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Optimizing circular economy practices through blockchain technology in reverse logistics

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Abstract

Purpose – This study aims to examine blockchain technology's transformative potential in advancing circular economy practices, specifically focusing on reverse logistics. This study investigates how supply chains may become more transparent, traceable and trustworthy by using blockchain's secure and unchangeable data exchange capabilities.

Design/methodology/approach – This study identifies and validates important circular economy behaviors using the Delphi technique and Grey Influential Analysis (GIA). GIA analysis helps in identifying the most influential circular economy practices through blockchain technology in reverse logistics.

Findings – This study highlighted the GIA technique, indicating that a more holistic conceptual framework is necessary to capture the complex interactions between technological, organizational and social factors for enabling blockchain-enabled reverse logistics. This study further contributes to the literature that is growing daily on the role of "emerging technologies" in the management of sustainable supply chains by uniquely placing in context how blockchain addresses the key challenges related to reverse logistics and the implementation of the circular economy.

Research limitations/implications – This study's limitations include potential bias in practice assessment, relying on literature and expert opinions.

Practical implications – This research will be very helpful and valuable to organizations that intend or seek to use blockchain technology in their circular economy and reverse logistics operations. The ranking of practices allows the business world to have a prioritized roadmap on which they can focus their efforts and resources on the most influential applications of blockchain technology.

Originality/value – Blockchain is a groundbreaking, innovative technology with immense potential to revolutionize industries. Past research has explored the benefits and challenges of blockchain implementation in various industries, but very little in the circular economy, specifically in reverse logistics. This creates a gap in research regarding systematically classifying and ranking the importance of blockchain in reverse logistics. The research would bridge the gap in identifying the gap and recognizing the prominent principles using the Delphi technique and GIA techniques.

Keywords Circular economy, Reverse logistics, Blockchain technology, Delphi technique, Grey influential analysis

Paper type Research paper

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1. Introduction

Environmental concerns are driving the growth of the circular economy. This prioritizes recycling, repair and reuse of products above disposal to build a more sustainable future. For this shift, circular supply chains, covering both forward and reverse logistics, become crucial. Effective reverse logistics is efficient in product recovery, reuse and recycling. Also, implementing resilient systems is essential for the success of circular economy efforts (Mallick *et al.*, 2023). Reverse logistics refers to the activities required to collect used products from customers for reuse, repair, remanufacture, recycling or disposal. The definition of reverse logistics has changed and evolved over the years. Authors have defined reverse logistics in different ways. Murphy and Poist (2000) defined reverse logistics, mentioning the reverse flow of goods. Ellram *et al.* (2008) introduced the "environment" in the definition of reverse logistics. Rogers and Tibben-Lembke (2001) focus on the purpose of reverse logistics and provide a widely accepted definition that explains the process of organizing, carrying out and managing the economical and efficient movement of raw materials, inventory for in-process products, completed items and associated data from the point of consumption back to the point of origin to recover value or dispose of waste properly.

Researchers and practitioners have continually focused on the forward supply chains while neglecting the reverse flow (Montag, 2023). The forward supply chain now encompasses the reverse flow of products, extending from the point of consumption to the source (Ren *et al.*, 2023). Over time, reverse logistics has become essential for all organizations due to the growing demand for environmental concerns, legislation, corporate social responsibility and sustainable competitiveness. Although efficient reverse logistics offers environmental and economic advantages, their implementation is nevertheless limited by various problems identified by the researchers (Butt *et al.*, 2023). According to Chen *et al.* (2022), the efficient management, preservation, transportation and disposal of returned products are all cost-dependent. According to Ramanathan *et al.* (2023), involving multiple interested parties at various stages of the reverse supply chain may lead to delays and inefficiency. The regulatory framework for product disposal, recycling and returns is defined, which is a nightmare for the organization. Recent research has pointed out blockchain technology (BCT) capability to contribute toward achieving a circular economy and minimizing challenges involving reverse logistics (Sadeghi *et al.*, 2024). BCT provides secure data storage and control helpful in areas like financial inclusion, identity management, records retrieval and service dissemination for many sectors like services, banking, manufacturing, etc. which might be (Schuetz and Venkatesh, 2020). BCT supports the digital revolution and financial inclusion, aligning with India's goals of enhancing financial literacy and accessibility, especially in rural areas, with the help of initiatives like Unified Payments Interface (Kandpal, 2023). BCT helps in retail by establishing data integrity in the retail supply chain without intermediaries, and helps in lowering the transaction charges (Aslam *et al.*, 2021). BCT helps in the media and content industry; online on-demand streaming platforms such as iTunes, Gaana.com and Spotify use the BCT for content transactions, giving creators and consumers more choice and freedom (Hald and Kinra, 2019).

The intrinsic characteristics of blockchain, such as immutability and transparency, would improve the tracking and tracing of products throughout their life cycle and increase the overall reverse logistics process (Centobelli *et al.*, 2022). Besides, smart contracts developed with the facilitation of BCT enable automated procedures for waste recycling and reverse logistics that have the potential to reduce costs and enhance efficiency significantly (Bhuiyan and Akter, 2024). Sustainability practices were left to be streamlined by enabling better waste recycling and product returns on the BCT (Dabees *et al.*, 2023). Reverse logistics is complex, notable technologies like Internet of Things (IoT), artificial intelligence and blockchain revolutionize reverse logistics. Table 1 below compares the usage of these technologies in reverse logistics related to Traceability and Transparency, Efficiency and Cost Reduction and Consumer Engagement and Sustainability aspects. Blockchain is more focused on trust, security and transparency, but may have some regularity issues related to energy consumption, costs, etc.

This study provides practical insights by engaging industry experts to validate and rank blockchain-enabled practices. Ranking helps in providing a practical roadmap to organizations that are seeking sustainable transformation. Using the Delphi method and Grey Influential Analysis (GIA), this study provides a robust framework for decision-makers to enhance their capability of efficiently allocating resources to optimize the process of reverse logistics. Authors have identified BCT practices into three key constructs, namely, Traceability and Transparency, Efficiency and Cost Reduction and Consumer Engagement and Sustainability. It will provide a clear strategic roadmap for integrating blockchain into reverse logistics systems based on these key constructs. The study demonstrates blockchain's core characteristics like immutability, transparency and automation, which help in supporting the environmental and sustainability objectives of any organization. Organizations could align their technological advancement with circular economy imperatives.

This paper has been structured so that the integration of BCT with circular economy practices in reverse logistics is tackled systemically. Section 2 presents the state of the literature, indicating an important lacuna in the literature concerning the optimization of these practices. Section 3 describes the research methodology based on the Delphi Method and GIA to showcase complex relationships. Section 4 presents the result analysis and discussions. Section 5 focuses explicitly on the empirical validation by showing the practical implications of the findings. Section 6 deals with theoretical and practical implications by highlighting the strategic benefits of the research. Finally, Section 7 concludes the study by summarizing key insights and suggesting avenues for future research.

Table 1. Compares usage of blockchain, IoT and AI

Aspects	Blockchain	IOT	AI
Traceability and transparency	Immutable data storage ensures the traceability of returned goods (Bajar *et al.*, 2024)	Real-time tracking of products and conditions with the help of smart sensors (Mo *et al.*, 2022)	AI analyzes data patterns but may lack full transparency (Mukherjee *et al.*, 2024)
Efficiency and cost reduction	Automates verification of return orders and ensures claims can be a slowly due to consensus (Sengupta *et al.*, 2023)	Provides instant visibility, reducing delays and losses (Yu and Sun, 2024)	It helps in optimizing return routes and predicts failures (Butt *et al.*, 2024)
Consumer engagement and sustainability	Ensures claims and return processes that increase consumer trust. Prevents fraud in returns and controls order return failures, leading to sustainable solutions for reverse logistics (Sathiya *et al.*, 2023)	Supports real-time tracking but lacks direct engagement features. It helps in monitoring environmental impact (Albreem *et al.*, 2021)	Personalizes return policies and recommends exchanges. It helps in predicting demand for products and reduces waste (Shahidzadeh and Shokouhyar, 2024)

2. Literature review

This section focuses on major aspects like Traceability and Transparency, Efficiency and Cost Reduction, Consumer Engagement and Sustainability in BCT that have transformative potential in advancing circular economy practices, for reverse logistics.

2.1 Traceability and transparency

BCT tracks all stages of a product's life, from extracting raw materials by showing certifications and their origin, manufacturing with several parts and processes, distribution and tracking shipment information and points of sale to reverse logistics (Adomako and Tran, 2022). In that sense, BCT allows the tracking of all stages in the life cycle of a product and tracing by all stakeholders since, being immutable to changes after input, modifications cannot be done on previous blocks (da Silva *et al.*, 2025). It allows an object's status and position tracking in its reverse logistics flow; therefore, it offers better real-time visibility. BCT enables real-time insight into the mass of data collected through a product's life cycle (Bajar *et al.*, 2024). On the other hand, the immutability achieved by BCT with Merkle trees helps improve traceability and real-time visibility of products moving through every step of logistics. This, in turn, promotes circular economy initiatives and helps to optimize the reverse logistics operation (Wu, 2022). BCT secures product authenticity (Sathiya *et al.*, 2023). It creates an indelible record impervious to meddling from production to return. The cryptographic hashing and distributed ledgers guarantee the integrity of the data and enable verification that products that are returned or refurbished are genuine (Zhou and Liu, 2022).

The entire tracking of the lifecycle of products and reintroduction of products in the supply chain after refurbishing or recycling is recorded and stored in nodes in the BCT; this results in improved monitoring of the recycling process by end consumers. These tokens, the digital assets that are converted into waste or recycling actions, can be used to incentivize recycling, track material flow and facilitate transactions within the recycling ecosystem (Kouhizadeh *et al.*, 2023). BCT supports the circular economy by tracking product lifecycles. Recording processes like transportation, sorting, recycling and remanufacturing enable calculating energy consumption and environmental impact. This data contributes to comprehensive environmental reporting across supply chains (Yildizbasi, 2021). Performance measurement for a circular economy using BCT is effective for products and processes that have been institutionally established, such as standardization, regulatory or process frameworks. The regulatory compliance by authority of all implemented transactions from initiation to termination is recorded, leading to real-time monitoring and audit trails; these are verified to maintain compliance per various legislations (Kouhizadeh *et al.*, 2023). To adhere to this regularity framework, blockchain has to maintain every piece of information in a node that is immutable in nature which consumes high energy to maintain every transactional information. To store all the details, nodes will require large storage space, which makes the system slow, and the frequent mining of the information requires higher computational speed, which encompasses critical challenges for the scalability of the blockchain (Alghamdi *et al.*, 2024).

2.2 Efficiency and cost reduction

The decentralized nature of BCT fosters enhanced stakeholder engagement and information exchange throughout the supply chain (Madhani, 2022). This real-time data sharing on production processes, material procurement and design modifications facilitates more efficient product revisions and accelerated development cycles (Sengupta *et al.*, 2023). BCT's inherent security and transparency improve product traceability (Zhou and Liu, 2022). Early identification of potential issues with materials or components becomes possible, preventing delays and product recalls. Furthermore, BCT streamlines inventory management and reduces costs (Li *et al.*, 2023). Improved inventory tracking allows for optimized stock levels and reduced storage costs (Govindasamy and Antonidoss, 2022). Timely communication and fewer documents for BCT transactions lower administrative costs and allow the reallocation of resources toward product development (Pu and Lam, 2021).

Smart contracts surfaced in the mid-1990s as a means of regulating information flow, performing entire transaction history, handling commercial transactions and so forth (Wang *et al.*, 2019; Jabbar *et al.*, 2021). Smart contracts represent tremendous promise for reverse logistics owing to BCT security and contract enforcement capability (Mohanta *et al.*, 2019). The function of smart contracts in task automation and improving supply chain transparency is well illustrated by Eggers *et al.* (2021), while Aleksieva *et al.* (2023) provide a model that integrates BCT, smart contracts and the IoT for real-time tracking and optimizing workflows in reverse logistics. Nevertheless, other challenges like safety risks and clarifying legal frameworks exist (Wu, 2022). Wang *et al.* (2021) report that smart contracts can improve returns processes based on the BCT-based system. BCT's real-time data regarding returned items is a powerful tool for focusing product development on inventory optimization (Govindasamy and Antonidoss, 2022). This data aids in identifying defective and undesired items (Zhou and Liu, 2022). This data stream would change how to proceed with the production and re-inventory process (Li *et al.*, 2023). Substandard quality, undesirable products can be identified well in due time, a process that saves the manufacturing business from potential production overruns and breaks; hence, provides flexibility and efficiency to the entire inventory mechanism during the process of new product development or order fulfillment for various customers using advanced logistics operations management (Wu *et al.*, 2021).

BCT has opened new frontiers in developing products to reduce fraudulent returns (Shih *et al.*, 2021). The key strength is creating an unhackable record of a product's information at every stage of the supply chain, from manufacturing and distribution to sales (Madhani, 2022). This distributed ledger system allows for identifying a unique product linked to verifiable data points, such as the state of a product at given times (Zhou and Liu, 2022). Discrepancies may be reported, perhaps indicating fraudulent activity, by scanning the unique identifier and comparing the documented condition with the returned item (Alkahtani *et al.*, 2021).

BCT applies data analytics to present a new direction in process improvement for product development (Akhter Md Hasib *et al.*, 2022). Contrasting with traditional approaches, BCT, through distributed ledger technology, offers a secure and unalterable record of all transactions and interactions within the supply chain that help optimize processes (Abdennadher *et al.*, 2024). This granular data provides advanced analytics tools covering logistics, material procurement and manufacturing processes (Jahani *et al.*, 2023). By using machine learning and data mining on BCT data, manufacturers could find insights into inefficiencies or bottlenecks in their product development processes that they were previously unaware of (Zhou and Liu, 2022).

The optimization of return and refurbishing operations is one of the biggest challenges in product development (Guide and Vanwassenhove, 2001). However, BCT does promise an answer: creating a transparent, safe record-keeping system throughout the supply chain, which reduces the number of return-related issues (Li and Chen, 2023). Bellaj *et al.* (2024) add that the distributed ledger system allows for distinctive product identifiers to be created, which can then be tracked through a product's life cycle, including returns and refurbished products. Returning products can become faster for manufacturing companies by using the real-time information flow throughout the journey of products, as observed by Helo and Thai (2024). In addition, Liu *et al.* (2023) provide reasons for returning products and data about their conditions to link up with BCT and enable analytics on which action, refurbishing or recycling, is most effective.

According to Dutta *et al.* (2021), BCT presents a new, novel method to improve supply chain documentation and cut administrative costs. Lifecycles for products have become affected due to inefficiencies through paper-based documentation and manually verifying the products. The blockchain (BC) can act as a secured, immutable, digital document repository associated with each stage in a product lifecycle, as Zheng and Zhou (2023) stated. This helps gain stakeholders' trust since no physical documents are involved in the manual verification of documents. Talwar *et al.* (2023) present that smart contracts are self-executing agreements stored on the BCT. These can be programmed to create documents independently whenever certain conditions are met. Automation speeds up supply chain operations, reduces errors in documentation and dramatically reduces administrative tasks (Qi *et al.*, 2023). Considering present challenges, BCT-based document automation provides an exceptional opportunity to release administrative burdens (Jabbar *et al.*, 2021).

2.3 Consumer engagement and sustainability

Li *et al.* (2023) identify consumer feedback on the recycling and return of goods as an important item of consideration. In traditional modes of return, such systems that will extract this critical information are usually lacking. The BCT is, therefore, availing a solution that has the potential to be transformational regarding the integration of feedback into the return process, thus enabling firms to glean important details that can indicate product problems or those that can be curbed (Wang *et al.*, 2021; Agag *et al.*, 2023). The BCTs allow clients to leave much longer feedback at lightning speed, thus improving cooperation and product development (Dutta *et al.*, 2021). However, at a challenging time, BCT presents an opportunity to collect relevant customer feedback in the return and recycling phase process (Centobelli *et al.*, 2022). An active consumer contributes to closing the loop in the circular economy regarding recovering resources and offering long-lasting products (Shevchenko *et al.*, 2023). BCT creates new opportunities for fostering participation through reward mechanisms (Sumter *et al.*, 2020). Depending on the organization with its incentive machinery activated through BCT around circular practices may be "product returns for recycling" and or good recycling-BCTs provide tokens upon disposal/quienes behaviors, becoming redeemable value offers on future consumer purchases or direct exchanges for things like eco-efficient rewards related specifically to recycling plans (Guo and Huang, 2023). This strategy encourages ethical consumption and cooperation between consumers and businesses in the circular economy.

Consumers' buying habits directly determine the environmental impact an item produces by changing consumer expectations (Creazza *et al.*, 2023). Without efficient consumer purchasing, the provision in BCT allows the revealing and enlightening sharing of products with environmental and social values (Upadhyay *et al.*, 2021). With access to safe BCT records made available through grant channels, consumers can be empowered by the companies in making decisions regarding their purchases (Li and Chen, 2023). These records can trace a product over the entire period, including the sustainable techniques applied at the sourcing level and energy expenditure during production (Tian *et al.*, 2023). This openness builds up decision-making processes between buyers that put some premium on environmental sustainability patterns (Adomako and Tran, 2022). Despite these obstacles surrounding privacy and BCT information trustworthiness, empowering consumers with access to BCT records indicates how they might encourage a more environmentally responsible choice (Upadhyay *et al.*, 2021). Communicating and expressing the degree of importance given to a resource-consumption circular economy approach often becomes generally difficult for the users and stakeholders (Esposito *et al.*, 2024). BCT enables the secured sharing of this verifiable information with stakeholders and customers to substantiate the advantages of conserving resources and the environment (Adomako and Tran, 2022). The data can be safely inscribed onto the BCT and would remain public for access by all players along the supply chain (Tian *et al.*, 2023). This would foster trust and create an understanding between those or entities that may eventually lead to more circular economic behavior. However, consumer awareness of the complex technology of BCT needs to be worked upon (Adomako and Tran, 2022).

2.4 Research gap

Despite the growing academic interest in BCT and its intersection with sustainability, particularly within the circular economy (CE), the empirical exploration of its applications in reverese logistics (RL) remains notably underdeveloped. Several studies have documented BCT's theoretical advantages in enhancing traceability, transparency and efficiency in reverse supply chains (Centobelli *et al.*, 2022; Kouhizadeh *et al.*, 2023; da Silva *et al.*, 2025). Moreover, works like Wu (2022) and Bhuiyan and Akter (2024) highlight how smart contracts and immutable ledgers can theoretically streamline returns processing and compliance. However, these studies often fall short in quantitatively validating or prioritizing specific practices based on real-world effectiveness. While prior literature has explored BCT's benefits in CE or RL separately (Adomako and Tran, 2022; Madhani, 2022; Rajesh, 2023a, 2023b), very few, if any, have systematically ranked or compared practices within the integrated BCT–CE–RL triad. Existing work focuses either on general frameworks (Saberi *et al.*, 2019) or conceptual overviews (Shevchenko *et al.*, 2023), lacking empirical grounding. Notably, none of the reviewed studies have used multicriteria decision-making (MCDM) techniques like the Delphi method and GIA to derive a prioritized roadmap of BCT-enabled CE practices specific to reverse logistics. This oversight is particularly critical given the increasing complexity and interdependencies among stakeholders in RL systems. Hence, this study addresses a novel research gap by empirically validating and ranking these practices, offering practitioners a structured approach for BCT integration in circular reverse logistics operations.

3. Research methodology

This study adopts a two-stage methodology combining the Delphi technique and GIA (step by step process is given in Appendices) to identify, validate and prioritize blockchain-enabled CE practices in reverse logistics. The Delphi method was used to gain consensus from a panel of experts on the most relevant CE practices, enabling refinement and validation through multiple structured rounds. GIA was then applied to analyze the interrelationships among these practices and to rank them based on their relative influence within the system.

The Delphi method is widely recognized for its ability to consolidate expert judgments in complex and interdisciplinary fields. It is particularly valuable where historical data is limited, and expert knowledge is essential, such as in forecasting, sustainability and technology adoption contexts (Barrios *et al.*, 2021; De Lima and Seuring, 2023; Saberi *et al.*, 2019; Wang *et al.*, 2019; Kouhizadeh *et al.*, 2021; Kumar *et al.*, 2020). GIA, a robust causal modeling tool, is increasingly applied in sustainability and supply chain management research to uncover and quantify influence relationships in complex systems. Unlike traditional MCDM techniques, GIA maintains the integrity of expert responses and provides a comprehensive view of the system dynamics (Rajesh, 2023a; Rajesh, 2023b; Kumar *et al.*, 2024;

Rajesh, 2024; Singh *et al.*, 2024). The integration of these two methods ensures that the derived practices are both expert-validated and empirically ranked, making the findings highly actionable for practitioners and policymakers.

Seven experts were carefully selected to participate in the Delphi study based on a set of predefined criteria. These included: a minimum of eight years of experience, postgraduate qualifications and demonstrated domain expertise in at least one of the following areas: reverse logistics operations, blockchain system development or circular economy strategy and policy. The panel consisted of professionals such as a BCT implementation lead, a logistics manager, a sustainability consultant and a data security specialist, thereby ensuring comprehensive representation of technical, operational and policy perspectives relevant to the study.

In the Delphi process, the first round included open-ended questions inviting experts to identify key blockchain-enabled practices relevant to reverse logistics. In subsequent rounds, the shortlisted practices were rated on a five-point Likert scale to establish consensus, with a threshold average score of 4.5 used for final inclusion. Experts were provided feedback summaries between rounds to refine their responses and enhance agreement. For the GIA phase, a structured questionnaire was developed using linguistic terms (e.g. "Very High," "High," "Moderate," etc.) to assess the degree of influence between identified practices. These terms were then mapped to gray numerical scales following established conventions in prior studies (Rajesh, 2023a, 2023b; Kumar *et al.*, 2024). Responses were reviewed for completeness, and gray matrices were constructed to analyze direct and indirect relationships among the practices. Equal weight was given to all expert inputs to preserve neutrality.

4. Result analysis and discussion

This section discusses the implementation of integrated Delphi and GIA approaches in detail to optimize circular economy practices through BCT in reverse logistics.

4.1 Delphi analysis

The current research used the Delphi method to determine critical principles for implementing BCT in reverse logistics due to its sound experience in reaching consensus among experts in the industry on complex, multifaceted issues. Seven representatives from institutions working in different areas identified themselves with manufacturing, supply chain and BCT and were scrutinized for their selection, representing the spectrum of industry demands. These experts, with 8–20 years of experience, were selected based on their high-level educational qualifications (mostly postgraduate degrees) and their relevant industry engagement in the sectors that provide significant inputs toward sustainability, logistics or BCT. The Delphi approach was carried out through three iterative rounds, each interspersed with feedback on the almost-considered practices. Experts provided input through a five-point Likert scale, where a threshold of 4.5 was set to establish the significance of each practice. Ultimately, 16 practices were finalized with consensus, while five were excluded due to lower relevance scores or redundancy.

Table 2 (below) outlines the profiles of the selected experts, while Table 3 provides the Delphi process results. Among the practices excluded, "lowering administrative overhead by automating documentation through BCT," "allowing consumers to access BCT records to understand the environmental impact of their product choices" and "tracking and reporting environmental impact metrics for reverse logistics operations" were rejected due to overlaps with other practices or insufficient impact on reverse logistics efficiency. Similarly, "minimizing fraud in returns by using BCT to verify product conditions" and "recording data

Table 2. Expert profile

Expert no.	Profile	Experience (years)	Industry	Education
1	BCT implementation lead	15	Manufacturing	MTech in engineering
2	Supply chain analyst	10	Retail and logistics	MBA in operations
3	Sustainability consultant	18	Environmental solutions	MTech in industrial engineering
4	Logistics manager	12	Consumer electronics	BTech in logistics
5	Data security specialist	20	Technology solutions	PhD in computer science
6	Circular economy strategist	18	E-waste management	MBA in sustainability
7	Product lifecycle manager	14	Consumer goods	MSc in supply chain

on the recycling process, including materials used and energy consumption" were omitted for being less impactful within the identified constructs.

A purified list of practices was obtained through the Delphi process, and the experts then grouped these into three key constructs: Traceability and transparency, efficiency and cost reduction and consumer engagement and sustainability. Experts evaluated and scored practices in three consecutive sessions using a five-point Likert scale with a significance criterion of 4.5 points. The processes improved based on input from the expert panel and would receive adjustments in the following rounds to reach the benchmark. The last round would see consensus on 16 practices, with higher scores for relevance, practicality and prospects for reverse logistics. This intense evaluation led to an aptly strong and validated paradigm for the application of BCT in reverse logistics, with a concern for sustainability and the involvement of consumers.

In reverse logistics, these methods pave the way for certain advantages, including tracking lifecycles through BCT and traceability with real-time visibility, which enhances operational effectiveness and, thereby, becomes a catalyst for transparency in product and material flow, allowing the ability to tackle counterfeiting problems. Furthermore, immutable audit trails and smart contracts improve compliance with regulations and diminish processing costs, with automated documentation alleviating administrative pressures. Ultimately, customer engagement strategies encompass incentive schemes for product returns and BCT-enabled feedback mechanisms. These helps align the consumers with sustainable practices, thus encouraging them to participate in a circular economy. These expert-recommended strategies create a comprehensive framework for integrating BCT into reverse logistics that can, for the very first time, potentially change conventional systems by introducing extended visibility, attestation and consumer participation in sustainability.

The final practices, as detailed in Table 3, reflect expert consensus on the most impactful strategies for implementing BCT in reverse logistics. Each practice rated above the 4.5 threshold, with a standard deviation under 1, indicating a high degree of agreement. This process validated the relevance and feasibility of the identified practices within the constructs of Traceability and Transparency, Efficiency and Cost Reduction and Consumer Engagement and Sustainability, providing a strategic framework for enhancing reverse logistics through BCT. The categorization of practices is presented in Figure 1.

Table 3. Delphi result

Practice	Average value	SD
Using BCT to record the entire lifecycle of a product, from manufacturing to disposal (P1)	4.8123	0.6534
Providing real-time visibility into product movements within the reverse supply chain (P2)	4.7291	0.5832
Verifying the authenticity of returned or refurbished products through BCT records (P3)	4.6457	0.7043
Recording data on the recycling process, including materials used and energy consumption (P4)	4.9112	0.6295
Tracking and reporting environmental impact metrics for reverse logistics operations (P5)	4.7384	0.5917
Creating immutable audit trails for regulatory compliance and accountability (P6)	4.6529	0.6831
Implementing smart contracts for automated processing of returns and payments (P7)	4.7146	0.5429
Optimizing inventory levels by having real-time information on returned products (P8)	4.823	0.6154
Minimizing fraud in returns by using BCT to verify product conditions (P9)	4.6873	0.7251
Leveraging BCT data for analytics to identify process optimization opportunities (P10)	4.7384	0.6942
Developing efficient processes for handling product returns and refurbishments (P11)	4.8276	0.6518
Lowering administrative overhead by automating documentation through BCT (P12)	4.9104	0.6023
Encouraging consumers to provide feedback on product returns and recycling through BCT-based systems (P13)	4.6812	0.6735
Creating BCT-based incentive programs to motivate consumers to participate in circular economy practices (P14)	4.7512	0.5617
Allowing consumers to access BCT records to understand the environmental impact of their product choices (P15)	4.8241	0.6215
Using BCT to disseminate information about the benefits of circular economy practices to consumers and stakeholders (P16)	4.7398	0.6634

4.2 Grey influential analysis result analysis

In the GIA analysis, linguistic labels like "Very High" and "Very Low" were used to capture varying levels of influence within the questionnaire, allowing respondents to rate each practice's importance and effect accurately. Responses were rigorously reviewed for completeness, ensuring the data provided was reliable and suitable for subsequent analysis. All experts' responses were assigned equal weights to maintain fairness and neutrality, preventing any expert's opinion from disproportionately impacting the results. The gray value of each response was computed using equation (1), standardizing input from all experts for a balanced evaluation.

Following this, equation (2) was used to aggregate individual responses, which enabled the generation of the critical, ideal and most typical values through the "whitenization" process. This process helped convert the gray-scale data into representative crisp values in Table 4. The Direct Influence Coefficient Matrix was established by systematically quantifying each factor's direct influence on others using equations (3) and (4), then capturing them in a structured matrix format, as shown in Table 4. It served as a basis for

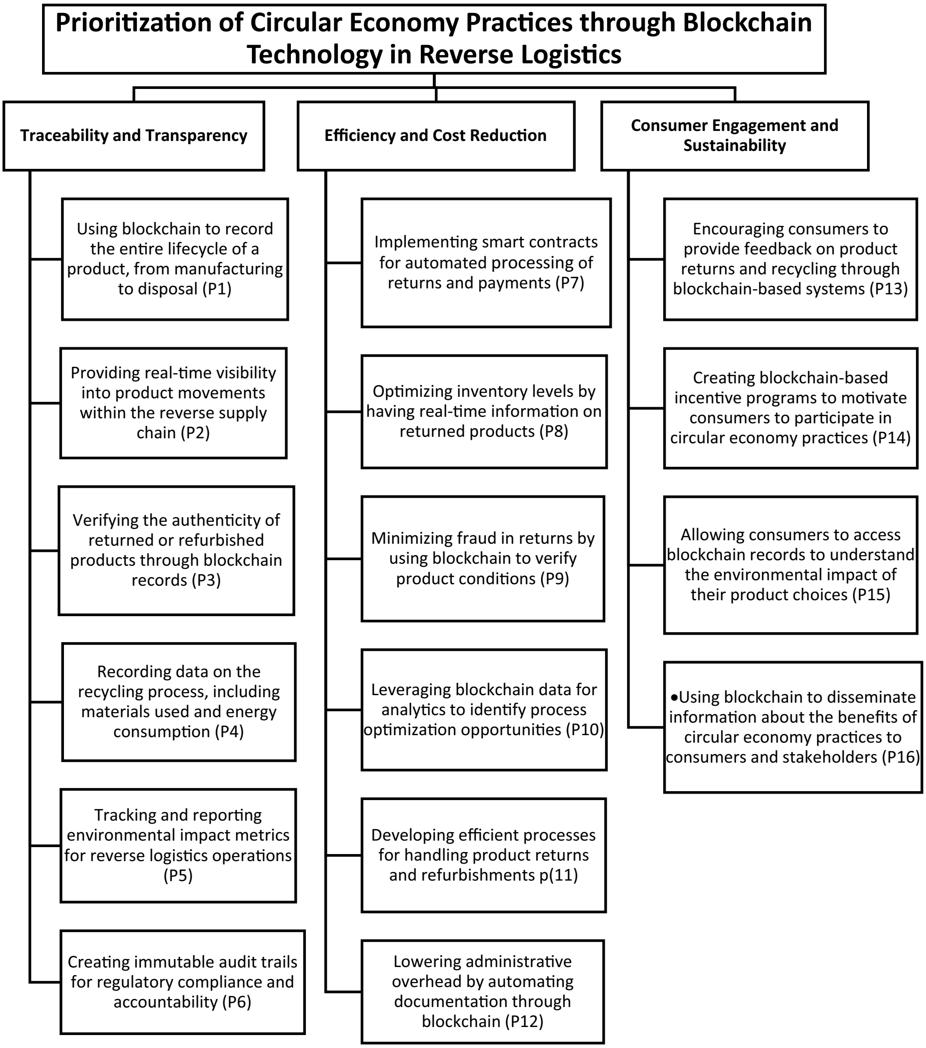

Figure 1. Categorization of practices

finding out how much each practice directly affected others within the reverse logistics practices network.

To expand the analysis, equations (5) and (6) were used to calculate the comprehensive influence coefficients, representing the partial influence that each practice gives to the general system. We also developed Gray Responsibility and Influence Coefficients using the coefficients in equations (7) and (8), respectively, expressing each practice’s influenced or influencing capability. These coefficients, which are crucial for understanding the contribution of each factor in the system, are listed in Table 5. Subsequently, equation (9) was used to determine the Gray Significance Coefficients, which allow the highlighting of

Table 4. Whitenized (critical, ideal and typical) responses

Practice	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
Critical																
P1	0	24	32	39	32	26	38	32	20	32	38	32	35	30	27	36
P2	27	0	26	26	35	34	34	24	48	36	24	42	30	36	40	38
P3	41	36	0	38	38	38	32	30	26	22	38	32	32	32	44	22
P4	32	44	30	0	30	36	32	28	34	28	16	15	30	28	30	22
P5	22	26	36	33	0	19	18	34	26	32	29	40	21	30	31	32
P6	40	42	32	19	25	0	39	20	34	33	36	30	37	29	27	39
P7	28	30	24	26	33	31	0	13	32	26	43	42	34	32	31	35
P8	25	38	25	38	28	24	44	0	30	28	28	26	36	38	17	42
P9	32	15	26	38	38	18	32	33	0	44	26	40	30	40	33	26
P10	40	32	44	22	30	46	35	46	44	0	34	32	34	32	40	34
P11	34	40	36	25	30	29	29	39	38	40	0	32	36	35	34	34
P12	20	32	22	29	40	28	33	36	23	20	30	0	18	31	32	33
P13	26	34	38	28	44	24	31	43	30	28	41	22	0	23	31	32
P14	28	38	19	36	28	30	42	36	42	20	33	32	21	0	30	32
P15	44	22	29	40	32	26	30	38	24	40	30	21	40	36	0	40
P16	31	25	34	16	20	31	33	32	32	25	36	30	40	30	30	0
Ideal																
P1	0	43	52	57	49	46	56	51	41	53	59	53	54	50	46	56
P2	45	0	47	46	52	53	54	45	63	55	44	60	51	55	58	57
P3	51	56	0	58	58	57	53	50	46	42	57	51	52	53	62	45
P4	51	61	50	0	50	57	52	49	52	48	37	35	49	49	51	42
P5	42	47	55	51	0	39	38	53	54	51	47	58	41	48	48	52
P6	59	58	51	39	44	0	55	39	52	50	54	49	54	48	45	55
P7	48	49	45	46	52	50	0	33	54	46	59	60	54	52	50	54
P8	44	57	45	58	47	45	63	0	51	47	49	46	55	57	37	61
P9	51	35	46	57	57	39	51	51	0	61	47	58	50	58	50	46
P10	57	52	63	43	50	63	54	59	61	0	53	52	55	52	59	52
P11	54	59	55	44	50	48	41	50	56	59	0	53	57	54	55	54
P12	41	52	43	41	58	48	52	45	40	40	50	0	38	49	51	51
P13	46	53	56	48	63	45	49	57	54	45	58	39	0	43	49	51
P14	48	56	39	55	48	49	60	47	59	41	51	52	40	0	51	52
P15	62	42	47	58	51	46	49	59	43	59	49	39	60	55	0	58
P16	50	44	54	37	41	49	51	50	53	45	55	50	59	49	49	0
Typical																
P1	0	33.5	42	48	40.5	36	47	41.5	30.5	42.5	48.5	42.5	44.5	40	36.5	46
P2	36	0	36.5	36	43.5	43.5	44	34.5	55.5	45.5	34	51	40.5	45.5	49	47.5
P3	46	46	0	48	48	47.5	42.5	40	36	32	47.5	41.5	42	42.5	53	33.5
P4	41.5	52.5	40	0	40	46.5	42	38.5	43	38	26.5	25	39.5	38.5	40.5	32
P5	32	36.5	45.5	42	0	29	28	43.5	40	41.5	38	49	31	39	39.5	42
P6	49.5	50	41.5	29	34.5	0	47	29.5	43	41.5	45	39.5	45.5	38.5	36	47
P7	38	39.5	34.5	36	42.5	40.5	0	23	43	36	51	51	44	42	40.5	44.5
P8	34.5	47.5	35	48	37.5	34.5	53.5	0	40.5	37.5	38.5	36	45.5	47.5	27	51.5
P9	41.5	25	36	47.5	47.5	28.5	41.5	42	0	52.5	36.5	49	40	49	41.5	36
P10	48.5	42	53.5	32.5	40	54.5	44.5	52.5	52.5	0	43.5	42	44.5	42	49.5	43
P11	44	49.5	45.5	34.5	40	38.5	35	44.5	47	49.5	0	42.5	46.5	44.5	44.5	44
P12	30.5	42	32.5	35	49	38	42.5	40.5	31.5	30	40	0	28	40	41.5	42
P13	36	43.5	47	38	53.5	34.5	40	50	42	36.5	49.5	30.5	0	33	40	41.5
P14	38	47	29	45.5	38	39.5	51	41.5	50.5	30.5	42	42	30.5	0	40.5	42
P15	53	32	38	49	41.5	36	39.5	48.5	33.5	49.5	39.5	30	50	45.5	0	49
P16	40.5	34.5	44	26.5	30.5	40	42	41	42.5	35	45.5	40	49.5	39.5	39.5	0

those practices that have been found to have the most meaningful combined effect within the context of BCT-enabled reverse logistics being studied. These significant coefficients, as recorded in Table 6, yield clear indications of which practices ought to be strategically emphasized.

Table 5. Direct influence coefficient matrices

Practice	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
Critical																
P1	0.0000	0.0502	0.0706	0.0861	0.0663	0.0591	0.0757	0.0661	0.0414	0.0705	0.0788	0.0684	0.0738	0.0622	0.0566	0.0724
P2	0.0574	0.0000	0.0574	0.0574	0.0725	0.0773	0.0677	0.0496	0.0994	0.0793	0.0498	0.0897	0.0633	0.0747	0.0839	0.0765
P3	0.0872	0.0753	0.0000	0.0839	0.0787	0.0864	0.0637	0.0620	0.0538	0.0485	0.0788	0.0684	0.0675	0.0664	0.0922	0.0443
P4	0.0681	0.0921	0.0662	0.0000	0.0621	0.0818	0.0637	0.0579	0.0704	0.0617	0.0332	0.0321	0.0633	0.0581	0.0629	0.0443
P5	0.0468	0.0544	0.0795	0.0728	0.0000	0.0432	0.0359	0.0702	0.0538	0.0705	0.0602	0.0855	0.0443	0.0622	0.0650	0.0644
P6	0.0851	0.0879	0.0706	0.0419	0.0518	0.0000	0.0777	0.0413	0.0704	0.0727	0.0747	0.0641	0.0781	0.0602	0.0566	0.0785
P7	0.0596	0.0628	0.0530	0.0574	0.0683	0.0705	0.0000	0.0269	0.0663	0.0573	0.0892	0.0897	0.0717	0.0664	0.0650	0.0704
P8	0.0532	0.0795	0.0552	0.0839	0.0580	0.0545	0.0876	0.0000	0.0621	0.0617	0.0581	0.0556	0.0759	0.0788	0.0356	0.0845
P9	0.0681	0.0314	0.0574	0.0839	0.0787	0.0409	0.0637	0.0682	0.0000	0.0969	0.0539	0.0855	0.0633	0.0830	0.0692	0.0523
P10	0.0851	0.0669	0.0971	0.0486	0.0621	0.1045	0.0697	0.0950	0.0911	0.0000	0.0705	0.0684	0.0717	0.0664	0.0839	0.0684
P11	0.0723	0.0837	0.0795	0.0552	0.0621	0.0659	0.0578	0.0806	0.0787	0.0881	0.0000	0.0684	0.0759	0.0726	0.0713	0.0684
P12	0.0426	0.0669	0.0486	0.0640	0.0828	0.0636	0.0657	0.0744	0.0476	0.0441	0.0622	0.0000	0.0380	0.0643	0.0671	0.0664
P13	0.0553	0.0711	0.0839	0.0618	0.0911	0.0545	0.0618	0.0888	0.0621	0.0617	0.0851	0.0470	0.0000	0.0477	0.0650	0.0644
P14	0.0596	0.0795	0.0419	0.0795	0.0580	0.0682	0.0837	0.0744	0.0870	0.0441	0.0685	0.0684	0.0443	0.0000	0.0629	0.0644
P15	0.0936	0.0460	0.0640	0.0883	0.0663	0.0591	0.0598	0.0785	0.0497	0.0881	0.0622	0.0449	0.0844	0.0747	0.0000	0.0805
P16	0.0660	0.0523	0.0751	0.0353	0.0414	0.0705	0.0657	0.0661	0.0663	0.0551	0.0747	0.0641	0.0844	0.0622	0.0629	0.0000
Ideal																
P1	0.0000	0.0563	0.0695	0.0772	0.0636	0.0627	0.0720	0.0691	0.0526	0.0714	0.0767	0.0702	0.0702	0.0648	0.0604	0.0712
P2	0.0601	0.0000	0.0628	0.0623	0.0675	0.0722	0.0694	0.0610	0.0809	0.0741	0.0572	0.0795	0.0663	0.0712	0.0762	0.0725
P3	0.0681	0.0733	0.0000	0.0786	0.0753	0.0777	0.0681	0.0678	0.0591	0.0566	0.0741	0.0675	0.0676	0.0687	0.0815	0.0573
P4	0.0681	0.0798	0.0668	0.0000	0.0649	0.0777	0.0668	0.0664	0.0668	0.0647	0.0481	0.0464	0.0637	0.0635	0.0670	0.0534
P5	0.0561	0.0615	0.0735	0.0691	0.0000	0.0531	0.0488	0.0718	0.0693	0.0687	0.0611	0.0768	0.0533	0.0622	0.0631	0.0662
P6	0.0788	0.0759	0.0682	0.0528	0.0571	0.0000	0.0707	0.0528	0.0668	0.0674	0.0702	0.0649	0.0702	0.0622	0.0591	0.0700
P7	0.0641	0.0641	0.0602	0.0623	0.0675	0.0681	0.0000	0.0447	0.0693	0.0620	0.0767	0.0795	0.0702	0.0674	0.0657	0.0687
P8	0.0587	0.0746	0.0602	0.0786	0.0610	0.0613	0.0810	0.0000	0.0655	0.0633	0.0637	0.0609	0.0715	0.0738	0.0486	0.0776
P9	0.0681	0.0458	0.0615	0.0772	0.0740	0.0531	0.0656	0.0691	0.0000	0.0822	0.0611	0.0768	0.0650	0.0751	0.0657	0.0585
P10	0.0761	0.0681	0.0842	0.0583	0.0649	0.0858	0.0694	0.0799	0.0783	0.0000	0.0689	0.0689	0.0715	0.0674	0.0775	0.0662
P11	0.0721	0.0772	0.0735	0.0596	0.0649	0.0654	0.0527	0.0678	0.0719	0.0795	0.0000	0.0702	0.0741	0.0699	0.0723	0.0687
P12	0.0547	0.0681	0.0575	0.0556	0.0753	0.0654	0.0668	0.0610	0.0513	0.0539	0.0650	0.0000	0.0494	0.0635	0.0670	0.0649
P13	0.0614	0.0694	0.0749	0.0650	0.0818	0.0613	0.0630	0.0772	0.0693	0.0606	0.0754	0.0517	0.0000	0.0557	0.0644	0.0649
P14	0.0641	0.0733	0.0521	0.0745	0.0623	0.0668	0.0771	0.0637	0.0757	0.0553	0.0663	0.0689	0.0520	0.0000	0.0670	0.0662
P15	0.0828	0.0550	0.0628	0.0786	0.0662	0.0627	0.0630	0.0799	0.0552	0.0795	0.0637	0.0517	0.0780	0.0712	0.0000	0.0738
Typical																
P16	0.0668	0.0576	0.0722	0.0501	0.0532	0.0668	0.0656	0.0678	0.0680	0.0606	0.0715	0.0662	0.0767	0.0635	0.0644	0.0000
P1	0.0000	0.0539	0.0699	0.0806	0.0646	0.0613	0.0734	0.0679	0.0483	0.0711	0.0775	0.0695	0.0716	0.0638	0.0590	0.0717
P2	0.0591	0.0000	0.0608	0.0605	0.0694	0.0741	0.0688	0.0565	0.0880	0.0761	0.0544	0.0834	0.0652	0.0726	0.0792	0.0740
P3	0.0755	0.0741	0.0000	0.0806	0.0766	0.0809	0.0664	0.0655	0.0571	0.0535	0.0759	0.0679	0.0676	0.0678	0.0856	0.0522
P4	0.0681	0.0845	0.0666	0.0000	0.0638	0.0792	0.0656	0.0630	0.0681	0.0635	0.0424	0.0409	0.0636	0.0614	0.0654	0.0499
P5	0.0525	0.0588	0.0758	0.0705	0.0000	0.0494	0.0438	0.0712	0.0634	0.0694	0.0608	0.0801	0.0499	0.0622	0.0638	0.0655
P6	0.0812	0.0805	0.0691	0.0487	0.0551	0.0000	0.0734	0.0483	0.0681	0.0694	0.0719	0.0646	0.0732	0.0614	0.0582	0.0733
P7	0.0623	0.0636	0.0575	0.0605	0.0678	0.0690	0.0000	0.0376	0.0681	0.0602	0.0815	0.0834	0.0708	0.0670	0.0654	0.0694
P8	0.0566	0.0765	0.0583	0.0806	0.0599	0.0588	0.0836	0.0000	0.0642	0.0627	0.0616	0.0589	0.0732	0.0758	0.0436	0.0803
P9	0.0681	0.0403	0.0600	0.0798	0.0758	0.0486	0.0648	0.0687	0.0000	0.0878	0.0584	0.0801	0.0644	0.0781	0.0670	0.0561
P10	0.0796	0.0676	0.0891	0.0546	0.0638	0.0928	0.0695	0.0859	0.0832	0.0000	0.0695	0.0687	0.0716	0.0670	0.0800	0.0670
P11	0.0722	0.0797	0.0758	0.0579	0.0638	0.0656	0.0547	0.0728	0.0745	0.0828	0.0000	0.0695	0.0748	0.0710	0.0719	0.0686
P12	0.0500	0.0676	0.0541	0.0588	0.0782	0.0647	0.0664	0.0663	0.0499	0.0502	0.0639	0.0000	0.0451	0.0638	0.0670	0.0655
P13	0.0591	0.0700	0.0783	0.0638	0.0854	0.0588	0.0625	0.0818	0.0666	0.0610	0.0791	0.0499	0.0000	0.0526	0.0646	0.0647
P14	0.0623	0.0757	0.0483	0.0764	0.0607	0.0673	0.0797	0.0679	0.0800	0.0510	0.0671	0.0687	0.0491	0.0000	0.0654	0.0655
P15	0.0870	0.0515	0.0633	0.0823	0.0662	0.0613	0.0617	0.0794	0.0531	0.0828	0.0631	0.0491	0.0805	0.0726	0.0000	0.0764
P16	0.0664	0.0556	0.0733	0.0445	0.0487	0.0681	0.0656	0.0671	0.0674	0.0585	0.0727	0.0654	0.0796	0.0630	0.0638	0.0000

Finally, using equation (10), the Gray Influence Model follows, which provides the analytical tool necessary to study this influence relationship internal to the system deeply. The model portrayed graphically represents the direct and indirect relations among the involved practices, using which it is possible to identify which elements will have the most influence and will, therefore, be prioritized for implementation. Hence, GIA results provide an overview of data-driven assessment that emphasizes reinforcement along the critical paths to optimally enable reverse logistics practices through BCT.

BCT implementation in reverse logistics for circular economy practices had huge potential across varied supply chain perspectives. The GIA technique identified and

Table 6. Gray responsibility, influence and the importance coefficients

Practices	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
Critical: Gray inf coeff	0.0663	0.0682	0.0661	0.0679	0.0653	0.0667	0.0655	0.0694	0.0667	0.0666	0.0668	0.0679	0.0666	0.0641	0.0659	0.0653
Critical: Gray resp coeff	0.0651	0.0621	0.0623	0.0742	0.0733	0.0656	0.0696	0.0676	0.0687	0.0569	0.0593	0.0735	0.0656	0.0673	0.0639	0.0702
Critical: Sum (GIC, GRC)	0.1314	0.1303	0.1284	0.1421	0.1386	0.1323	0.1351	0.1371	0.1354	0.1236	0.1260	0.1415	0.1322	0.1314	0.1298	0.1354
Ideal: Gray inf coeff	0.0623	0.0629	0.0624	0.0629	0.0622	0.0625	0.0624	0.0628	0.0626	0.0625	0.0624	0.0631	0.0626	0.0618	0.0624	0.0621
Ideal: Gray resp coeff	0.0617	0.0601	0.0598	0.0651	0.0655	0.0631	0.0631	0.0626	0.0629	0.0572	0.0597	0.0678	0.0626	0.0633	0.0614	0.0641
Ideal: Sum (GIC, GRC)	0.1240	0.1230	0.1221	0.1281	0.1277	0.1256	0.1255	0.1254	0.1255	0.1198	0.1221	0.1308	0.1253	0.1252	0.1237	0.1261
Typical: Gray inf coeff	0.0623	0.0632	0.0623	0.0631	0.0620	0.0625	0.0622	0.0633	0.0626	0.0626	0.0625	0.0633	0.0626	0.0614	0.0622	0.0618
Typical: Gray resp coeff	0.0616	0.0595	0.0593	0.0667	0.0667	0.0626	0.0637	0.0630	0.0634	0.0558	0.0583	0.0682	0.0623	0.0633	0.0609	0.0647
Typical: Sum (GIC, GRC)	0.1239	0.1227	0.1216	0.1298	0.1287	0.1251	0.1259	0.1263	0.1260	0.1184	0.1208	0.1315	0.1250	0.1247	0.1232	0.1266
Aggregate: Gray inf coeff	0.0630	0.0640	0.0629	0.0639	0.0626	0.0632	0.0628	0.0643	0.0633	0.0633	0.0632	0.0640	0.0633	0.0619	0.0629	0.0625
Aggregate: Gray resp coeff	0.0622	0.0601	0.0599	0.0677	0.0676	0.0632	0.0646	0.0637	0.0642	0.0563	0.0587	0.0690	0.0629	0.0640	0.0615	0.0655
Total influence	0.1252	0.1240	0.1228	0.1316	0.1302	0.1264	0.1274	0.1279	0.1275	0.1195	0.1219	0.1330	0.1262	0.1259	0.1244	0.1280
Rank (total influence)	11	13	14	2	3	8	7	5	6	16	15	1	9	10	12	4

prioritized 16 practices based on their total influence. This discussion reports on the top ten practices, exploring their importance and interrelations in the circular economy and reverse logistics context. The most ranked practices obtained with the GIA technique highlight how BCT could enable the full circle of circular economy practices using reverse logistics. From administrative processing and data transparency to higher levels of consumer engagement and operational efficiencies, BCT provides options to address some of the challenges that could be experienced in implementing a circular economic model.

The highest ranking of practices is based on the total influence measure obtained by "lowering administrative overhead by automating documentation through BCT (P12)." This practice exploits the potential of BCT in lightening the administrative headache attached to reverse logistics operations and reducing costs through attempts at increasing the efficiency of the operations. This supports Bai and Sarkis (2020) arguments concerning the potential of BCT to improve the visibility and shrink information asymmetry in supply chains of the circular economy. Automating documentation by an enterprise reduces errors, accelerates transaction cycles, and thus enables better management of resource consumption (Kouhizadeh *et al.*, 2021). This also relates closely to "immutable audit trails creation for regulatory compliance and accountability (P6)," ranking eighth among the practices, because automated documentation will create temper-proof and more transparent records, which can increase trust a lot among the different stakeholders, and it will also help in making the facilitation of regulatory requirements easy (Saberi *et al.*, 2019). Narayan and Tidström (2020) expressed that BCT-based audit trails allow for the substantial enhancement of verification from sustainability claims and, therefore, support regulatory compliance with the circular economy practices. This practice will also provide "Leveraging BCT data analytics to identify process optimization opportunities (P10)." Since it is ranked sixteenth, automated documentation will be a rich data set to assess and continuously improve reverse logistics processes.

Practices ranked second and third were "Recording data on the recycling process, including materials used and energy consumption (P4)" and "Tracking and reporting environmental impact metrics for reverse logistics operations (P5)," respectively. Both practices are related to recording data and the transparency of circular economy practices. Considering your practices, both practices fit into an integral relationship, contributing to a greater understanding of the environmental impact related to reverse logistics operations. Upadhyay *et al.* (2021) have identified that transparent and reliable information related to recycling processes and environmental metrics can enable continuous improvement and development of innovation regarding reverse logistics operations. These practices may also underpin more advanced life cycle assessments at product and service levels. As highlighted by Kopyto *et al.* (2020), integrating BCT into LCA methodologies could develop environmental impact data that is both more precise and timelier to enable better-informed decision-making along the product life cycle. Detailed data recording on recycling processes and tracking of environmental metrics are ways companies can demonstrate their improvements in commitment to sustainability (Kouhizadeh and Sarkis, 2018). Ranked tenth practice, it will also help enable "allow consumers to access BCT records to understand the environmental impact of their product choices (P15)," to make better decisions and foster a feeling of coresponsibility in circular economy practices.

The best-practice rankings are grouped into product lifecycle management and consumer involvement. "BCT to diffuse information on the benefits of circular economy practices to customers or stakeholders (P16)," ranked fourth, would thus indicate that BCT can be used as a tool in communicating and creating awareness for better involvement in circular economic practice involvement. Tan *et al.* (2022) also present that BCT could be one of the strong tools to enhance transparency and trust between firms and customers in circular economy practices. It is very closely related to practices ranked ninth, "Encouraging consumers to provide feedback on product returns and recycling through BCT-based systems (P13)," and number tenth, "Creating BC-based incentive programs to motivate consumers to participate in circular economy practices (P14)." Böhmecke-Schwafert *et al.* (2022) indicate that BCT-based incentive systems significantly increase consumer involvement in product return and circular economy recycling practices. Agrawal *et al.* (2022) urge the collaborative essence of the community, showing that some success was yielded from a consumer perspective inside circular economy initiatives. Various enhancements, such as increasing communication, collection of feedback and motivational incentives can further empower companies toward their circular economy through open banking. A survey study listed certain practices as follows: "Optimization of inventory levels through real-time information on returned products" – with a ranking of fifth then the "Fraud reduction in returns through BCT-based verification of product conditions" – placed at sixth indicates BCT's ability to improve operational efficiency and reduce risks in reverse logistics. According to Agrawal *et al.* (2022), BCT facilitates the real-time tracking of inventory, resulting in reduced cost and effective management of returned products. Moreover, verifying product conditions via BCT records might lead to fraud, which has become a significant problem in e-commerce and circular economy activities (Yadav *et al.*, 2022). As for "Implementation of smart contracts for automated processing of returns and payments," it is rated eighth, which optimizes the whole reverse logistics operation quite efficiently and significantly improves the circular economy model (Chidepatil *et al.*, 2020). Such tasks can include automating reverse logistical processes through smart contracts, reducing transaction costs, and thus improving overall efficiency in circular economy projects (Choi *et al.*, 2020).

Figure 2 shows the gray influence and responsibility coefficient and total influence values of various BCT-based reverse logistics practices (P1–P16) in a graphical representation. The green line represents total influences that comment on the overall impact of practices; the orange lines represent the aggregated gray influence, and the yellow explains the aggregated gray responsibility. P12 and P4 practice closer to the outer rings with a more excellent value of influence, which informs that they would likely be even more significant in the reverse logistics system. In contrast, practices closer to the center, like P10, show lower values, indicating a relatively lesser impact on the system. This visualization highlights the varying levels of influence and responsibility among the practices, emphasizing key areas for optimization in BCT-enabled reverse logistics.

The relationship between the practices depicted in Figure 3 illustrates the intricate interdependencies among BCT-enabled circular economy initiatives within reverse logistics. At the core, practices such as leveraging BCT data for analytics (P10), automating documentation through BCT to reduce administrative overhead (P12) and creating immutable audit trails for regulatory compliance (P6) serve as enablers for more specialized applications. For example, the use of BCT to track and report environmental impact metrics (P5) or to optimize inventory levels with real-time data (P8) is supported by foundational practices that ensure data accuracy, transparency and traceability. These relationships highlight the centrality of BCT as a unifying technology that underpins various operational improvements in reverse logistics.

In addition, consumer-focused practices such as allowing access to BCT records for transparency (P15) and encouraging feedback on product returns (P13) are intertwined with BCT's ability to enhance product tracking (P5) and create incentive programs (P14). Practices such as implementing smart contracts (P7) and minimizing fraud in returns (P9) build upon BCT's inherent features to ensure trust and efficiency in reverse logistics

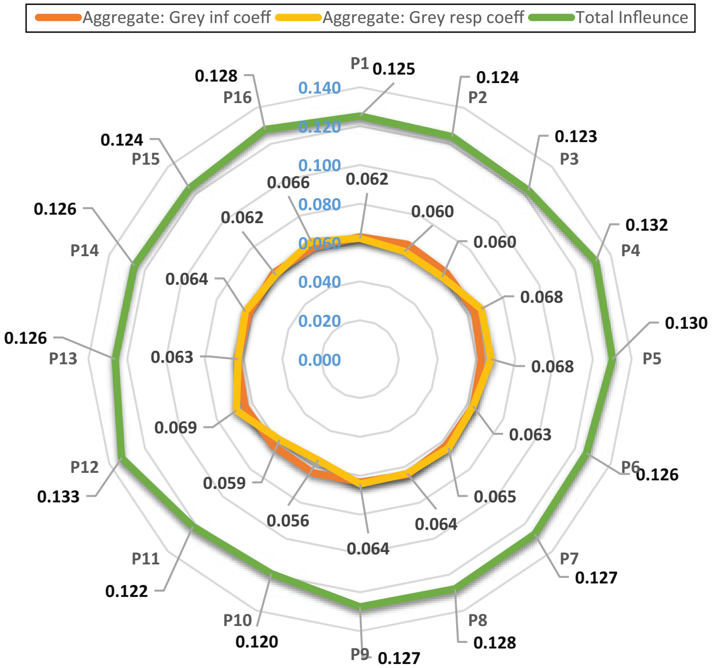

Figure 2. Graphical representation of influence, responsibility and total influence

operations. The cascading relationships suggest that foundational practices, like data recording and verification (P3, P4), enable more advanced functionalities, which collectively drive the adoption of circular economy principles. This interconnected framework underscores the need for an integrated approach, where technical, operational and consumer-focused aspects of BCT work in synergy to optimize reverse logistics processes.

5. Empirical validation

The empirical study was performed to achieve the relative importance of different practices enabling circular economy practices with the help of BCT in reverse logistics. In this regard, 109 diversified background experts with experience in BCT, reverse logistics, and the circular economy were asked to rate the importance of various practices on a five-point rating scale. These were teachers/instructors and research scholars in universities/institutes like IIT, IIIT, IIM, NIT, Central/State/Deemed Universities and Research Council Institutes. The two samples from a population of 109 included 12 representing IIT, 14 from IIIT, 16 from IIM, 12 from the NITs, 43 from Central/State/Deemed Universities and the remaining 12 from Research Council Institutes. The distribution consists of 57 teachers/instructors out of 109 respondents; the rest were research scholars. Of these 109, the breakdown of respondents was as follows: 38 were from North India, 26 from East India, 31 from South India and the remaining 14 were from West India. Responses were collected using both online and offline modes in closed-ended questionnaires. Then, the results of this empirical study are compared with the findings obtained through the GIA. Table 7 represents a comparison of the ranking of the practice as obtained from the empirical study and GIA. The mean value of the response

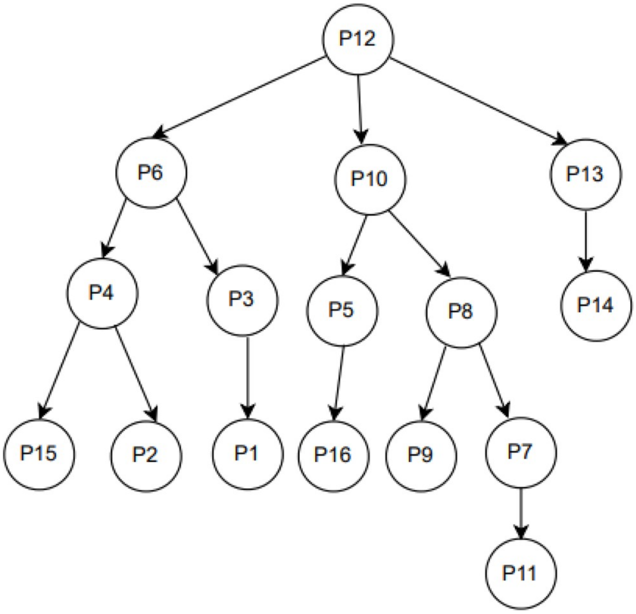

Figure 3. Relationship between the practices

ratings was combined with the rankings of the practices in Column 3. It will be realized from the results that both methods gave similar results, thereby increasing the reliability of the findings from this GIA analysis.

The similarity in the ranking list from empirical results and the ranking obtained using the GIA method confirms the coherence and reliability of this study evaluation to identify those practices that contribute most to the optimization of circular economy practices using BCT in reverse logistics. Both ranking procedures underline the practices that would most contribute to the goals of a circular economy, underlining the consistency between the experts' perceptions and the analytical strength. For example, "Lowering administrative overhead by automating documentation using BCT" was ranked as the best practice in both methods (Empirical Rank 1 and GIA Rank 1), emphasizing that it is necessary to reduce manual documentation to improve reverse logistics processes. According to practitioners, this automation and transparent, trackable recording offered by BCT is particularly valued because it cuts directly into sources of inefficiency, cost and operational efficiency.

Similarly, environmental impact-related practices such as "Keeping records on the recycling process in terms of materials involved and energy consumed" and "Collecting and reporting the metrics on the environmental impact for reverse logistics operations" were also ranked among the first positions in the empirical findings and GIA continuously, respectively (Empirical Ranks 2 and 3; GIA Ranks 2 and 3). These practices align with the increased importance of environmental sustainability and accountability in reverse logistics, where tracking and reporting on environmental metrics is highly relevant for regulatory compliance and corporate reputation. BCT can maintain immutable records that include ease of access, thus making things highly transparent, which will help organizations show stakeholders how much concern they have about sustainability. The fact that these practices are closely aligned

Table 7. Empirical findings

Practice	Mean value	Empirical rank	GIA rank
Using BCT to record the entire lifecycle of a product, from manufacturing to disposal (P1)	3.8521	11	11
Providing real-time visibility into product movements within the reverse supply chain (P2)	3.7423	15	13
Verifying the authenticity of returned or refurbished products through BCT records (P3)	3.6753	16	14
Recording data on the recycling process, including materials used and energy consumption (P4)	4.2945	2	2
Tracking and reporting environmental impact metrics for reverse logistics operations (P5)	4.2166	3	3
Creating immutable audit trails for regulatory compliance and accountability (P6)	3.9434	8	8
Implementing smart contracts for automated processing of returns and payments (P7)	3.9764	7	7
Optimizing inventory levels by having real-time information on returned products (P8)	4.0563	5	5
Minimizing fraud in returns by using BCT to verify product conditions (P9)	4.0137	6	6
Leveraging BCT data for analytics to identify process optimization opportunities (P10)	3.7445	14	16
Developing efficient processes for handling product returns and refurbishments (P11)	3.8247	12	15
Lowering administrative overhead by automating documentation through BCT (P12)	4.3567	1	1
Encouraging consumers to provide feedback on product returns and recycling through BCT-based systems (P13)	3.9040	9	9
Creating BCT-based incentive programs to motivate consumers to participate in circular economy practices (P14)	3.8892	10	10
Allowing consumers to access BCT records to understand the environmental impact of their product choices (P15)	3.7623	13	12
Using BCT to disseminate information about the benefits of circular economy practices to consumers and stakeholders (P16)	4.1276	4	4

in rankings across the two methods underlines their relevance and the consensus of experts on their impact on optimizing circular economy practices through BCT in reverse logistics.

6. Theoretical and practical implications

This research significantly contributes to the theoretical development of BCT adoption in the context of optimal circular economy practices enabled by reverse logistics. This study ranked 16 practices through the GIA technique and presents novel means of evaluating several BCT applications in order of their relative importance. The results indicated that administrative efficiency, tracking environmental impact and consumer engagement are the most influential practices in their total influence; thus, there is a shift in theoretical focus from purely technical aspects of BCT to its more significant organizational and social implications. P12, ranked highest, is still automated documentation for lowering administrative overhead and thus hints at the ability of BCT to revise end-to-end organizational processes, corroborating transaction cost theory and information asymmetry reduction in supply chains (Bai and Sarkis, 2020). The high ranking of the practices related to environmental impact tracking supports the integration of BCT with the theories on sustainability concerning the LCA methodologies (Kopyto *et al.*, 2020).

Further supported by the prominence in the top ten rankings of consumer-focused practices (P16, P13 and P14), this reiterates the importance of stakeholder theory and consumer behavior models toward an all-rounded understanding of the full potential of BCT in circular economy initiatives. Rehabilitation of these practices, highlighted by the GIA technique, indicates that a more holistic conceptual framework is necessary to capture the complex interactions between technological, organizational and social factors for enabling BCT-enabled circular economy systems. This study further contributes to the literature that is growing daily on the role of 'emerging technologies' in the management of sustainable supply chains by uniquely placing in context how BCT addresses the key challenges related to reverse logistics and the implementation of the circular economy. This study identifies and ranks such practices; therefore, it sets a base for future work regarding the theoretical investigation of how BCT can enhance transparency, traceability and trust in the circular economy ecosystems. The findings of this study further underline that such interdisciplinary theoretical approaches are needed to integrate insights from information systems, supply chain management, environmental science and behavioral economics if the transformational potential of BCT is to significantly contribute to advancing the principles of the circular economy.

It, therefore, brings many practical implications that are very helpful and valuable to organizations that intend or seek to use BCT in their circular economy and reverse logistics operations. The ranking of practices allows the business world to have a prioritized roadmap on which they can focus their efforts and resources on the most influential applications of BCT. The high-ranking practice P12, related to automatization, suggests that each organization should focus on digitizing and automating its processes using BCT, aiming at a maximum compliance cost reduction with enhanced efficiency. High rankings related to tracking environmental impact, P4 and P5, suggest that companies should invest in robust collection and reporting systems for quantifying and communicating sustainability activities. This will enhance internal decision-making and the level of transparency and credibility for the external stakeholders. The fact that P16, P13 and P14 are in the top ten ranking positions underlines that it is highly relevant to involve consumers within a circular economy. The organizations shall create BCT-based platforms to share information, collect feedback and incentivize consumer participation in sustainable behavior. Its findings also underline the need for a holistic approach to BC implementation insofar as the potential impacts of such implementation cut across from the most operational efficiencies up to and including stakeholder engagement. In turn, practices are interdependent and practitioners should be aware of integrated solutions leveraging BCT capabilities across multiple areas simultaneously. P8 is related to inventory optimization, and P9 is related to fraud prevention. Their high ranking among all propositions indicates that business entities should investigate BCT as an enabler to improve efficiency and integrity in reverse logistics operations by real-time tracking systems or developing verification mechanisms through BCT for returned products. Moreover, immunity against tampering of audit trails in the future (P6) and the development and implementation of smart contracts (P7) make BCT a tool to consider first for enhancing regulatory compliance and automating key processes in the circular initiatives of organizations.

7. Conclusion

The research highlights the transformative potential of BCT in enhancing circular economy practices, particularly within reverse logistics. By leveraging BCT's capabilities for safe and immutable data exchange. The study highlights that improving supply chains across all the stakeholders can improve transparency, traceability and trust, essential elements for fostering broader acceptance of circular behaviors. BCT integration resolves logistical and technical issues for long-term development support.

This study identifies and evaluates important circular economy practices by an astute application of the Delphi technique and gives insight into their interdependencies. This systematic methodology guarantees the practical synthesis of expert opinions, providing strategic guidelines for BCT integration to enhance sustainability outcomes. Furthermore, applying GIA enables an extensive probing of the wide interrelations of different elements, subsequently contributing to the findings. Managing large data sets without losing any vital information makes GIA an excellent choice for probing causal dynamics, contributing to a thorough review of the elements of reverse logistics. Findings from the research extend the current understanding of emergent technologies in sustainable supply chains and provide practical implications for companies. The report lays out pivotal information for companies eager to deploy BCT, which is important because it marks these practices as ranked and presents a prioritized roadmap. This cross-disciplinary methodology is important in the total assistance of the BCT to implement the ideas of circular economy principles, thus facilitating more resilient and sustainable business ventures.

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Further reading

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Appendix. The step-by-step process of the GIA technique is given below

Definition (i)

Suppose that $\otimes_{aij}$, i, j = 1, 2, 3, $\cdots$, n represents the influence of *i*th factor on the *j*th factor, determined in gray scales. Then, the influence matrix can be denoted as follows:

$$A(\otimes) = [\otimes_{aij}]\ n \times n = \begin{bmatrix} \otimes a11 & \dots & \otimes a1n \\ \vdots & \ddots & \vdots \\ \otimes an1 & \dots & \otimes ann \end{bmatrix} \quad (1)$$

Definition (ii)

Let's assume that $\otimes\ a_{ij}$; i, $j = 1, 2, 3, \cdots, n$, represents the influence as shown above and $\otimes a_j$ be the sum of influence that a factor j exposes into the system. Then we proceed to compute:

$$\otimes_{pij} = \frac{\otimes_{aij}}{\otimes_{aj}}, i, j = 1, 2, 3 \dots n \quad (2)$$

labeled as the direct influence coefficient. This denotes the degree of influence of factor j over i, indicating their close relation.

Definition (iii)

The matrix demonstrating all values of $\otimes_{pij}$ can be constructed, they can be labeled as the direct influence coefficient matrix, which is denoted as below:

$$P(\otimes) = [\otimes_{pij}]\ n \times n = \begin{bmatrix} \otimes p11 & \dots & \otimes p1n \\ \vdots & \ddots & \vdots \\ \otimes pn1 & \dots & \otimes pnn \end{bmatrix} \quad (3)$$

Definition (iv)

The complete influence coefficient matrix Q is calculated as below:

$$Q\ (\otimes) = \left((I - P\ (\otimes))^{-1} - I\right) \quad (4)$$

where I imply the identity matrix of the similar dimension of P. Here, Q represents the degree of gray connections among factors and the matrix can be denoted as below:

$$Q(\otimes) = [\otimes_{qij}]\ n \times n = \begin{bmatrix} \otimes q11 & \dots & \otimes q1n \\ \vdots & \ddots & \vdots \\ \otimes qn1 & \dots & \otimes qnn \end{bmatrix} \quad (5)$$

Definition (v)

Assume $Q\ (\otimes) = ((I - P\ (\otimes))^{-1} - I)$ signifies the complete influence coefficient matrix, then the gray responsibility coefficient can be calculated as the ith factor as below:

$$ri(\otimes) = \frac{\sum_{j=1}^{n} q_{ij}(\otimes)}{\frac{1}{n}\sum_{i=1}^{n}\ \sum_{j=1}^{n} q_{ij}(\otimes)} \quad (6)$$

Definition (vi)

Let's additionally suppose B = ((I − A) − 1 − I) signifies the complete influence coefficient matrix, then the gray influence coefficient of the jth factor can be shown as follows:

$$sj(\otimes) = \frac{\sum_{i=1}^{n} q_{ij}(\otimes)}{\frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n} q_{ij}(\otimes)} \tag{7}$$

Definition (vii)

The gray responsibility coefficient indicates how much one factor can influence other factors within the system. The gray influence coefficient indicates how much the factor *j* is affected by other system factors. The concept of gray importance coefficients represents how important the factor is for the system, reflecting whether it is influencing or being influenced by other factors. The gray importance coefficients can be computed as below:

$$uij\ (\otimes) = ri\ (\otimes) + sj\ (\otimes)\ \forall i = j \tag{8}$$

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