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Developing a Sustainability Index for Implementing Big Data Analytics in the Logistics Sector

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ABSTRACT

This study identifies Critical Success Factors (CSFs) for implementing Big Data Analytics (BDA) for sustainable logistics practices in the context of an emerging economy. Through a combination of literature review and experts' opinions, the study identifies 18 CSFs essential for the effective application of BDA in the logistics sector. The identified CSFs are further classified into four major categories: Organizational Efforts (OE), Technological Capabilities (TC), Environmental Practices (EP), and Social Factors (SF) using TOE and stakeholders theory. With the help of experts, the identified CSFs are later ranked using the Best-Worst Method (BWM). A real-life Indian logistics company is studied to comprehend its existing operations, technological abilities, workforce competencies, and organizational environment. Further, the Graph Theory Matrix Approach (GTMA) is used to develop a sustainability index for analyzing the case study and expert remarks. The prioritization of CSFs under different categories can guide logistics companies in implementing BDA to achieve sustainability in logistics. The findings from the study reflect that OE and TC are the most important CSFs. The sustainability index value guides the evaluation of the current sustainability of the case company and assists in improving performance by benchmarking the best index values of the same industry. Logistics companies can learn from benchmarked companies and can adopt their strategies for achieving goals, simultaneously considering the ranking of identified CSFs for implementing BDA.

1 | Introduction

Big Data Analytics (BDA) has the ability to transform the logistics sector and help businesses reach more sustainable decisions. Logistics organizations can improve efficiency and lessen environmental impact by utilizing large volumes of data from avenues like sensors, navigational aids, and social media platforms. Both business and academia have largely acknowledged the importance of BDA implementation in sustainable logistics methods (Barreto et al. 2017; Abdirad and Krishnan 2020; Chauhan et al. 2022). According to Darvazeh et al. (2020), favorable effects on various performance variables associated with supply chains and operations management include green supply chain, sustainable manufacturing, sustainable procurement, and enhanced organization values. Several researchers in the literature have discussed the positive impacts of BDA on financial performance, profitability, and productivity (Loon and Peing 2019; Ertz et al. 2025).

Logistics companies can adopt BDA for their logistics operations to reap many benefits that enhance competitiveness (Lai et al. 2018; Thekkoote 2022). The adoption of BDA in the logistics sector can provide accurate weather and traffic forecasts drawing from huge real-time data gathered through Global Positioning System (GPS) devices and satellites (Hopkins and Hawking 2018; Raj et al. 2023). These insights can support logistics firms in traffic congestion reduction and efficient route planning (Hassanin et al. 2021). Further, BDA can be applied to past data trends and customer demand patterns to make informed order management and inventory planning decisions (Lee and Mangalaraj 2022). Moreover, BDA can be a powerful tool for logistics companies to meet sustainable goals, that is, by collecting data on fuel usage and carbon emissions to help track and reduce carbon footprints (Gupta et al. 2024). Using alternative energy sources, optimized routes and energy-efficient vehicles, and reducing waste can be innovative solutions suggested through technological advancements in the logistics sector (Hassanin et al. 2021; Al Doghan and Sundram 2023). Also, BDA can provide opportunities for firms to offer customized solutions while examining customer behavioral and feedback trends (Lai et al. 2018).

Logistics firms need to consider a few factors when adopting BDA for their processes. Data compatibility among different platforms can be an important reason for concern. Further, data quality, privacy, and security also require steady attention (Mageto 2021). A number of obstacles such as the lack of adequate infrastructure (Raut et al. 2021), lack of financial support (Gupta and Singh 2021), and inadequate skilled manpower (Darvazeh et al. 2020) cannot be ignored. Another obstacle is the lack of coordination among different supply chain stakeholders (Keshavarz-Ghorabaee et al. 2020). Governance structures are not stringent enough to regulate BDA protocols in the logistics sector, which is also an obstacle. The technical infrastructure needs to be updated to handle large volumes of data for BDA analysis (Gupta and Singh 2021).

Such difficulties underline the requirement for efficient instruments and techniques for handling, processing, and analyzing big data in logistics to achieve sustainability targets. There is a need for a comprehensive approach that addresses data standardization, data compatibility, data quality and privacy, stakeholder alignment, and governance (Mageto 2021; Pawar and Paluri 2022). Logistics firms also need to adopt sustainable practices to lower their environmental impact, enhance productivity, and provide better customer service. However, past studies have observed that integrating BDA into businesses substantially affects the supply chain and provides a competitive advantage (Dahiya et al. 2022; Gangwar et al. 2023).

Despite growing interest in BDA applications, there is still a knowledge gap surrounding its successful implementation in the logistics sector (Mageto 2021; Bag et al. 2022). Though BDA has been adopted in several industries for process performance improvement, there is limited research on its use, specifically in logistics. Moreover, most of the previous research focuses on the benefits of BDA regarding cost reduction and operational effectiveness enhancement rather than its ability to increase sustainability (Bag et al. 2020). Therefore, this study attempts to identify critical success factors (CSFs) for BDA adoption in the logistics sector. Further, a real-life case illustration of a logistics company has been deliberated to comprehend the application of BDA for achieving sustainability goals; this is further quantified by finding a sustainability index. The study raises the following Research Questions (RQs).

RQ1. What organizational, technological, environmental, and social factors drive successful BDA adoption in logistics?

RQ2. How do logistics companies achieve sustainability goals with BDA adoption?

The study comprises the following sections. Section 2 reviews the literature on digital technologies in logistics, sustainability in logistics, and BDA for sustainability in logistics. Section 3 presents the theoretical framework for identifying CSFs. Section 4 provides the research methodology, including techniques for gathering and analyzing data. The results, case study, and evaluation of the sustainability index are discussed in Section 5. Sections 6 and 7 provide the study's discussion and theoretical and practical contributions. In Section 8, the study concludes with recommendations for future research.

2 | Literature Review

In existing literature, researchers have explored BDA, its application in logistics operations, and its potential to support sustainable practices in the logistics sector. The literature review explores the CSFs for effective BDA implementation.

2.1 | Digital Technology Adoption in the Logistics Sector

The logistics sector has experienced notable transformations over the past years due to factors such as modifications in regulatory policies, growth of information and technology, changes in industrial models, environmental concerns, infrastructural challenges, and technical advancements (Cichosz et al. 2020; Gupta and Singh 2021). Though the logistics sector continues to improve, the supply chain needs to be more robust, and stakeholders' collaboration needs to be enhanced through standardization of processes (Darvazeh et al. 2020). There are possibilities and challenges associated with the adoption of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Blockchain, and BDA (Jiao et al. 2018; Abdirad and Krishnan 2020). Digital technologies can assist logistics firms in building intelligent networks and creative business models to improve connectivity and interoperability with suppliers and consumers (Barreto et al. 2017). Businesses can improve efficiency, adaptability, and resilience by incorporating advanced digital technologies into their logistics operations.

Mikalef et al. (2020) highlighted the importance of BDA in supply chain and logistics, stating that it can boost a firm's productivity while offering it a competitive advantage. Logistics firms can utilize BDA for large-scale data collection, storage, and analysis from different perspectives (Lai et al. 2018; Queiroz and Telles 2018). BDA offers a cohesive structure for instantaneous data analysis under different crucial decision-making scenarios and supports tracking customer engagement, enhancing supply chain visibility, and mitigating the associated risks of supply chain disruptions and failures (Chauhan et al. 2022).

Logistics firms can adopt BDA for several benefits, including improved demand forecasting, better risk management, enhanced productivity and efficiency, increased visibility, and improved customer service (Raut et al. 2021). BDA can help businesses understand important demand patterns and data from large datasets, and its insights can help them devise impactful future business strategies (Darvazeh et al. 2020). However, despite the many advantages of BDA, there are a few difficulties with BDA adoption in logistics, including high investment, shortage of skilled manpower, restricted mindset of employees, compatibility with existing systems, data availability, privacy, and quality of data (Keshavarz-Ghorabaee et al. 2020).

2.2 | BDA for Sustainability in Logistics

Sustainability in logistics refers to adopting eco-friendly methods, reducing wastage in delivering shipments, and adopting other sustainable practices for logistics operations. It includes responsible management of logistics operations to maintain a balance between current needs and preserving opportunities for succeeding generations to satisfy their requirements (WCED 1987). In the logistics sector, long-term goals related to the economy, environment, and society are aligned with sustainable goals. To achieve these sustainable goals, logistics firms adopt cost-cutting strategies to yield economic benefits, use alternate options to save resources for future generations, and implement renewable alternatives to reduce carbon footprints to save the environment (Sun et al. 2021). Logistics firms are now encouraged to adopt sustainable procurement, production, and distribution to increase circular practices. After COVID-19, businesses underlined the importance of sustainable logistics and distributions and revised their traditional processes to sustainable methods. The implementation of sustainable practices assists businesses in reducing their environmental influence and improving their resilience to shocks (Jinru et al. 2021). The implementation of sustainable initiatives in logistics may face obstacles due to inadequate regulatory support, insufficient knowledge and expertise, low customer demand, inadequate infrastructure, non-availability of capital, and resistance to change. Coordination and collaboration of all stakeholders (logistics companies, legislators, suppliers, and customers) are required to remove such challenges by raising awareness, offering legal and financial support, and fostering cooperation and knowledge sharing (Chhabra and Kr Singh 2024).

Abdirad and Krishnan (2020) highlighted the importance of digital technologies for supporting sustainable production and the circular economy since they increase the effectiveness of resources and decrease waste in supply chains. The major resources needed for such technologies to be implemented are human, financial, technological, and regulatory (Barbosa et al. 2018). Logistics firms can decrease the environmental impact caused by their operations and contribute to achieving sustainability goals by investing in such resources (Fosso Wamba et al. 2020; Bag, Pretorius, et al. 2021; Bag, Yadav, et al. 2021). BDA has a major role to play in technological contexts rather than in just strategic and operational contexts. Being an Industry 4.0 technology, BDA can contribute to increasing intelligence, production, and design efficiency; however, it also assists in operation planning to handle problems with day-to-day logistics operations, procurement, and inventories. The advantages of utilizing BDA in the supply chain and logistics are well documented in past studies. BDA can help optimize resource allocation at different facets of the supply chain (Tamym et al. 2023). Furthermore, businesses are trying to attain sustainability goals and maintain their competitiveness in the existing business environment, which now heavily depends on BDA (Darvazeh et al. 2020; Mikalef et al. 2020). Businesses with higher BDA competence levels are more likely to attain increased sustainability in their supply chains through increased transparency and traceability, improved productivity, and better planning and forecasting. This can be accomplished by creating a data-driven culture, establishing reliable supplier relationships, and supporting training and development initiatives to acquire sustainable competencies (Jeble et al. 2018).

BDA helps logistics firms identify inefficient supply chain practices and allows them to optimize their processes by reducing expenses and negative environmental effects. Businesses can utilize BDA to track and monitor their materials and shipments along the supply chain, thus boosting transparency and enabling effective decision-making. This technology can also assist firms in detecting possible supply chain risks and suggesting risk mitigation strategies using sustainable practices. To attain sustainability, logistics firms should concentrate on creating a data-driven culture that prioritizes data management and invests in data analytics tools and technologies across the entire supply chain (Raut et al. 2021).

2.3 | Research Gaps

The literature on BDA for sustainability in the logistics sector is summarized in Table 1.

Table 1 highlights that the studies conducted in the past have either discussed the basic understanding of BDA or the sustainability aspect is missing. As per the authors' information, the sustainable supply chain is evident in the past literature, but specific consideration for the logistics sector with a sustainable perspective is completely missing. Furthermore, developed countries have different infrastructural and technical concerns and the studies conducted in developed countries cannot be the right fit for developing countries. Based on the discussions and Table 1, the following Research Gaps (RGs) have been identified.

RG1: In literature, most of the research is conducted to study BDA in sustainable supply chain management in the context of developed countries, such as European and North American countries (Tseng et al. 2019; Bag et al. 2020; Mageto 2021), whereas very few studies have investigated the factors that affect the execution of BDA in the logistics sector in the context of developing countries. Therefore, this study discusses the extension of previous studies and explores the possibilities of BDA implementation in the logistics sector in developing countries, such as India.

RG2: The second research gap highlights that there is hardly any study that links BDA, the logistics sector, and sustainability existing in the current literature. This study fills the existing gap by proposing CSFs that can guide logistics companies in effectively implementing BDA to achieve their sustainability goals.

TABLE 1 | Summary of past studies on BDA for sustainable logistics.

Source	Country/domain	Main purpose of the study	Factors	Theories/tools applied	Research gaps
Lai et al. (2018)	China/Logistics and supply chain	To explore the firm's intention to adopt BDA for daily operations	Drivers: Perceived benefits, management support Barriers: Environmental uncertainty	Diffusion Innovation Theory, PLS-SEM	– Early-stage understanding of drivers and barriers of BDA – Respondents from the IT domain only – Lack of holistic validation – The sustainability aspect is missing
Bag et al. (2020)	South Africa/Mining industry	To investigate the roles of BDA in sustainable supply chain outcomes	Drivers: BDA management, talent capabilities	Dynamic Capability Theory	– Basic understanding of BDA (drivers) – Focused mainly on mining – Limited exploration of BDA capabilities with the lens of talent – The sustainability component is missing in defining drivers
Mageto (2021)	South Africa/Manufacturing	To study the effect of BDA on a sustainable supply chain concerning the manufacturing sector	Drivers: Real-time data, transparency, risk management, and organizational culture	Toulmin's Argumentation Conceptual Model	– Initial stage of analyzing drivers – Sustainable and environmental concerns are lacking – Real-world validation of BDA is missing
Alalawneh and Alkhatib (2021)	Jordan/Multiple sectors	To identify the barriers to BDA and their relative importance across sectors to understand sectors' readiness for BDA	Barriers: Technological, organizational, human, economic, external, and environmental barriers	AHP-TOPSIS	– Barriers to BDA were explored – Mostly focused on developed economies – Sustainability component is missing
Gangwar et al. (2023)	India/E-commerce (Fashion)	To develop a sustainability evaluation framework to evaluate potential drivers of BDA	Drivers: Economic, social, and environmental drivers	SEM, F-AHP	– Limited studies linking BDA and sustainability in e-commerce in emerging economies – Providing information about drivers and potential evaluation, but the factors that have to be prioritized while implementing BDA are lacking

(Continues)

TABLE 1 | (Continued)

Source	Country/domain	Main purpose of the study	Factors	Theories/ tools applied	Research gaps
Jain et al. (2024)	India/Manufacturing	To address the issue of the implementation of BDA in manufacturing for a sustainable supply chain	Factors: Political, economic, social, technological, environmental, and legal factors	PESTEL framework, TISM, MICMAC	– Focused on the manufacturing sector – Contextual relationship among factors created, but a robust framework for sustainability evaluation is missing
This study	India/Logistics sector	To identify and prioritize critical success factors for implementing BDA in the logistics sector to achieve sustainability goals	CSFs: Organizational efforts, technological capabilities, environmental practices, and social factors	TOE and Stakeholder Theory Tools: BWM and GTMA	Gaps addressed: – Focus on the logistics sector – Focus on developing countries – Prioritize CSFs to guide companies in BDA implementation – Evaluate a sustainability index that can help logistics companies in developing strategies to achieve sustainability goals

RG3: The third research gap highlights the methodologies used for model development for BDA in past studies. In the literature, various tools and techniques have been used by several authors for the analysis of barriers and readiness factors for BDA (Gangwar et al. 2023; Jain et al. 2024). As per the author's information, despite many benefits, no study has evaluated the sustainability Index for the analysis. The authors considered a real-life case illustration and evaluated the sustainability index to help logistics companies meet sustainable objectives using advanced technologies such as BDA.

3 | Theoretical Background to Identifying CSFs

From the research gaps, it can be noted that the sustainability focus within BDA for the logistics domain requires attention. This study addresses the gap by identifying CSFs required by logistics companies to implement BDA for sustainable initiatives. This identification of CSFs is theoretically complemented by existing theories in literature. This study adopts a combination of the Technology, Organization, Environment (TOE) theory and Stakeholder Theory (ST) to identify CSFs for implementing BDA in the logistics sector. In past studies, Resource-Based View (RBV) and Dynamic Capabilities Theory (DCT) were widely referred to as addressing a firm's internal resources and adaptive capabilities but were limited in catering to complex and multiple layered factors impacting technology adoption in dynamic and resource-constrained environments (Kero and Bogale 2023). TOE and ST are preferred over the integration of RBV and DCT in this study, as TOE effectively captures technological advancements, organizational readiness, and external environmental pressures influencing BDA adoption. This is more prevalent in the context of developing countries, where organizational capacity and technological disparities are common, and environmental considerations are increasingly critical for achieving sustainability. Meanwhile, the integration of the TOE framework with ST enables a comprehensive understanding of how diverse stakeholders (ranging from government, regulatory bodies, suppliers, to customers) collectively influence stakeholder dynamics and facilitate technological integration across all levels of the supply chain, thereby supporting the achievement of sustainability goals.

The recent extensions of the TOE framework, such as the Technological-Organizational-Environmental-Sustainability (TOES) framework, explicitly include sustainability as a vital dimension influencing technology adoption (Satyro et al. 2024). Similarly, Hörisch et al. (2014) emphasized the importance of sustainability in ST to create engagement strategies that can empower all stakeholders to contribute toward sustainable transition (Gibson 2012). This expanded view enables researchers to assess the interplay between technological development, organizational capabilities, environmental concerns, and sustainable development goals. This perspective is empirically validated by Dadhich and Hiran (2022), incorporating corporate environmental sustainability into the TOE framework. This theoretical alignment of integrating TOE and ST for acknowledging sustainability concerns provides a robust foundation for examining BDA adoption for sustainable logistics in developing countries, considering both internal readiness and wider socio-environmental aspects.

3.1 | Technology, Organization and Environment (TOE) Theory

Tornatzky and Fleischer (1990) proposed an organization-level theory that understands and analyzes innovation, focusing on three contexts: technology, organization, and environment. The technology context helps organizations explore technological features and the potential benefits of the latest technologies (Awa et al. 2017; Gupta et al. 2024). In this study, the features and applications of BDA can provide actionable insights into how technology can reshape existing processes. The context can help organizations understand their readiness and resource availability for BDA implementation (Hanna et al. 2020). It advocates the support of organizational culture, structure, and resources for the successful implementation of digital technologies. The environmental context incorporates the environmental dimension where an organization takes sustainable steps to create awareness and concern for eco-friendly operations (Amini and Bakri 2015). The applications of BDA in logistics operations promote better inventory planning, resulting in waste reduction and resource optimization. The TOE framework can be well suited for this study as it covers multiple perspectives, including those at the technology, organization, and environmental levels. In most of the theories, the environmental aspect remains untouched. It can be applied to all phases of the innovation cycle, from adoption to implementation, including sustainability concerns.

3.2 | Stakeholder's Theory

Freeman (1984) introduced stakeholder theory, which covers the social perspective of the study that was not covered by the TOE theory. It asserts that organizations are influenced by various internal and external stakeholders (Freeman and Dmytriyev 2017). Several stakeholders, including government, supply chain partners, manufacturers, third-party logistics, employees, customers, and society communities, are involved when it comes to BDA implementation in the logistics sector. The stakeholders, all of whom are affected by the organization's actions, will be considered in a holistic approach (Kaler 2006; Parmar et al. 2010). The theory focuses mainly on organizations that are broadly responsible for all the stakeholders who contribute to creating value for businesses (Garvare and Johansson 2010). Bonnafous-Boucher and Rendtorff (2016) highlighted the importance of interconnections among management and stakeholders in the successful implementation of processes and systems. The innovations in processes lead to mutual benefits and ensure long-term business success as well as social and sustainable benefits.

Based on the integration of TOE and ST theories, the following broader categories of CSFs for BDA adoption have been identified.

3.2.1 | Technological Capabilities (TC)

Logistics firms must gain technological capabilities to adopt and implement BDA to achieve sustainability goals. The huge data gathered at various supply chain stages can be processed and analyzed through such skills to provide actionable insights, enabling firms to make effective decisions (Naway and Rahmat 2019; Moldabekova et al. 2021). Organizations must develop technical infrastructure, provide hardware and software support, and manage data compatibility issues. Specific hands-on training is required for employees to fill the gap between existing and advanced digital technologies that need to be implemented. Developing and investing in technological capabilities is much needed to implement BDA in logistics (Gupta and Singh 2021; Parhi et al. 2022).

3.2.2 | Organizational Efforts (OE)

Top management must be involved in order to implement BDA in the logistics sector. The strategies devised at the organizational level drive all the processes and systems at internal and external sources (Daugherty et al. 2011; Karagöz and Akgün 2015). Management efforts and effective decision-making enhance the efficiency and productivity of business processes like procurement planning, sales optimization, inventory management, and customer management (Gupta and Singh 2021; Raut et al. 2021). The organization must train employees with the desired skill sets for implementing BDA and collaborate with supply chain partners to create value throughout the supply chain.

3.2.3 | Environmental Practices (EP)

Logistics firms are also adopting BDA to achieve environmental targets. Researchers in past studies explored the benefits of using digital technologies to reduce logistics operations' negative impact on the ecosystem (Parmentola et al. 2022; Qureshi et al. 2024). Organizations can adopt energy source alternatives for reducing wastage and minimizing the carbon footprint through technological support (Gupta et al. 2024). Government policies and concern for the environment can also encourage organizations to construct technological advancements in their sustainable logistics practices. BDA adoption can help logistics firms solve environmental concerns and meet sustainability targets (Sanders 2016; Singh and El-Kassar 2019).

3.2.4 | Social Factors (SF)

Social factors influence the adoption of BDA in the logistics sector. Policymakers and Government agencies must take action to develop social policies, execute strategies, and assist in the integration of sustainable logistics systems. Legal actions are required to safeguard social media data. In the Indian setting, regulatory norms play a crucial role in encouraging socially conscious BDA practices in enterprises (Raut et al. 2021; Parhi et al. 2022).

3.3 | Identification and Contextualization of CSFs

The categories have been extracted from TOE and ST theories, and 18 CSFs for implementing BDA have been identified from the literature review. After consulting with experts, the identified CSFs are clubbed under four categories: Technological

Capabilities (TC), Organizational Efforts (OE), Environmental Practices (EP), and Social Factors (SF). Table 2 presents CSFs for implementing BDA, along with their categories.

Figure 1 highlights the alignment of CSFs with sustainability outcomes.

The experts considered for this study are from supply chain, logistics and IT domains with rich experience in the logistics industry and also working with sustainable practices. The experts' details are provided in Table 3.

4 | Research Methodology

In literature, various Multi Criteria Decision Making (MCDM) techniques have been applied by several researchers to analyze the factors, barriers, and drivers, as discussed in Table 1. In this study, the Best-Worst Method (BWM) is preferred over other MCDM methods due to its inherent benefits and limitations of other methods.

The research methodology is a three-step process that involves different phases. The first step consists of a vast literature review, expert opinion, and identification of CSFs for implementing BDA in the logistics sector. In the second step, the BWM is applied to identified CSFs for prioritization based on inputs from industry experts. In the last step, the Graph Theory Matrix Approach (GTMA) is applied to evaluate the sustainability index of a case logistics company. The steps followed in the research methodology are presented in Figure 2.

The comparison among similar MCDM methods with BWM is discussed in Table 4.

4.1 | Best-Worst Method (BWM)

This study employs the BWM to prioritize these CSFs (Rezaei et al. 2015; Salimi and Rezaei 2018). BWM deals with a large number of criteria and alternatives and provides more effective results while taking inputs from multiple decision-makers. BWM has been applied in several research studies due to its

TABLE 2 | CSFs for implementing BDA.

Categories	CSFs for implementing BDA	References
Technological Capabilities (TC)	Technical Infrastructure (TC_1)	(Gupta and Singh 2021; Wang et al. 2020)
	Trained and technically skilled manpower (TC_2)	(Darvazeh et al. 2020; Gupta et al. 2022)
	Use of data mining and data storage tools for sustainable practices (TC_3)	(Raut et al. 2021; Parhi et al. 2022)
	Use of energy-efficient technologies for reducing CHCs (TC_4)	(Raut et al. 2021)
	Improve scalability (TC_5)	(Dubey et al. 2019)
Organizational Efforts (OE)	Top management's commitment and interest (OE_1)	(Raut et al. 2021)
	Training and education of employees (OE_2)	(Raut et al. 2021; Parhi et al. 2022)
	Motivate employees to use digital and sustainable technologies (OE_3)	(Raut et al. 2021; Parhi et al. 2022)
	Formation of stringent sustainable and digital policies (OE_4)	(Keshavarz-Ghorabaee et al. 2020; Raut et al. 2021; Papadopoulos et al. 2017)
	Coordination and collaboration among supply chain partners (OE_5)	(Raut et al. 2021; Parhi et al. 2022)
Environmental Practices (EP)	Use of alternate fuel sources for reducing carbon footprints (EP_1)	(Singh and El-Kassar 2019; Gupta et al. 2024; Yasir et al. 2023)
	Use of reusable and recyclable materials (EP_2)	(Sanders 2016; Parhi et al. 2022)
	Adoption of lean and six sigma practices (EP_3)	(Raut et al. 2021; Shukla et al. 2021)
	Allocation of resources for optimization (EP_4)	(Gupta and Singh 2021; Hazen and Byrd 2012)
Social Factors (SF)	Government incentive policies for sustainability (SF_1)	(Raut et al. 2021; Maheshwari et al. 2021)
	Concerns towards data privacy and security (SF_2)	(Loon and Peing 2019; Parhi et al. 2022)
	Regulatory pressure to promote sustainability (SF_3)	(Raut et al. 2021; Gangwar et al. 2023)
	Corporate social responsibility for sustainable business practices (SF_4)	(Gupta and Singh 2021)

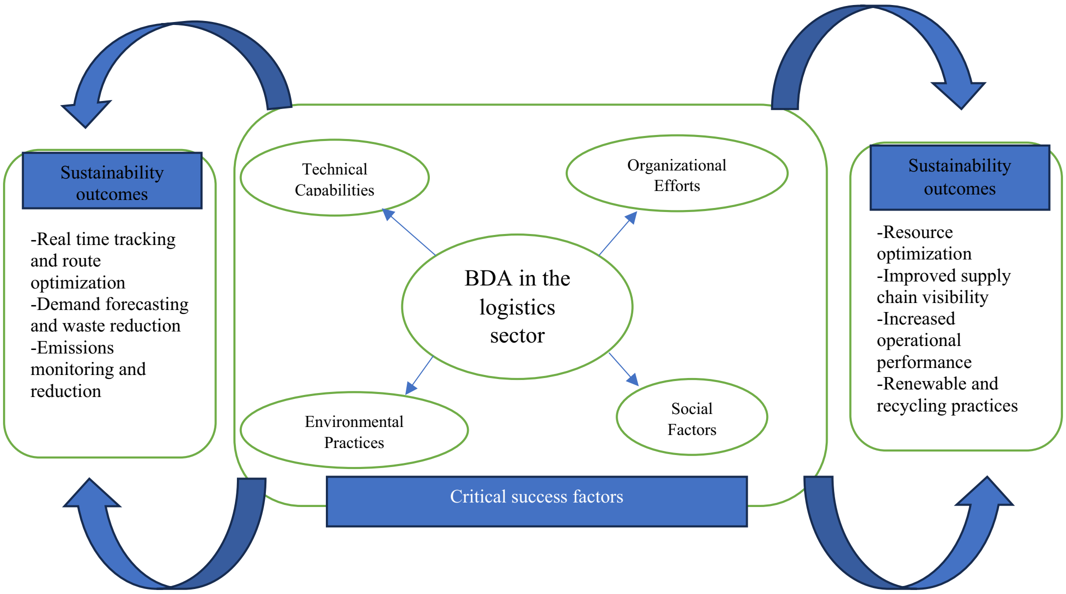

FIGURE 1 | Alignment of CSFs with sustainability outcomes.

TABLE 3 | Brief details of experts involved in the study.

Expert ID	Domain of expertise	Designation	Experience (in years)
Expert 1	Logistics management and green SC practices	Head, Logistics & Sustainability	11
Expert 2	Supply chain operations and technology	Manager, Supply chain management	16
Expert 3	AI/ML in supply chain operations	Lead, Digital transformation	12
Expert 4	Data handling using emerging technologies	Head, Data management	13
Expert 5	Technology transfer	Senior Manager, IT	15
Expert 6	Freight transportation	Head, Logistics	20
Expert 7	Supply chain operations	Regional Manager, Supply chain management	14
Expert 8	Procurement and risk mitigation	Senior Executive, Sourcing	13
Expert 9	Green Supply chain operations & ESG reporting	Senior Manager, Supply chain and sustainable operations	15
Expert 10	Technology management in SC operations	Head, IT Department	21

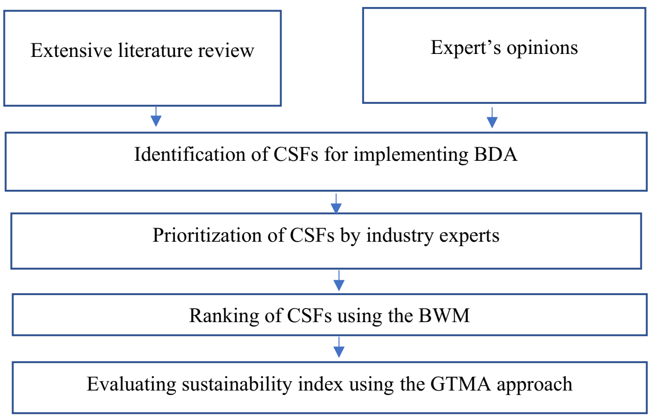

FIGURE 2 | Research methodology.

multiple advantages. For instance, Amiri et al. (2021) applied it to evaluate and select sustainable suppliers. Gupta and Singh (2021) prioritized CSFs for emerging technologies applications in the logistics sector. Dehshiri et al. (2022) used this approach for implementing blockchain technology in the automotive supply chain. Alshamrani et al. (2023) ranked alternatives and applications of renewable energy sources using this method.

The steps of the BWM method are as follows (Rezaei et al. 2015; Rezaei et al. 2016):

Step 1. Identify CSFs as ($C1, C2, C3, \ldots, Cn$).

Step 2. Decision makers select the best (B) and worst (W) CSFs.

TABLE 4 | Comparison of similar MCDM methods.

Method	Purpose	Strengths	Limitations	Source
AHP (Analytical Hierarchy Process)	Evaluating criteria weights through pair-wise comparison matrices	• Structured/hierarchical • Select the best alternative from all the given options • Precise judgements from experts based on crisp values	• Small problems' computation is manageable, but become complicated in case of complex and big problems • It doesn't handle vagueness or uncertainty well	Saaty (1977)
F-AHP (Fuzzy- Analytical Hierarchy Process)	Handling fuzziness and vagueness in decision-making	• Incorporates fuzzy logic to manage uncertainty in criteria weights • Provides more flexibility for the experts	• Computation is more complex and time-consuming • Need to handle defuzzification • Subjectivity	Van Laarhoven and Pedrycz (1983)
TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)	Evaluating and ranking different alternatives based on multiple criteria	• Does not require pair-wise comparison matrices as in AHP • Emphasis on the distance between positive and negative alternatives and selecting the best alternative based on its closeness to the ideal solution	• Requires initial weights to be defined for the criteria being evaluated • Sensitive to the scale of data	Hwang et al. (1981)
Fuzzy TOPSIS	Handling fuzziness and vagueness in finding the best alternative based on multiple criteria	• Manage uncertainties in real-world complex problems • Choose the best solution based on the distance between alternatives	• Requires initial weights to proceed • Requires accurate fuzzy data • Intensive computation	Chen and Hwang (1992)
BWM	Finding the best alternative based on the best and worst criteria comparisons	• Fewer calculations • Less number of comparisons are needed • More consistency in judgments • Structured	• Concern about uncertainty is not addressed • Difficult to manage complex and big problems	Rezaei et al. (2015)

Step 3. Create a Best-to-Others (BO) vector (A_B) using a 1–9 scale (Table 5):

$$A_B = \left(a_{B1,}\ a_{B2,\ldots}\ a_{Bn}\right) \tag{1}$$

where a_{Bj} represents the importance of Best Criterion B with criterion j.

Step 4. Create an Others-to-Worst (WO) vector (A_W) using the same scale:

$$A_W = (a_{1w,}\ a_{2w,}\ \ldots\ , a_{nw)} \tag{2}$$

where a_{ww} denotes the importance of criterion j over the worst criterion W.

Step 5. Calculate optimal weights (w^*_1, w^*_2, ..., w^*_n) to minimize the maximum absolute differences using a min–max model:

Minimize the maximum value across all j in the set

$$\left\{|w_B - a_{Bj}w_j|, |w_j - a_{jw}w_w|\right\}$$

Subject to,

$$\sum_i w_j = 1$$

$$w_j \geq 0, \text{for all } j \tag{3}$$

This can be reformulated into a linear programming problem:

$$\text{Min } \xi^L$$

Subject to,

$$|\ w_B - a_{Bj}w_j\ | \ \leq \xi^L, \text{for all } j$$

$$|\ w_j - a_{jw}w_w\ | \ \leq \xi^L \text{ for all } j$$

$$\sum_i w_j = 1$$

TABLE 5 | Scale used for comparison (Rezaei et al. 2015).

Value	Scale
1	Equal importance
2	Somewhat between equal and moderate
3	Moderately more important than
4	Somewhat between moderate and strong
5	Strongly more important than
6	Somewhat between strong and very strong
7	Very strongly important than
8	Somewhat between very strong and absolute
9	Absolutely more important than

$$w_j \geq 0, \text{for all } j \tag{4}$$

It yields the ideal weight for all criteria and the objective function ξ^L. A lower ξ^L indicates greater consistency, while a higher ξ^L suggests less consistency.

4.2 | Graph Theory Matrix Approach (GTMA)

GTMA is applied in this research to evaluate the sustainability index of the case logistics company, which has implemented BDA for its logistics operations. GTMA is a general method that simultaneously considers qualitative and quantitative variables (Wagner and Neshat 2010). This method uses mathematical analysis to develop interrelationships among variables (Hudnurkar and Ambekar 2019; Rao 2006). GTMA is better than other traditional methods because of its simple representation and easy quantification (Gupta et al. 2020). It shows a graphical representation of variables in the form of diagraphs, which provides a clear and systematic structure. The inputs from diagraphs are further used to form permanent functions and matrices. The traditional index-calculating methods only emphasize the quantitative aspect and consider only independent variables, whereas GTMA explicitly models the interdependencies between variables (Altomare et al. 2019; Agarwal et al. 2022). As in this study, GTMA helps in understanding complex problems such as BDA implementation, where all the factors influence each other.

GTMA has been applied to several studies in multiple domains, including evaluating sustainability index for logistics service providers (Gupta and Singh 2020), identifying innovative technology adopters for drones (Ali et al. 2023), managing design principles for sustainable manufacturing of I4.0 (Shupti et al. 2024), and index barrier intensity index for blockchain adoption for carbon reduction (Gupta et al. 2024).

5 | Analysis and Results

This section is divided into two sub-sections. In the first section, the prioritization of CSFs is performed using the BWM approach. The second section evaluates the sustainability index for logistics companies.

5.1 | Prioritization of CSFs

For this study, 10 industry experts from logistics companies were contacted, and their valuable insights on the prioritization of CSFs for implementing BDA in the logistics sector were taken and noted (Details of experts are given in Table 3). The experts were chosen based on their experience in the logistics sector and the suitability of their profile for the study. Multiple online and offline meetings were conducted to gather relevant information. The given inputs are used for finding optimal weights of all categories and CSFs using BWM and are summarized in Tables 6 and 7. Based on optimal weights, the ranking of CSFs is determined and presented in Table 7.

The four major categories are considered crucial for implementing BDA in the logistics sector. As shown in Table 6, TC (0.5278) is

TABLE 6 | Optimal weights of categories of CSFs.

Decision-maker	Optimal weights of categories				
	TC	OE	EP	SF	Ksi*
1	0.520	0.230	0.080	0.170	0.17
2	0.600	0.180	0.170	0.050	0.14
3	0.300	0.510	0.070	0.120	0.09
4	0.770	0.080	0.020	0.130	0.27
5	0.528	0.372	0.002	0.098	0.25
6	0.410	0.350	0.160	0.080	0.26
7	0.770	0.200	0.020	0.010	0.25
8	0.250	0.250	0.300	0.200	0.22
9	0.780	0.200	0.010	0.010	0.19
10	0.350	0.180	0.110	0.360	0.19
Average	**0.5278**	**0.2552**	**0.09424**	**0.12276**	**0.203**

the most impactful factor, followed by OE (0.2552), SF (0.12276), and EP (0.09424). Under TC, technical infrastructure is required to understand digital transformations and accommodate desired advancements in existing systems. Under OE, coordinating and collaborating among supply chain partners is most important in adopting and implementing BDA to ensure effective data mining, inventory handling, and route optimization. Under EP, the adoption of lean and six sigma practices is found to be most important, and logistics companies need to revise their processes to become digital and sustainable. Under SF, data privacy and security concerns are found to be the most important factors for logistics companies to push for more sustainable practices.

5.2 | Evaluating Sustainability Index for Logistics Companies

To answer the second RQ, the application of BDA for sustainability is empirically evaluated through a real-life case illustration of a logistics company. A real-life case illustration is considered to better observe the role of BDA in sustainability in Indian logistics companies. *XYZ* Logistics (name changed to maintain anonymity), is a global logistics leader with a $140 million annual turnover and a workforce of 5500 people with a large infrastructure, yet they still had problems with data overload, poor inventory management, and ineffective route planning. Before the implementation of BDA, traditional systems offered limited insights that resulted in delayed deliveries, high fuel consumption, and inefficient order and inventory management. This affected customer satisfaction and profit margins remained relatively low, and the company's environmental impact was significant with increased carbon emissions. We have discussed the identified CSFs and their prioritization for implementing BDA in their organization.

Then, the company teamed up with Google Cloud to harness BDA and experienced a substantial transformation. *XYZ* Logistics gathered information on vehicle movements through GPS devices and used predictive analytics for route optimization, significantly reducing delivery times by 15%. The company was facing issues with data management, including overloading and inefficient processing, but these tools have enabled real-time dashboards and advanced analytics to provide accurate demand forecasting and improved inventory management. As a result, fuel consumption was reduced by 10% and inventory expenses dropped by 12%, reflecting both cost-effective and sustainable benefits. Additionally, the adoption of advanced technologies and customized logistics solutions boosted the sales and profit margins to 5%, ultimately resulting in a notable increase of 20% in customer satisfaction, with an achieved 85%+OTIF rate (on-time-in-full) and reduced re-deliveries. Also, the company has reported a 20% carbon reduction per package after optimizing routes using BDA tools. After implementing BDA, the company reduced fuel consumption and carbon footprint to show its commitment to sustainability. In conclusion, *XYZ* Logistics' collaboration with Google Cloud and BDA optimization revolutionized its processes. This case study shows how data-driven insights can help the logistics company achieve sustainability goals while enhancing productivity, profitability, and customer satisfaction.

The company experts have given their inputs for CSFs and helped in understanding BDA's impact on improving their logistics operations and processes. A questionnaire was prepared and distributed to the relevant individuals. The inputs were used to develop a permanent matrix to find the sustainability index of *XYZ* logistics using GTMA. In the permanent matrix, CSFs are placed at the diagonal, and other values are found based on the correlation among CSFs. A 5-point scale is used to scale diagonal elements, with 5 considered the most important and 1 the least important. The remaining values are scaled based on Table 8. After calculating the permanent value for all categories of CSFs, the best and worst values for each category are evaluated. The detailed steps for evaluating the sustainability index are discussed in subsequent sections, as given by Hudnurkar and Ambekar (2019).

5.2.1 | Variable Digraphs

The variable digraph illustrates the CSFs. They are indicated by the nodes in this diagram, and their relationships are indicated by the edges. "X_i" indicates factor inheritance, while "x_{ij}" indicates the dependence of one factor on another. Such dependencies are shown by the directional edges that connect node "*i*" to node "*j*". This digraph visually represents the relationships between all the CSFs, which helps in a comprehensive and in-depth analysis. Figure 3 displays the relationships between all the major categories.

OE digraph is displayed in Figure 4, with the sub-factors represented by the nodes OE_1, OE_2, OE_3, OE_4, and OE_5 and their interrelationships represented by x_{ij}. In a similar manner, digraphs are created for TC, EP, and SF.

5.2.2 | Matrix Representation

Matrix representations of all the major categories are discussed. A 4-by-4 matrix is represented by considering the four major categories of CSFs. The CSFs TC, OE, EP, and SF are represented by nodes in the matrix "*R*," and the significance of the *i*th factor

TABLE 7 | Ranking of CSFs.

Category	Weight	CSFs	Local weight	Local ranking	Global weight	Global ranking
TC	0.5278	TC_1	0.370077	1	0.1953	1
		TC_2	0.232094	2	0.1225	2
		TC_3	0.128090	4	0.0676	5
		TC_4	0.163414	3	0.0862	4
		TC_5	0.106326	5	0.0561	7
OE	0.2552	OE_1	0.223496	2	0.0570	6
		OE_2	0.133223	4	0.0340	12
		OE_3	0.164993	3	0.0421	8
		OE_4	0.102700	5	0.0262	14
		OE_5	0.375588	1	0.0959	3
EP	0.09424	EP_1	0.162048	3	0.0153	17
		EP_2	0.309859	2	0.0292	13
		EP_3	0.412048	1	0.0388	9
		EP_4	0.116045	4	0.0109	18
SF	0.12276	SF_1	0.302604	2	0.0371	11
		SF_2	0.305467	1	0.0375	10
		SF_3	0.197847	3	0.0243	15
		SF_4	0.194082	4	0.0238	16

TABLE 8 | Relative dependence of CSFs.

Qualitative measures of interdependencies	Relative dependence of CSFs	
	x_{ij}	$x_{ji}=10-x_{ij}$
Two factors are of equal importance	5	5
One factor is slightly dependent on the other	6	4
One factor is very dependent on the other	7	3
One factor is most dependent on the other	8	2
One factor is extremely dependent on the other	9	1
One factor is exceptionally dependent on the other	10	0

compared to the *j*th factor is shown by the edges, denoted by x_{ij} in Equation (5).

$$R=\begin{vmatrix} TC & x_{12} & x_{13} & x_{14} \\ x_{21} & OE & x_{23} & x_{24} \\ x_{31} & x_{32} & EP & x_{34} \\ x_{41} & x_{42} & x_{43} & SF \end{vmatrix} \tag{5}$$

The permanent function of the sustainability index is shown in Equation (6).

$$\text{Perm (OE)} = \text{Perm}\left(X_1\right) = \begin{vmatrix} X^1 1 & X^1_{12} & X^1_{13} & X^1_{14} & X^1_{15} \\ X^1_{21} & X^1 2 & X^1_{23} & X^1_{24} & X^1_{25} \\ X^1_{31} & X^1_{32} & X^1 3 & X^1_{34} & X^1_{35} \\ X^1_{41} & X^1_{42} & X^1_{43} & X^1 4 & X^1_{45} \\ X^1_{51} & X^1_{52} & X^1_{53} & X^1_{54} & X^1 5 \end{vmatrix} \tag{6}$$

where $X^1 1$, $X^1 2$, $X^1 3$, $X^1 4$, and $X^1 5$ represent OE_1, OE_2, OE_3, OE_4, and OE_5 respectively.

Similar matrices for TC, EP, and SF are developed.

5.2.3 | Quantification of Interdependencies

To determine the output of the permanent function (Perm X), quantitative values must be assigned to X_i's and x_{ij}'s, as shown in Equations (5) and (6). A scale of 1 to 5 is used to assess the qualitative assessment of the major categories (x_i), with 5 being the highest rating and 1 being the lowest. Table 8 discusses the quantification of the qualitative measures of interdependencies among CSFs (x_{ij}), based on the relative dependence as evaluated by experts. The experts were asked to evaluate the significance of the CSFs and the level of interdependence between them using the specified criteria.

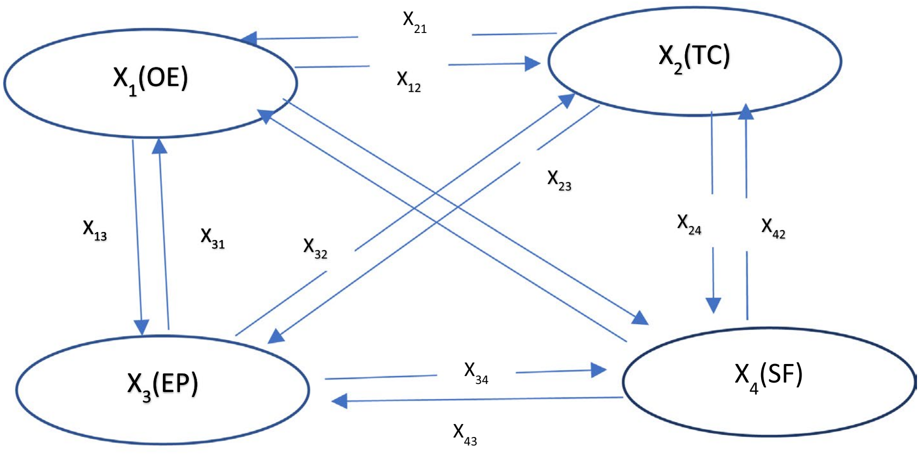

FIGURE 3 | Digraphs of major categories.

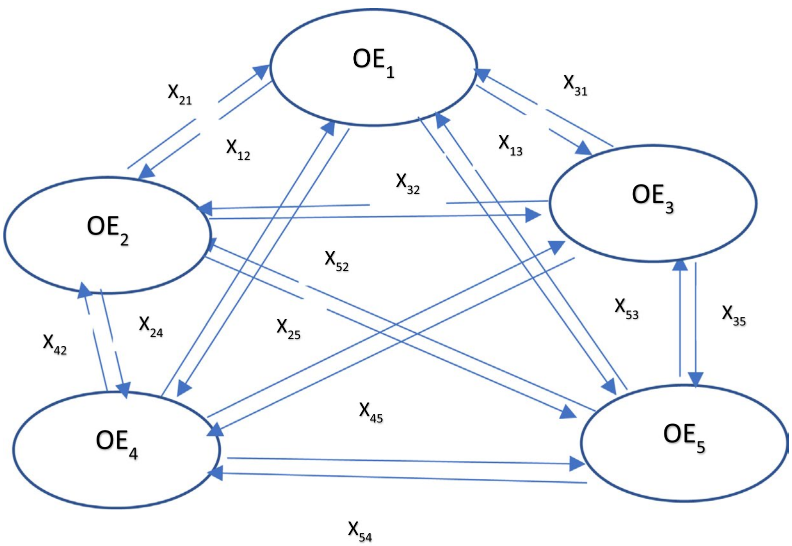

FIGURE 4 | Digraph for OE.

5.2.4 | Calculation of Permanent Matrix

The index of sustainability for the case company in the logistics sector is calculated using a permanent function. Calculating the permanent function is like finding a matrix determinant that specifically focuses on positive terms. The output of the permanent matrix (Perm R) is derived by using Equation (7), which is given as follows.

$$Per(F) = \prod_{i=1}^{4} Fi + \sum_i \sum_j \sum_k \sum_l (r_{ij} r_{ji} \; F_k \; F_l \;) + \sum_i \sum_j \sum_k \sum_l (r_{ij} r_{jk} r_{kl+} r_{ik} r_{kj} r_{ji)} \; F_{1+} \left[\sum_i \sum_j \sum_k \sum_l (r_{ij} r_{ji} \;) * \; (r_{kl} r_{lk}\,) + \sum_i \sum_j \sum_k \sum_l (r_{ij} r_{jk} r_{kl} \; r_{li} \; _+ \; r_{il} r_{lk} r_{kj} \; r_{ji)} \right] \tag{7}$$

To determine the permanent value of the matrix for OE, the values of the permanent matrix are substituted in Equation (7).

$$\text{Perm OE } (X_1) = \begin{vmatrix} X^1 1 & X^1_{12} & X^1_{13} & X^1_{14} & X^1_{15} \\ X^1_{21} & X^1 2 & X^1_{23} & X^1_{24} & X^1_{25} \\ X^1_{31} & X^1_{32} & X^1 3 & X^1_{34} & X^1_{35} \\ X^1_{41} & X^1_{42} & X^1_{43} & X^1 4 & X^1_{45} \\ X^1_{51} & X^1_{52} & X^1_{53} & X^1_{54} & X^1 5 \end{vmatrix} = \begin{vmatrix} 4 & 6 & 7 & 8 & 5 \\ 4 & 3 & 6 & 7 & 5 \\ 3 & 4 & 4 & 7 & 6 \\ 2 & 3 & 3 & 3 & 5 \\ 5 & 5 & 4 & 5 & 5 \end{vmatrix}$$

Perm (X_1*) = 251,045

Similarly, permanent values for TC, EP, and SF can be calculated using Equation (7).

$$\text{Perm TC } (X_2) = \begin{vmatrix} X^2 1 & X^2_{12} & X^2_{13} & X^2_{14} & X^2_{15} \\ X^2_{21} & X^2 2 & X^2_{23} & X^2_{24} & X^2_{25} \\ X^2_{31} & X^2_{32} & X^2 3 & X^2_{34} & X^2_{35} \\ X^2_{41} & X^2_{42} & X^2_{43} & X^2 4 & X^2_{45} \\ X^2_{51} & X^2_{52} & X^2_{53} & X^2_{54} & X^2 5 \end{vmatrix} = \begin{vmatrix} 5 & 6 & 7 & 8 & 9 \\ 4 & 4 & 6 & 6 & 8 \\ 3 & 4 & 3 & 7 & 8 \\ 2 & 4 & 3 & 3 & 8 \\ 1 & 2 & 2 & 2 & 2 \end{vmatrix}$$

Perm (X_2*) = 140,744

$$\text{Perm EP}\left(X_3\right)=\begin{vmatrix} X^{3}1 & X^{3}_{12} & X^{3}_{13} & X^{3}_{14} \\ X^{3}_{21} & X^{3}2 & X^{3}_{23} & X^{3}_{24} \\ X^{3}_{31} & X^{3}_{32} & X^{3}3 & X^{3}_{34} \\ X^{3}_{41} & X^{3}_{42} & X^{3}_{43} & X^{3}4 \end{vmatrix}=\begin{vmatrix} 4 & 6 & 5 & 7 \\ 4 & 4 & 5 & 7 \\ 5 & 5 & 5 & 8 \\ 3 & 3 & 2 & 3 \end{vmatrix}$$

Perm $(X_3^*) = 10{,}000$

$$\text{Perm SF}\left(X_4\right)=\begin{vmatrix} X^{4}1 & X^{4}_{12} & X^{4}_{13} & X^{4}_{14} \\ X^{4}_{21} & X^{4}2 & X^{4}_{23} & X^{4}_{24} \\ X^{4}_{31} & X^{4}_{32} & X^{4}3 & X^{4}_{34} \\ X^{4}_{41} & X^{4}_{42} & X^{4}_{43} & X^{4}4 \end{vmatrix}=\begin{vmatrix} 4 & 6 & 7 & 8 \\ 4 & 5 & 7 & 8 \\ 3 & 3 & 4 & 7 \\ 2 & 2 & 3 & 3 \end{vmatrix}$$

Perm $(X_4^*) = 8439$

$$R=\begin{vmatrix} x_1 & x_{12} & x_{13} & x_{14} \\ x_{21} & x_2 & x_{23} & x_{24} \\ x_{31} & x_{32} & x_3 & x_{34} \\ x_{41} & x_{42} & x_{43} & x_4 \end{vmatrix}=\begin{vmatrix} 251{,}045 & 5 & 7 & 8 \\ 5 & 140{,}744 & 8 & 9 \\ 3 & 2 & 10{,}000 & 7 \\ 2 & 1 & 3 & 8439 \end{vmatrix}$$

Perm (R) = $\mathbf{2.98 \times 10^{18}}$

5.2.5 | Best and Worst Values

All variables are set to their maximum values to establish the highest potential index. This entails maintaining the values in the permanent matrix's diagonal cells at 5 and setting the inheritance values for all sustainable behaviors to 5. The maximum index, represented by R*, is used as an indicator for comparing sustainability performance. It can be used to compare logistics companies and helps to assess their position in terms of adopting CSFs. This information helps logistics companies analyze the significance and interrelationships of these factors and implement them in their organizations to enhance sustainability practices.

The maximum theoretical index of organizational efforts is as follows.

$$\text{Perm OE}\left(X_1\right)=\begin{vmatrix} X^{1}1 & X^{1}_{12} & X^{1}_{13} & X^{1}_{14} & X^{1}_{15} \\ X^{1}_{21} & X^{1}2 & X^{1}_{23} & X^{1}_{24} & X^{1}_{25} \\ X^{1}_{31} & X^{1}_{32} & X^{1}3 & X^{1}_{34} & X^{1}_{35} \\ X^{1}_{41} & X^{1}_{42} & X^{1}_{43} & X^{1}4 & X^{1}_{45} \\ X^{1}_{51} & X^{1}_{52} & X^{1}_{53} & X^{1}_{54} & X^{1}5 \end{vmatrix}=\begin{vmatrix} 5 & 6 & 7 & 8 & 5 \\ 4 & 5 & 6 & 7 & 5 \\ 2 & 4 & 5 & 7 & 6 \\ 2 & 3 & 3 & 5 & 5 \\ 5 & 5 & 4 & 5 & 5 \end{vmatrix}$$

Perm $(X_1^*) = X_1{}^*{}_{max} = 325{,}625$

Similarly, we substitute 1 for all inheritance values to calculate the worst theoretical index:

$$\text{Perm OE}\left(X_1\right)=\begin{vmatrix} X^{1}1 & X^{1}_{12} & X^{1}_{13} & X^{1}_{14} & X^{1}_{15} \\ X^{1}_{21} & X^{1}2 & X^{1}_{23} & X^{1}_{24} & X^{1}_{25} \\ X^{1}_{31} & X^{1}_{32} & X^{1}3 & X^{1}_{34} & X^{1}_{35} \\ X^{1}_{41} & X^{1}_{42} & X^{1}_{43} & X^{1}4 & X^{1}_{45} \\ X^{1}_{51} & X^{1}_{52} & X^{1}_{53} & X^{1}_{54} & X^{1}5 \end{vmatrix}=\begin{vmatrix} 1 & 6 & 7 & 8 & 5 \\ 4 & 1 & 6 & 7 & 5 \\ 3 & 4 & 1 & 7 & 6 \\ 2 & 3 & 3 & 1 & 5 \\ 5 & 5 & 4 & 5 & 1 \end{vmatrix}$$

Perm $(X_1^*) = X_1{}^*{}_{min} = 142{,}333$

The sustainability index's best and worst values, according to theory, are determined and shown in Table 9.

R is the sustainability index of the company. This value of the sustainability index can be used to compare the index of sustainability of any other logistics company. It gives insight into the case company where they stand with respect to the range of best and worst sustainable practices followed in the industry. R* max defines the maximum sustainability when all the CSFs are fulfilled with maximum satisfaction and R*min can be defined vice versa. This is a self-assessment framework which can guide logistics companies to benchmark best practices in the logistics industry. In this study, the sustainability index is calculated to be 2.98×10^{18} with values ranging from a minimum of 2.72×10^{17} (worst case) to a maximum of 9.13×10^{18} (best case) values. Similar types of analyses have been conducted by several researchers in the literature, though in the context of different research problems.

Previous studies have commonly benchmarked index values against their respective best and worst possible values. For instance, Singh and Kumar (2019) reported a flexibility index of 3.7×10^4 for the supply chain of ABC company, comparing it with its maximum benchmark value of 3.8×10^5. Similarly, Gupta and Singh (2020) applied the GTMA approach to assess the sustainability index of logistics service providers, finding a value of 2.3×10^{11}, which was evaluated against a best-case value of 3.6×10^{12}. Agarwal et al. (2022) computed the supply chain resilience index to be 3.97×10^{14}, noting that it falls within a range defined by the worst-case value of 2.51×10^{13} and the best-case value of 4.43×10^{14}. This index gives direction to the logistics companies to achieve sustainability goals. This can help in understanding what practices other logistics companies are following and what can be adopted. The ranking of CSFs can help in designing their strategies for enabling BDA implementation for meeting sustainability targets.

6 | Discussion on the Findings

The pervasive digital transformation across various business operations is reshaping the landscape and leading in the era of BDA. Simultaneously, the growing environmental concerns are driving an imperative focus on sustainability. This study explores and evaluates the pivotal factors essential for

TABLE 9 | Best and worst values of R (R*).

Permanent function of categories and CSFs	Best value	Worst value	Current value
R*	9.13×10^{18}	2.72×10^{17}	2.98×10^{18}

organizations to embrace BDA as a catalyst for sustainability. Past studies have advocated that the e-commerce sector has evolved with a sustainability evaluation model to measure BDA's potential for sustainability development (Gangwar et al. 2023). Inamdar et al. (2021) conducted a bibliometric analysis on BDA adoption and observed that most of the past studies (32% of the total studies) contributed toward BDA adoption in the manufacturing and service sectors. Ariffin et al. (2023) explored the positive significant impact of BDA adoption on SMEs in the manufacturing and construction industries in developing economies. Al Teneiji et al. (2024) conducted a systematic literature review on adopting and applying BDA in healthcare contexts and explored the associated theories, methods, challenges and opportunities. Several studies emphasized BDA adoption, implementation and applications for supply chain practices (Alsadi et al. 2021; Narwane et al. 2023), but the logistics sector is still not well explored. The issues pertaining to the logistics sector are discussed in this study. In the logistics industry, technology adoption is witnessing substantial growth owing to its various advantages. However, many service providers within this sector have yet to fully harness this potential. Despite the existence of several infrastructural challenges, organizations must prioritize technological advancements to achieve sustainability.

This study identifies the CSFs for implementing BDA to enhance sustainability in logistics practices. This is significantly different from past studies, which focused on developing frameworks for BDA adoption for supply chain practices (Kamble and Gunasekaran 2020; Margaritis et al. 2022). Thereafter, a comprehensive review of the literature is conducted and four broader categories, TC, OE, EP, and SF, are extracted from TOE and ST theories. After a vast literature review, 18 CSFs for BDA implementation in the logistics sector have been identified. The experts believe that 18 CSFs are grouped under the above-identified categories. BWM is applied to prioritize them. Table 7 shows the results; Technical infrastructure (TC_1) (0.1953) and trained and technically skilled manpower (TC_2) (0.1225) are required for the adoption of digital advancements. Also, coordination and collaboration among supply chain partners (OE_5) (0.0959) are important for adopting the changed digital processes. Logistics firms also need to have a commitment from the top management, adopt lean and six sigma practices, and procure reusable raw materials to meet sustainable objectives. Logistics companies can give less importance to the allocation of resources for optimization, regulatory pressure by the government, and corporate social responsibility for sustainable business practices, as these can be automatically achieved when other important CSFs are adopted. This differs slightly from the results of earlier studies, including the effect of COVID-19. In past studies, organizational factors ranked higher than technical factors although both technological advancements and organizational support are very important (Gupta and Singh 2021). This can be due to changing scenarios. After COVID-19, there has been an increasing need to implement emerging technologies to make processes resilient. Therefore, the increasing need for technological capabilities overshadowed organizational efforts as organizations became eager to accept technological advancements. The results align with another study where technology factors ranked higher than organizations (Parhi et al. 2022). This can be because implementing technology is one of the key characteristics in a volatile environment.

The GTMA methodology's practical applications are shown in a real-life case study featuring an Indian logistics company, providing a tangible example for understanding and assessing the sustainability index. This case meticulously considers all relevant factors, including OE, TC, EP, and SF, with expert insights sought to leverage the adoption of the GTMA technique to determine the sustainability index. In the contemporary era of digitalization, logistics organizations are actively addressing impending technological challenges by prioritizing the development of sustainable competencies. This strategic approach enables these organizations to position themselves in terms of preparedness, allowing for a comparative analysis with peer companies. The resulting sustainability index becomes a valuable tool for strategizing the application of Industry 4.0 practices, aligning the organization's efforts with sustainability objectives. The sustainability index, calculated across OE (251,045), TC (140,744), EP (10,000), and SF (8439), offers a detailed perspective. This breakdown assists the logistics company in identifying specific areas for improvement within each category. The company places the most importance on organizational intentions, which is the same as in past studies (Kumar et al. 2022).

The comprehensive sustainability index, computed as 2.98×10^{18}, serves as a guiding metric for the logistics company. It signifies the current state of sustainability and provides a directional guide for analysis and strategy formulation. Breaking down the overall index into its constituent factors enables the organization to pinpoint strengths and areas for improvement, fostering a comprehensive approach to enhancing business performance. The optimum values serve as the target a company aims to attain, while the minimum threshold values represent the baseline a company must meet. The spectrum from the minimum to the maximum indicates the potential for improvement in a company's current index value.

By exploring specific organizational, environmental, technological, and social factors, the logistics company gains practical insights to drive targeted improvements. The resulting sustainability index becomes a strategic asset, guiding the organization in formulating effective strategies for sustainable business performance in the dynamic logistical landscape. This study has provided enriching empirical insights that can benefit BDA adoption in the logistics sector, which has remained unexplored in most past studies (Kamble and Gunasekaran 2020; Jain et al. 2024). Based on the above discussions, a framework for linking BDA, logistics, and sustainability is proposed in Figure 5.

7 | Implications of the Study

The findings of this study offer practical guidance for professionals in the supply chain and logistics sectors to adopt and implement digital strategies that can assist in achieving sustainable development goals. Decision-makers can incorporate prioritized CSFs into BDA implementation attempts, which will contribute to environmental preservation. "Technical infrastructure" is the most critical factor for logistics companies to adopt and implement BDA technologies. The Government of India has started investing in digital infrastructure initiatives, including

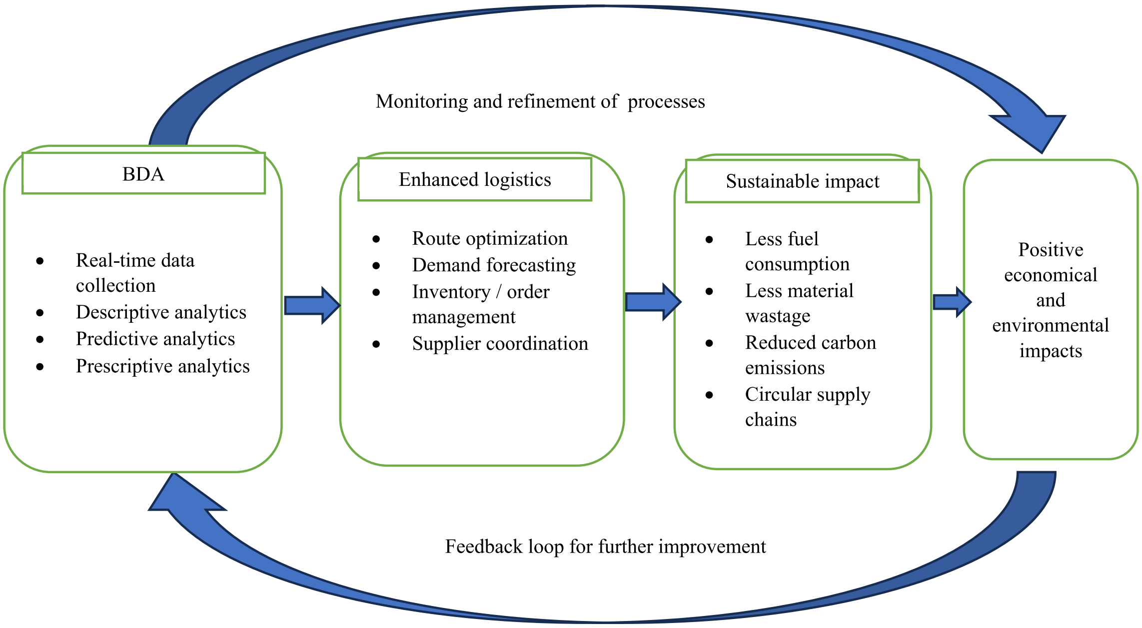

FIGURE 5 | Alignment between BDA, logistics, and sustainability.

the National Logistics Policy (NLP) (Jain and Dhar 2022) and the Unified Logistics Interface Platform (ULIP) (Press Release Bureau 2022). These gateways can help logistics companies operate through a single window platform and connect with all supply chain partners. Further, due to the fragmented and unrecognized nature of the Indian logistics industry, their implementation in the entire logistics movement is extremely challenging. Developing technical infrastructure that supports data privacy, security, and transparency in transport networks is a critical point of focus for policymakers. By enhancing such aspects, policymakers can build trust, improve efficiency, and ensure a more resilient logistics system. Supply chain professionals also need to look forward to the growing "requirement of technically trained manpower" to satisfactorily manage digitally enabled technical systems. Such supply chain professionals can collaborate with well-established educational institutes to offer short-term courses to fill this gap and thus, create skilled and tech-ready trained manpower (Gupta and Singh 2021). Policymakers need to work on the "coordination and collaboration among supply chain partners" for seamless data sharing and accurate demand forecasting, reducing delays and errors across the supply chain (Raut et al. 2021; Gupta et al. 2024). The results of the study suggest that "corporate social responsibility for sustainable business practices," "use of alternative fuels for reducing carbon footprints," and "allocation of resources for optimization" are less critical components for adopting BDA in the logistics sector in developing countries. Thus, prioritizing CSFs can help policymakers understand and evaluate the focus areas. Based on the ranking of CSFs, policymakers can develop policies for investing in digital infrastructure and integrate BDA with national policy frameworks so that companies can achieve SDG 9 (Industry, Innovation and Infrastructure). Similarly, companies can work towards SDG 12 (Responsible Consumption and Production) which can be supported through the promotion of lean and circular logistics practices. The study can assist policymakers in formulating climate-focused strategies (SDG 13—Climate Action) that encourage the adoption of green technologies and enhance sustainability reporting across the logistics sector.

This study can also help supply chain professionals develop innovative digital solutions for long-term business sustainability (Sun et al. 2022). The sustainability index can also provide insightful information about an organization's performance and areas for development. Comparing theoretical best and worst values with current indices finds opportunities for improvement and provides logistics organizations with a diagnostic tool to improve. The theoretical indices can be set as benchmarks for logistics firms to meet their sustainability goals. The results of this study can provide insightful direction to all logistics professionals and help devise impactful strategies to fill the gap between existing indicia and theoretical maxima. Sustainability indices can be considered a powerful tool for improving a business's image and promoting socially responsible practices (Gupta et al. 2024). A firm with a higher sustainability index is considered more responsible concerning sustainable actions and environmental concerns, giving it a competitive advantage (Mani et al. 2017).

This study offers ample opportunities for research scholars to understand the CSFs required for implementing BDA, specifically in the logistics sector in developing economies. This study uses TOE and stakeholder's theory to analyze innovation through technological, organizational, environmental and social perspectives. Many theories like RBV, DCV, sustainability theories, innovation theories, technology adoption theories and governance-related theories can be extracted from past studies and insights can be drawn to develop new innovative research work, which may be applicable for technological and sustainability purposes in the same or any other industry sector (Touboulic and Walker 2015; Hazarika and Zhang 2019). Research scholars and supply chain practitioners can take ideas from the case company and explore innovative ways to implement BDA in other logistics companies. The identified CSFs can help them devise

TABLE 10 | Suggested strategic actions for CSFs to implement BDA.

CSFs for implementing BDA	Suggested strategic actions
Technical Infrastructure (TC1)	Invest in AI-driven optimization and cloud-enabled SCM platforms to enhance infrastructure, efficiency and flexibility
Trained and technically skilled manpower (TC2)	Conduct technical training programs in IoT, data analytics, and sustainability to enhance technical skills
Use of data mining and data storage tools for sustainable practices (TC3)	Deploy data analytical tools for monitoring sustainable key performance metrics
Use of energy-efficient technologies for reducing CHCs (TC4)	Adopt electric or alternative fueled vehicles, solar-powered warehouses, rainwater harvesting, and paperless processes
Improve scalability (TC5)	Understand demand patterns using digital platforms and develop modular and scalable processes to meet changing supply chain needs
Top management's commitment and interest (OE1)	Create awareness towards sustainability through digitalization and provide support
Training and education of employees (OE2)	Introducing mandatory certifications on digital systems/ platforms, SDGs and green logistics for employees
Motivate employees to use digital and sustainable technologies (OE3)	Implement recognition and incentive-based rewards to encourage innovative solutions for overcoming digital and sustainable adoption challenges
Formation of stringent sustainable and digital policies (OE4)	Develop and impose strict policies towards green procurement, production, and distribution using digital tools
Coordination and collaboration among supply chain partners (OE5)	Develop hubs and joint sustainability reporting frameworks with supply chain partners through EDI
Use of alternate fuel sources for reducing carbon footprints (EP1)	Transition of the fleet to electric, hydrogen and biofuel transportation alternative solutions
Use of reusable and recyclable materials (EP2)	Promote the culture of reusability and recycling practices across the supply chain
Adoption of lean and six sigma practices (EP3)	Roll out waste reduction target-oriented programs in logistics and warehouse processes
Allocation of resources for optimization (EP4)	Plan and optimize the use of scarce resources through digital and green innovation solutions
Government incentive policies for sustainability (SF1)	Explore and apply for government subsidies and schemes related to digital and sustainable policies
Concerns towards data privacy and security (SF2)	Implement strict cyber security and data governance frameworks for data management
Regulatory pressure to promote sustainability (SF3)	Conduct regular compliance to meet quality assurance and SDG criteria
Corporate social responsibility for sustainable business practices (SF4)	Take responsibility for conducting community-based green programs and set targets for annual sustainability goals

successful implementation strategies at the organization level, considering technological, environmental, and social perspectives as well.

8 | Conclusions, Limitations and Future Research Scopes

This study constructs several key inferences regarding the implementation of BDA in the logistics sector. It adopts a novel strategy by concentrating on the CSFs required for the successful application of BDA, in contrast to most of the current literature that mostly covers the benefits and difficulties of BDA. The study follows a holistic approach, considering technological, organizational, environmental, and social aspects of implementing BDA in the logistics sector. The study can provide practical guidance to industry professionals through empirical evidence and suggests that "organizational efforts" and "technological capabilities" are the most important categories. To implement BDA and reach sustainability, logistics companies require the vision and support of senior management, manpower training, cutting-edge technology infrastructure, and highly qualified labor. Companies can benefit from the study findings and improve energy-efficient technologies and data storage tools for better data handling, thus reducing the wastage of resources. The sustainability index can serve as a guiding metric for companies and can provide directions for further analysis and strategy formulation.

To conclude, the current study contributes to identifying the CSFs required by logistics firms to implement BDA to achieve sustainability goals. The study's outcomes can help logistics firms make informed decisions as they move towards a more sustainable future. The suggested strategic actions for CSFs that the logistics companies can adopt to achieve sustainability goals are presented in Table 10.

The findings of this study can serve as a helpful reference for logistics companies and supply chain professionals to work on their technological initiatives and long-term success. This study can greatly benefit logistics firms by encouraging them to incorporate sustainable practices into their daily logistics operations. In addition, the framework suggested can help them compare their performance to global benchmarks. The study's validity might be improved by getting more experts' input and broadening the focus to establish a strategy structure for the logistics sector's integration of digitization and sustainability.

This study has a few limitations as well. First, the number of experts consulted is limited to 10, which could be expanded in future research to gain more in-depth insights. Second, the analysis is based on a single logistics case company; incorporating multiple case studies in future work could have broader exposure to digital and sustainable practices. Lastly, as the study focuses on developing countries, specifically the Indian context – its findings may have limited generalizability at the global level due to varying infrastructural and economic conditions.

The scope of future research can be expanded by incorporating insights from a big pool of industry experts to increase the depth and validity of findings. Researchers can develop a comprehensive strategic framework by integrating digitalization and sustainability in the logistics sector. The suggested framework can support industry professionals in addressing specific implementation challenges and can provide a clear roadmap for sustainable digital transformation for logistics operations. The study can be extended further to compare sustainable logistics practices for emerging nations. The comparison with emerging nations can further support logistics companies in developing their cutting-edge sustainable practices, leading to continuous improvements. Researchers can explore similar studies with different mathematical tools and models, and results can be compared for validation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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