a single point in time, which may threaten the validity of the research findings. To address this issue, the study used the single-factor test proposed by Harman, which is a common method in social sciences research [48]. SPSS version 26 was used to analyze it. The findings show that the former factor explains 38.301 percent of the variance. According to the literature, CMB is not considered a severe problem when the explained variance of a single factor falls below 50 percent [49]. Thus, the results indicate that CMB does not prevail in this research.

Statistically, Harman's single-factor test was initially conducted as a preliminary diagnostic procedure. However, given the limitations of Harman's test in detecting common method variance, an additional full collinearity assessment was performed in line with contemporary PLS-SEM recommendations. The full collinearity VIF values for the latent constructs ranged. Moreover, the outer VIF ranges from 1.633 to 4.042, which is below the 5 thresholds, indicating it is acceptable. Also, the Inner VIF ranges from 1.929 to 2.365, well below the threshold of 3.3. These results indicate that pathological collinearity and common method bias are unlikely to pose a serious threat to the validity of the findings. Therefore, the results provide sufficient confidence that common method bias is not a major concern in this study.

4. Results

4.1. Analytical Procedure and Research Algorithm

To improve methodological transparency and reproducibility, this study employed a sequential analytical procedure that combined PLS-SEM and Necessary Condition Analysis (NCA). First, the research problem and conceptual framework were developed based on circular economy practices, green value co-creation, green collaboration, green supply chain integration, digital maturity, and signaling theory. Second, measurement items were adapted from previously validated scales and refined according to the study context. Third, data were collected from supplier and customer representatives operating in Pakistan's industrial and service sectors. Fourth, the dataset was screened by removing incomplete and ineligible responses, resulting in 493 valid responses. Fifth, the measurement model was assessed using Smart-PLS v4 by examining factor loadings, Cronbach's alpha, composite reliability, average variance extracted, and discriminant validity. Sixth, the structural model was evaluated using PLS-SEM to test the direct, mediating, and moderating relationships proposed in the conceptual framework. Seventh, a necessary condition analysis was performed to ascertain whether the chosen antecedent factors are indispensable for attaining elevated levels of green value co-creation, green collaboration, and green supply chain integration. Subsequently, the results derived from both PLS-SEM and NCA were examined conjointly, yielding complementary sufficiency-oriented and necessity-oriented perspectives on the advancement of sustainable supply chain performance.

4.2. Measurement Model Assessment

The findings indicate high internal consistency, with Cronbach's alpha ranging from 0.828 to 0.903. to determine composite reliability (CR) ranged from 0.888 to 0.931, and the average variance extracted (AVE) ranged from 0.664 to 0.743. The values above the established criteria of 0.70 for Cronbach's alpha and CR, and 0.50 for AVE, indicate that reliability and convergent validity are satisfactory [43]. Moreover, the analysis results indicate sufficient inter-item reliability, as all factor loadings exceed the recommended value of 0.70 [50]. These results indicate that the measurement model has no issues with reliability or convergent validity. Table 1 presents the detailed item loadings for each construct that meet the acceptable criteria.

Table 1. Measurement model results.

Constructs	Loadings	Variables Name	Cronbach's Alpha	CR	AVE
CE1	0.823	Circular Economy	0.832	0.888	0.664
CE2	0.786				
CE3	0.851				
CE4	0.799				
GV1	0.843	Green Value	0.828	0.897	0.743
GV2	0.882				
GV3	0.861				
GC1	0.792	Green Collaborative	0.876	0.916	0.731
GC2	0.845				
GC3	0.900				
GC4	0.879				

Table 1. Cont.

Constructs	Loadings	Variables Name	Cronbach's Alpha	CR	AVE
GSCI1	0.815	Green Supply Chain Integration	0.911	0.931	0.695
GSCI2	0.804				
GSCI3	0.871				
GSCI4	0.893				
GSCI5	0.870				
GSCI6	0.737				
DM1	0.870	Digital Maturity	0.903	0.928	0.722
DM2	0.875				
DM3	0.774				
DM4	0.857				
DM5	0.867				

Discriminant validity is used to test the empirical distinctness of constructs in relation to each other. This research assessed the usefulness of the HTMT ratio, defined as <0.85 [43]. Table 2 presents the HTMT results; all values lie below the threshold, indicating that this research has no issues with discriminant validity [51].

Table 2. Heterotrait–Monotrait Ratio (HTMT).

Constructs	CE	DM	GC	GSCMI	GV
CE					
DM	0.822				
GC	0.805	0.754			
GSCI	0.690	0.710	0.658		
GV	0.822	0.795	0.727	0.668	

4.3. Path Model Assessment

After discussing the measurement model, the research evaluates the proposed hypothesis using path analysis. Each proposed construct is positively associated with the endogenous variables. SmartPLS v4 was employed to test the study's hypotheses. The results, including effect size (β coefficients) and statistical significance (t -values and p -values), are presented in Table 3 and Figure 2. The results indicate that CE is positively associated with the GV ($\beta = 0.694$, $t = 35.699$, $p < 0.000$). Similarly, GV also shows a positive relationship with the GC ($\beta = 0.298$, $T = 7.250$, and $p < 0.000$). Additionally, H3 and H4 meet the threshold and show a significant positive association.

Table 3. Direct and indirect path coefficient.

Hypothesis	Relationships	β Value	Mean	SD	t Value	F^2	p Values	Decision
H1	CE $\rightarrow$ GV	0.694	0.695	0.019	35.669	0.927	0.000	Accepted
H2	GV $\rightarrow$ GC	0.298	0.299	0.041	7.250	0.092	0.000	Accepted
H3	GV $\rightarrow$ GSCI	0.190	0.191	0.049	3.901	0.034	0.000	Accepted
H4	GC $\rightarrow$ GSCI	0.247	0.246	0.046	5.413	0.059	0.000	Accepted
Meditation Path								
H6a	CE $\rightarrow$ GV $\rightarrow$ GC	0.206	0.208	0.030	6.933		0.000	Accepted
H6b	CE $\rightarrow$ GV $\rightarrow$ GSCI	0.131	0.133	0.034	3.828		0.000	Accepted

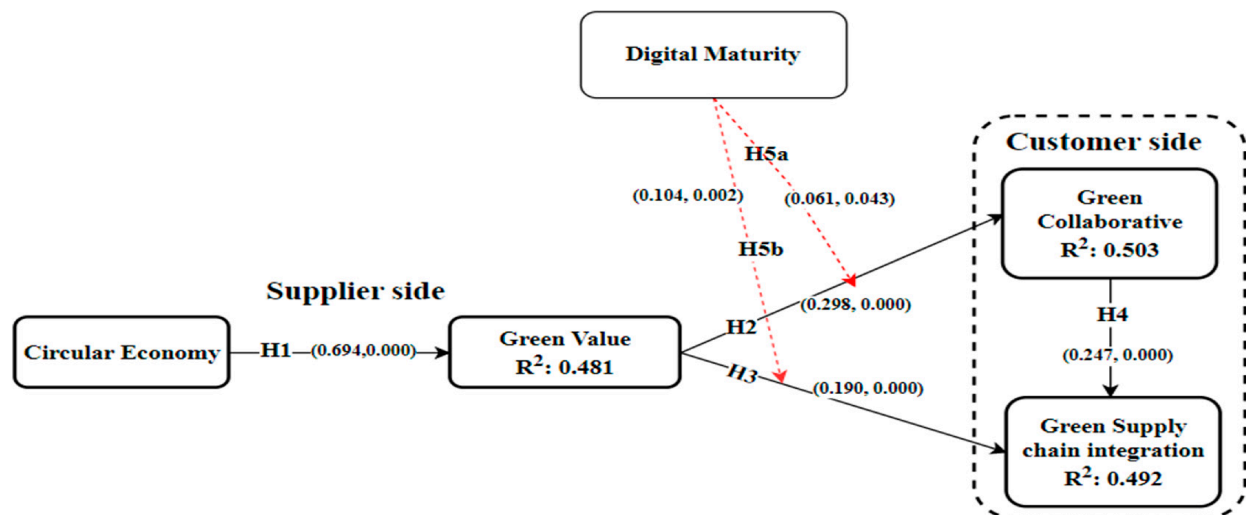


Figure 2. Structural model.

The mediation analysis was conducted to examine whether green value co-creation mediates the effect of CE practices on green collaboration and GSCI. As displayed in Table 3, the indirect effect of CE on GC through GV was positive and statistically significant ($\beta = 0.206$, $t = 6.933$, $p < 0.001$), supporting H6a. This finding indicates that CE practices enhance GC not only directly through sustainability-oriented practices, but also indirectly by creating GV with supply chain partners. In other words, when firms adopt CE practices, these practices help develop a shared environmental value, which in turn encourages stronger green collaboration.

Similarly, the indirect effect of CE on GSCI through GV was also positive and statistically significant ($\beta = 0.131$, $t = 3.828$, $p < 0.001$), supporting H6b. This result suggests that GV acts as an important relational mechanism through which circular economy practices are translated into GSCI. However, the size of the indirect effect for H6b is smaller than that for H6a, indicating that GV has a stronger mediating role in promoting green collaboration than in directly enhancing GSCI. Overall, these findings confirm that GV serves as a meaningful intermediary mechanism linking CE practices with downstream green supply chain outcomes.

The moderation analysis was conducted to examine whether DM strengthens the relationship between GV and the two outcome variables, namely GC and GSCI. As shown in Table 4 and Figure 3, the $DM \times GV$ interaction effect on GC was positive and statistically significant ($\beta = 0.061$, $t = 2.025$, $p = 0.043$), supporting H5a. However, the f^2 value for this interaction was 0.007, which is below the recommended small-effect threshold of 0.02. This indicates that although the moderating effect is statistically significant, its practical magnitude is negligible. Therefore, the moderating role of DM in the relationship between GV and GC should be interpreted cautiously. Similarly, the interaction effect of $DM \times GV$ on GSCI was positive and statistically significant ($\beta = 0.104$, $t = 3.046$, $p = 0.002$), supporting H5b. The corresponding f^2 value was 0.020, which reaches the threshold for a small effect. This suggests that DM has a statistically significant but practically small moderating influence on the relationship between GV and GSCI. Overall, these findings indicate that DM plays a positive boundary role; however, the small effect sizes suggest that its moderating influence is limited rather than strong. This interpretation is consistent with PLS-SEM guidelines, where f^2 values of 0.02, 0.15, and 0.35 represent small, medium, and large effects, respectively [52,53]. The simple slope analysis further confirms the moderating role of DM. The relationship between GV and GC is stronger when DM is high, as the slope increases from

0.474 under low DM to 0.718 under high DM. Similarly, the relationship between GV and GSCI becomes stronger under high DM, with the slope increasing from 0.172 to 0.588. These results indicate that DM strengthens the positive effects of GV on both GC and GSCI; however, considering the small f^2 values, the practical magnitude of these moderation effects should be interpreted cautiously.

Table 4. Moderation path.

Hypothesis	Relationships	β Value	Mean	SD	t Value	F^2	p Values	Decision
H5a	$DM \times GV \rightarrow GC$	0.061	0.060	0.030	2.025	0.007	0.043	Accepted
H5b	$DM \times GV \rightarrow GSCI$	0.104	0.103	0.034	3.046	0.020	0.002	Accepted

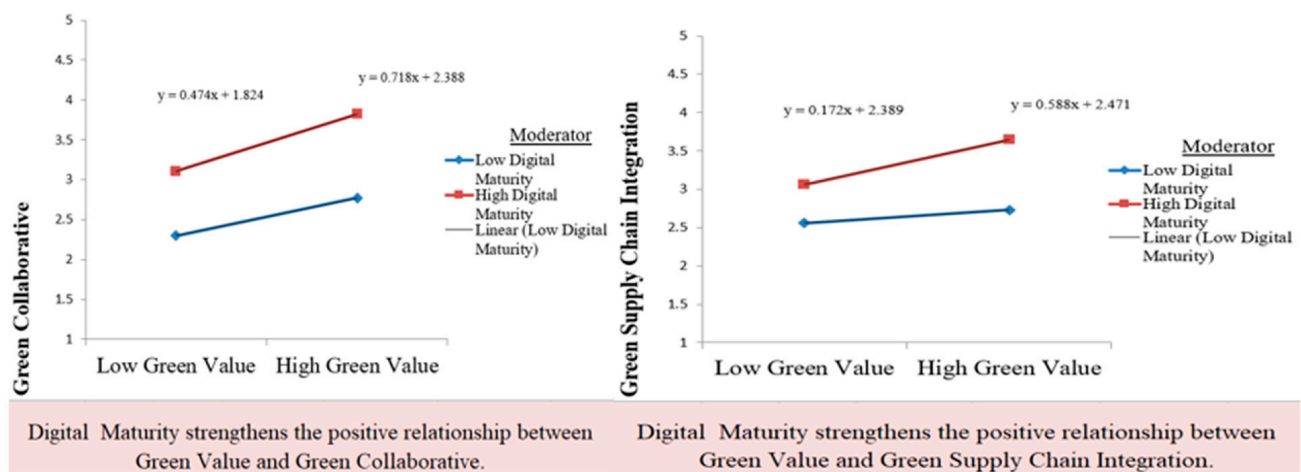


Figure 3. Moderation Figure of Green Collaborative and Green supply chain integration.

The f^2 effect size was examined to determine the practical contribution of each exogenous construct to the corresponding endogenous construct. Following the conventional guidelines, f^2 values of 0.02, 0.15, and 0.35 represent small, medium, and large effects, respectively, while values below 0.02 indicate negligible practical effects. The f^2 effect size was used to evaluate the practical contribution of each exogenous construct to the corresponding endogenous construct. Following [52] guidelines, which are commonly applied in PLS-SEM studies, f^2 values of 0.02, 0.15, and 0.35 represent small, medium, and large effects, respectively, while values below 0.02 indicate negligible practical effects [52,53]. As reported in Tables 3 and 4, CE had a large effect on GV ($f^2 = 0.927$), indicating that CE practices make a substantial practical contribution to explaining green value. GV had small effects on GC ($f^2 = 0.092$) and GSCI ($f^2 = 0.034$), while GC also had a small effect on GSCI ($f^2 = 0.059$). For the moderation paths, the interaction effect of $DM \times GV$ on GC showed a negligible effect size ($f^2 = 0.007$), whereas the interaction effect of $DM \times GV$ on GSCI reached the small-effect threshold ($f^2 = 0.020$). These findings indicate that the model contains one large effect, several small effects, and one negligible moderation effect; therefore, the statistically significant paths should be interpreted together with their practical effect sizes.

In addition to effect sizes, model fit was assessed using the standardized root mean square residual (SRMR). The estimated model SRMR value was 0.080, which is at the commonly recommended threshold of 0.08. Therefore, the model fit can be considered acceptable, although the value should be interpreted cautiously and together with other PLS-SEM quality indicators such as R^2 , Q^2 , f^2 , and collinearity diagnostics [54,55]. Overall, these additional diagnostics strengthen the structural model assessment by providing evidence of both practical significance and acceptable model fit beyond path coefficients, t -values, and p -values alone.

4.4. Construct Cross-Validated Redundancy

The predictive power was tested via blindfolding. Assess the model predictive performance [56], the Stone-Geisser Q^2 value was used. A Q^2 value above zero [57] means that the model possesses reasonable predictive relevance. Moreover, R^2 was used to assess the model strength. The comprehensive findings are presented in Table 5, which indicates the extent of variation in the dependent variables attributable to the independent variables.

Table 5. Predictive relevance.

Constructs	SSO	SSE	Q^2	R^2
GC	1972.000	1259.541	0.361	0.503
GSCI	2958.000	1973.680	0.333	0.492
GV	1479.000	962.064	0.350	0.481

4.5. Importance-Performance Map Analysis (IPMA)

The IPMA results indicate that the most significant construct affecting GSCI is DM, followed by GV and GC, with CE being the least important. GV is the best-performing, with DM performance being good [58,59]. Nevertheless, the level of performance of GC and CE is somewhat lower. This suggests that enhanced GC and CE could yield high returns in EP. Therefore, companies must focus on these spheres to achieve general efficiency and sustainability. Moreover, Table 6 and Figure 4 present the IPMA results.

Table 6. Importance-Performance Map Analysis (IPMA).

Constructs	Importance	Performance
CE	0.182	48.608
DM	0.467	52.181
GC	0.247	45.372
GV	0.263	53.510
Average	0.290	49.918

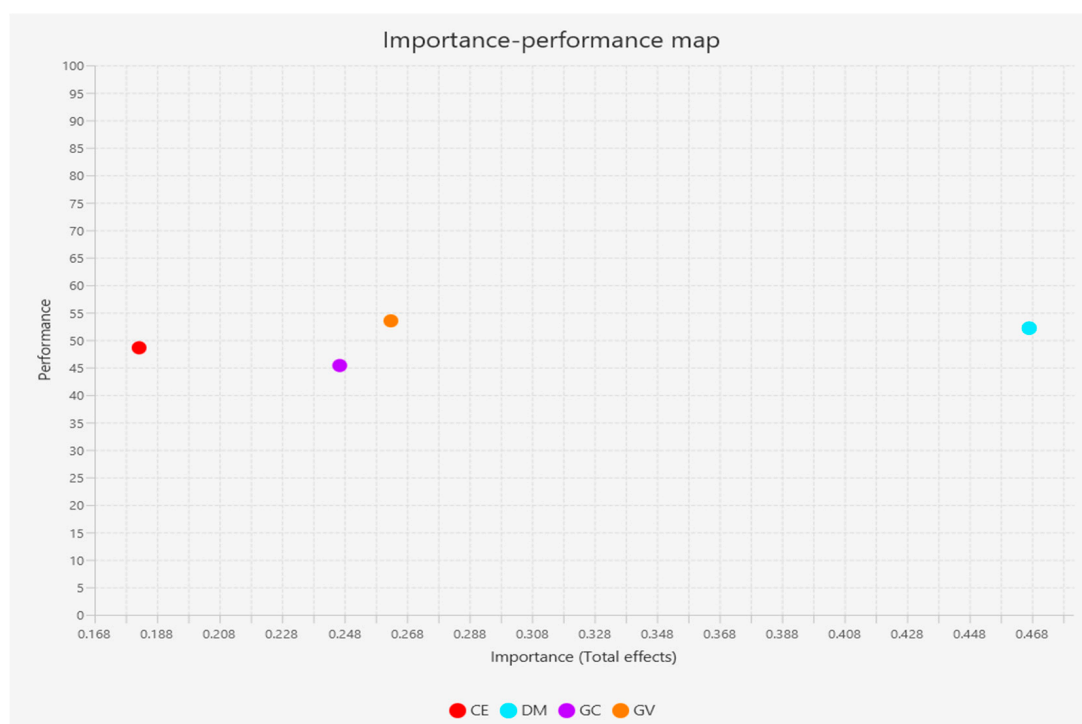


Figure 4. Importance-performance map.

4.6. NCA Model Results

Three evaluation criteria based on the framework proposed by [60] were used to identify the required conditions. To begin with, there is a solid theoretical basis for the anticipated relationships among the predictor variables: CE, Digital Maturity, Green Collaboration, Green Value Co-Creation, and GSCI. Second, the conditions have non-zero effect sizes, confirming that they are relevant and necessary. Third, permutation tests were used to assess statistical significance and reduce type I errors, and were evaluated using p -values at standard significance levels (e.g., $p < 0.05$).

The results of the analysis were performed with the help of latent variables based on PLS-SEM, which makes it possible to interpret the NCA results Cartesian. The method used was the Ceiling Regression-Free Disposal Hull (CR-FDH), as it is suitable for both continuous and discrete data [61]. This method revealed both locations of dense observations and places with limited data. The statistical significance of the effect sizes was tested using a permutation test on 493 random samples [60]. As shown in Table 7, various conditions are required for Green Supply Chain Integration. Digital Maturity has the largest effect size (0.217), then Green Value Co-Creation (0.161), Circular Economy (0.156), and Green Collaboration (0.120). Report that all effect sizes are moderate and within the necessary range ($0.1 \leq d < 0.3$), indicating that all conditions are significant contributors to the desired outcome.

Table 7. NCA effect size.

Conditions	Green Supply Chain Integration		
	CE-FDH (d)	CR-FDH	
		(d)	C-Accuracy (95%)
Circular Economy	0.172	0.156	0.038
Digital Maturity	0.209	0.217	0.065
Green Collaborative	0.118	0.120	0.042
Green Value Co-Creation	0.180	0.161	0.046

Together, the bottleneck analysis and NCA ceiling line charts depict the minimum levels of Circular Economy, Digital Maturity, Green Collaboration, and Green Value Co-Creation (GV) required to attain higher degrees of Green Supply Chain Integration. The findings suggest that at low percentiles, most conditions are not binding (NN), and that DM is an early condition, with GV and CE emerging at middle performance levels. With the increase in the desired outcome (more than 60–70 percent), all conditions, DM, and GV become increasingly necessary, and the effects of bottlenecks become stronger. These findings are also supported by the ceiling line graphs, which show empty spaces that attest to the necessity relationships. In general, the findings indicate that achieving higher integration levels is possible only through the joint enhancement of all the conditions, specifically Digital Maturity and Green Value Co-Creation. Table 8 and Figure 5 represent the results.

Table 8. Bottleneck analysis.

Percentile	CE	DM	GC	GV
Bottleneck CE-FDH				
0%	NN	NN	NN	NN
10%	NN	1.179	NN	NN
20%	NN	1.251	NN	NN
30%	NN	1.251	NN	NN
40%	NN	1.533	NN	1.263

Table 8. Cont.

Percentile	CE	DM	GC	GV
50%	1.312	1.533	NN	1.263
60%	1.446	1.533	1.589	1.737
70%	2.000	2.000	1.589	2.000
80%	2.625	3.000	1.589	2.958
90%	3.242	3.000	2.335	2.958
100%	3.688	3.858	3.925	4.000

Bottleneck CR-FDH				
Percentile	CE	DM	GC	GV
0%	NN	NN	NN	NN
10%	NN	NN	NN	NN
20%	NN	NN	NN	NN
30%	NN	1.109	NN	NN
40%	NN	1.432	NN	NN
50%	NN	1.755	NN	1.009
60%	1.429	2.078	NN	1.521
70%	1.971	2.401	1.594	2.033
80%	2.513	2.724	2.200	2.545
90%	3.055	3.047	2.806	3.057
100%	3.597	3.370	3.412	3.569

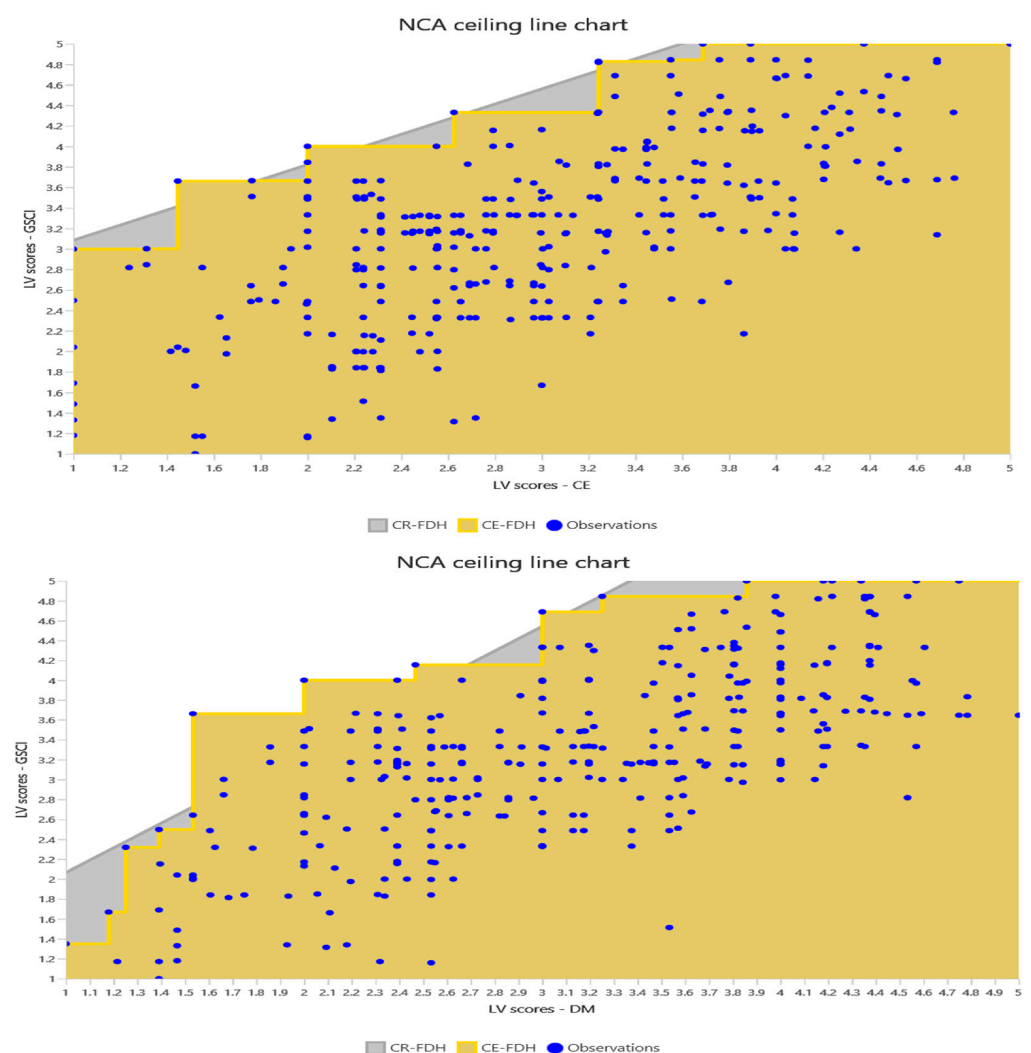


Figure 5. Cont.

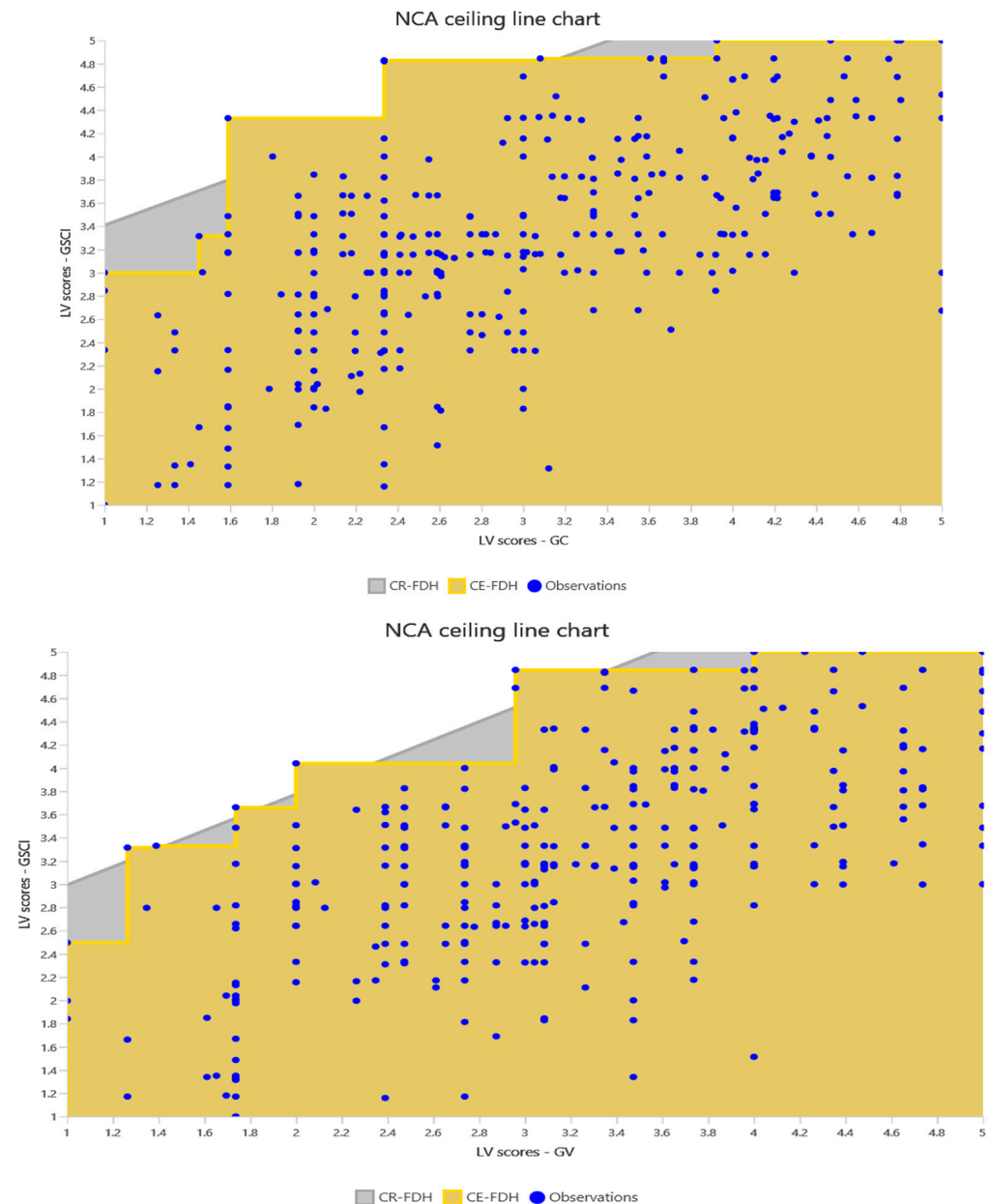


Figure 5. NCA scatter plot of GC, DM, CE, and GV.

5. Discussion

This paper examines the mechanisms behind how the CE leads to green collaborative practices and green supply chain integration. In particular, it analyzes how the concept of green value co-creation can mediate these relationships, with an additional emphasis on the moderating effect of digital maturity. By combining these variables, the research offers more detailed insight into how CE initiatives can be transformed into more sustainable cooperation and supply chain integration.

The findings of this study support the view that the transition toward CE practices serves as a key driver of sustainable inter-organizational relationships. Specifically, our results show that CE practices significantly enhance green value co-creation between suppliers and customers. This aligns with and extends previous studies that highlight the role of CE in fostering collaboration, transparency, and shared environmental responsibility [2,62]. While earlier research has mainly emphasized internal benefits or single-firm perspectives, this study demonstrates the relational impact of CE practices across dyadic supplier–customer interactions.

These findings strongly support Hypothesis 1, which posits that the CE is positively and strongly associated with green value co-creation. This observation aligns with previous theoretical arguments that CE practices, including resource regeneration, material reuse, waste minimization, and fostering an environment conducive to interorganizational cooperation [18]. Beyond its technical and operational ramifications, the CE serves as a strategic enabler, facilitating the joint generation of environmental and social value while aligning stakeholder objectives around shared sustainability targets [2]. The signaling theory suggests that CE practices serve as credible evidence of a firm's environmental commitment, helping to alleviate information asymmetry and motivating partners to participate in green value co-creation [7,8]. But these signals are not effective unless they are believed to be authentic. The current study contributes to the literature by providing empirical evidence on the dyadic relationship between suppliers and customers about green value co-creation in developing nations, where authenticity can be successfully implemented.

Hypothesis 2 is also supported, stating that green value co-creation is positively related to green collaborative practices. In particular, green value co-creation, evaluated by suppliers rather than customers, manifested as visible collaborative efforts through the customer lens, including green vendor certification packages, investment in supplier environmental efforts, and ongoing joint improvement. This is consistent with previous studies, which have highlighted the role of green value co-creation in knowledge exchange and use of synergistic capabilities as well as in the collaborative development of new environmentally oriented solutions [63]. In addition, through active participation in co-creative processes, stakeholders can create reinforcing operational and relational benefits, thereby enhancing adaptive capacity and maintaining innovative output in the long term [38]. According to signaling theory, green value co-creation is a powerful relational signal of a firm's sustainability stance. This is a signal that fosters trust and enhances the work that can be done within supply chain partnerships [7,34]. This study contributes to the literature by providing empirical evidence from an emerging economy on the successful transformation of green value co-creation into meaningful collaborative practices in dyadic supplier–customer relationships.

Moreover, the findings substantiate Hypothesis 3, which suggests that the co-creation of green values is a very strong positive influence on GSCI. In particular, green value co-creation that suppliers experience in their relations with customers helps further integrate environmentally oriented practices throughout the entire supply chain in the eyes of its customers. This observation highlights the need to coordinate activities with strategic partners to support sustainable initiatives. This alignment enhances the coherence, consistency, and effectiveness of the environmental strategies deployed throughout the supply chain. The observation aligns with other studies that co-creation is essential to the application of sustainable processes. In particular, co-creation improves competitive performance, promotes customer-centric innovation and widens the scope and depth of sustainability efforts [36]. In B2B settings, proactive collaboration between actors in the supply chain has been found to facilitate the implementation of ecological solutions, reducing business costs and improving positioning [37]. The study contributes to the existing literature by providing dyadic evidence that green value co-creation is an important mechanism for realizing GSCI in the context of an emerging economy.

The findings also confirm Hypothesis 4, indicating a strong positive correlation between green collaboration and green supply chain integration. For the customer, integration across the supply chain is enhanced by green collaborative practices, typified by trust between the customer and the organization, open communication, and risk sharing. This observation indicates that effective working relationships with suppliers facilitate more

successful, coordinated execution of environmental programs. In line with previous research, teamwork grounded in trust and transparency is essential for achieving operational success in implementing sustainability practices [38]. Furthermore, green collaborative practices can improve forecasting, increase accuracy, reduce the risk of stockouts, and diminish operational inefficiencies, thereby enhancing the overall resilience of the supply chain [33]. This study uses dyadic evidence to show that green collaborative practices serve as a critical link between relational practices and green supply chain integration in an emerging market context.

Additionally, this research examined the moderating influence of digital maturity on two key linkages: the relationship between green value co-creation and green collaborative practices, and the relationship between green value co-creation and GSCI. Digital maturity is a measure of an organization's ability to use digital technologies efficiently, integrate data, and develop systems that improve decision-making and operational efficiency. In particular, the association between green value co-creation and green collaborative practices is stronger in situations with greater digital maturity than in those with lower digital maturity. The slope analysis indicates that although green value co-creation has a positive impact on collaborative practices in both cases, this impact is stronger when organizations have advanced digital capacity, enabling them to coordinate, share information, and communicate in real time. Although the moderation effects are statistically significant, their practical magnitude is limited; therefore, the role of digital maturity should be interpreted as a modest boundary condition rather than as strong evidence of moderation. This observation aligns with recent research emphasizing the enabling power of digital technologies to achieve sustainability in supply chains [37,39]. Building digital maturity enhances the credibility and visibility of sustainability signals, thereby increasing their impact on inter-organizational outcomes, according to a signaling theory perspective. Unlike other studies, this study empirically demonstrates this boundary condition, while acknowledging that its practical influence is limited in an emerging economy using dual-source supplier and customer data.

6. Research Implications, Limitations, and Future Prospects

6.1. Theoretical Implications

The present study offers multiple contributions to the extant scholarly discourse on CE, GSCM green value co-creation, and inter-organizational sustainability. First and foremost, by adopting a dual perspective on suppliers and customers, the study broadens the scope of research beyond studies that previously relied solely on single-level firm data. This research indicates that CE practices not only improve firms' internal operations but also signal trust and legitimacy among supply chain allies. By analyzing data drawn from both supplier and customer sources, this approach illuminates how clients perceive and legitimize their suppliers' shift toward circular strategies. This, in turn, facilitates a more granular investigation of the relational dynamics underpinning sustainable supply chain conduct [1]. Second, this research advances theoretical knowledge by positioning green value co-creation as a pivotal mechanism linking CE initiatives, collaborative practices, and supply chain integration. Whereas previous scholarship has predominantly framed co-creation as either an internal organizational process or a consumer-facing interaction [20], our dyadic evidence demonstrates that, in B2B environments, co-creation serves as a relational conduit linking suppliers' environmental strategies to customers' collaborative involvement. In doing so, the study broadens co-creation theory into the domain of interorganizational sustainability and highlights its relevance for both operational and relational performance indicators, including certification schemes, knowledge exchange, and integration efforts [64].

Third, by bringing in signaling theory, this study advances a more nuanced understanding of how environmental practices are signaled, understood, and validated beyond organizational borders. Our findings indicate that CE initiatives and co-creation endeavors function as both strategic and relational signals of legitimacy and trust among partnering firms, thereby facilitating integration. Concurrently, however, the results suggest that the efficacy of these signals is tempered by stakeholders' perceptions of authenticity and genuine value co-creation in nurturing co-opetition and integration. By doing so, this finding contributes to signaling theory by revealing the reputational costs of engaging in symbolic or inconsistent sustainability practices. Finally, beyond this specific contribution, the study develops an empirical finding that sustainable commitment does not unconditionally correlate with collaboration or integration, but may depend on co-creation when integrating sustainability and legitimation, contingent on the perceived authenticity of sustainability signals in the outdoor supply chain. This discovery contributes to a more complex, relational view of how to integrate supply chains; it shows that trust, transparency, and authenticity are critical conditions that must be in place before environmental strategies can be enacted interorganizational in a coordinated and verifiable way.

These contributions, when considered together, move the CE beyond the mere technical-operational dimension and transform it into an interactive and communicative catalyst that can stimulate co-creation, collaboration, and integration within supply chain networks. The study offers insights from both supplier and customer perspectives, thereby contributing to theoretical discussions on the co-constitution of sustainability across organizational boundaries.

6.2. Managerial Implications

Practically, the results highlight the need to put circular economy concepts into action: into real, measurable sustainability actions. Managers are encouraged to establish formal transparency and traceability systems, such as independent audits and digital platforms with product/tracking features, to strengthen the credibility of environmental commitments. Organizations are also encouraged to create cross-functional teams spanning procurement, logistics, and product development, and to ensure all functions agree on circularity goals. The team should focus on specific metrics, such as material recovery rate and regenerative design goals, and continuously monitor them using digital tools, including IoT-enabled sensors and data-driven dashboards.

Interorganizational managers need to encourage structured, formalized collaborations, such as joint training programs, real-time environmental data-sharing platforms, and formal agreements for the joint development of products or processes. These mechanisms foster the creation of authentic, enduring sustainability partnerships based on mutual trust. Utilizing such governance instruments and collaborative routines can allow organizations to underpin their sustainability signals with greater authenticity, higher stakeholder confidence, and multidimensional market competitiveness in increasingly discerning markets where transparency is paramount.

6.3. Limitations and Future Prospective

This research makes several theoretical and managerial contributions, each offering interesting directions for future research.

The first limitation was that we tested a proposed model in a specific empirical context, thereby limiting the generalizability of our findings across different industrial domains or locations. This may substantially impact CE practices and green value co-creation, as cultural norms, market maturity, and supply chain structures are likely to

diverge. Therefore, further studies are recommended to test and expand this research across diverse sectors, including manufacturing, logistics, retail, and leading technology-based industries, in multiple countries/regions. Cross-cultural comparative studies would be especially valuable for analyzing how contextual factors, such as collectivism vs. individualism, uncertainty avoidance, and environmental regulatory stringency, shape the relational dynamics observed here. This study used convenience sampling; the findings should be interpreted with caution regarding statistical representativeness. The results are most applicable to firms and respondents with supply chain involvement and sustainability-related awareness in the Pakistani context. Future research should use probability-based sampling, stratified sampling, or larger cross-sectoral datasets to improve representativeness and enhance the generalizability of the findings.

Second, future studies should ensure that participating firms have comparable supply chain structures and sufficient involvement in circular economy or sustainability-related practices. Third, respondent selection should remain role-specific, focusing on individuals with direct knowledge of supply chain operations, environmental practices, collaboration, and digital capabilities. Fourth, researchers should consider firm size, sectoral characteristics, digital readiness, regulatory pressure, and the maturity of sustainability practices, as these factors may influence both the interpretation of circular economy signals and the effectiveness of green value co-creation. Finally, if the methodology is extended to a fully dyadic or multi-tier supply chain design, supplier and customer responses should be formally matched through identifiable relationship pairs to improve relational validity and allow stronger conclusions about inter-firm interactions.

Furthermore, this study used a cross-sectional research design, collecting data at a single point in time. Although that approach captures some meaningful aspects of the interconnections among CE practices, co-creation, collaboration, and supply chain integration, it cannot reflect the fact that these relations are essentially dynamic and continuous. Trust, legitimacy, and collective routines are built gradually across multiple cycles of action, feedback, and adjustment. To overcome this shortcoming, future studies should use longitudinal designs (e.g., multi-wave surveys, panel data analyses, and prolonged case studies) to capture the genesis, progress, and decline of green value co-creation in different stages of buyer-supplier relationships. This research mainly examined dyadic relations between direct suppliers and clients, without accounting for potential network effects. Many supply chains are influenced not only by immediate partners in sustainability practices and interpretations, but also by second-tier suppliers, industry consortia, certification bodies, and even competitors. Future research could use a network lens to explore the diffusion of circular-economy signals across multiple tiers and how co-creation practices in one dyad are echoed in laterally connected relationships. For exploring these interdependencies, social network analysis or agent-based modeling may be especially fruitful methodological approaches. Lastly, we used digital maturity as a moderating variable; future research is recommended to use power asymmetry and prior relational trust to strengthen or weaken the observed effects, thus enriching the existing practical and theoretical knowledge paradigm.

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Institutional Review Board Statement: This study is waived for ethical review as it involved a non-clinical, minimal-risk survey of adult respondents, the survey did not involve patients, minors, vulnerable groups, clinical procedures, biological samples, medical records, or sensitive, identifiable personal information by Fujian Agriculture and Forestry University.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: Data will be made available on request.

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Conflicts of Interest: The authors declare that they have no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

Appendix A. Questionnaire

Construct	Questionnaire Item	Reference
Circular Economy	This organization implements practices aimed at reducing waste and improving resource efficiency.	Centobelli et al. [46]
	Materials are reused, recycled, or recovered wherever possible in organizational operations.	
	Operational processes are designed to minimize material consumption and environmental impact.	
	Circular practices are applied in the management of raw materials, inputs, and outputs.	
Green Value Co-Creation	This organization engages with supply chain partners to create environmental value.	Borah et al. (2023) [28]
	Green practices contribute to the creation of shared value with suppliers or customers.	
	Sustainability-related activities generate mutual environmental and business benefits for supply chain partners.	
Green Collaborative	This organization collaborates with supply chain partners to improve environmental performance.	Mena and Schoenherr (2023) [38]
	Environmental information is shared with relevant suppliers or customers.	
	Environmentally friendly solutions are jointly developed with supply chain partners.	
	Cooperation with supply chain partners supports the achievement of green objectives.	
Green Supply Chain Integration	Environmental considerations are integrated into supply chain activities.	(Bai et al. 2024) [35]
	Green supply chain practices are coordinated with relevant supply chain partners.	

Construct	Questionnaire Item	Reference
Green Supply Chain Integration	Sustainability goals are aligned with suppliers and customers.	(Bai et al. 2024) [35]
	Environmental criteria are considered in supply chain decision-making.	
	Suppliers and customers are involved in improving green supply chain performance.	
	Green practices are integrated into procurement, operations, logistics, or distribution activities.	
Digital Maturity	Digital technologies are used to support supply chain decision-making.	(Jie et al., 2025) [47]
	The organization has digital capabilities that support operational and environmental performance.	
	Digital systems are used to collect, process, and share supply chain information.	
	Digital infrastructure supports coordination with suppliers and customers.	
	Digital tools are used to monitor, manage, and improve sustainability-related activities.	

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