Journal of Cleaner Production 472 (2024) 143460

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

QFD-based optimization model for mitigating sustainable supply chain management adoption challenges for Bangladeshi RMG industries

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ARTICLE INFO

Handling Editor: Jian Zuo

Keywords:
Quality function deployment
Optimization model
Sustainable supply chain management
Sustainability performance

ABSTRACT

In response to heightened pressures from regulatory mandates, global competition, and evolving customer expectations, industries worldwide are compelled to prioritize environmental initiatives, often at the expense of economic considerations. The research gap addressed in this study is the lack of a comprehensive, data-driven optimization model for effectively mitigating sustainable supply chain management adoption challenges specific to the Bangladeshi Readymade Garments (RMG) industry. While previous studies often relied on single techniques, this research proposes a novel AHP integrated QFD-based MILP optimization model. This innovative approach empowers Bangladeshi RMG industries to make data-driven decisions for prioritizing sustainability challenges and selecting cost-effective mitigation strategies to promote the integration of sustainability initiatives within the sector. The study identifies and prioritizes 25 sustainable supply chain management adoption challenges and proposes 16 mitigation strategies. The model emphasizes the critical interplay between sustainability performance and implementation costs, achieving a sustainability performance score of 0.4511 while effectively implementing 12 out of 16 strategies within the expected budget. The optimal solution incorporates green strategies, technology integration, and aspects of Industry 5.0, demonstrating a holistic approach to sustainable supply chain management. The findings are crucial for Bangladeshi RMG industries aiming for global market competitiveness and contribute significantly to the academic field by introducing a robust, data-driven decisions for sustainable supply chain optimization. The implications extend beyond the RMG sector, offering a replicable model for other industries and regions facing similar sustainability challenges.

1. Introduction

The Bangladeshi RMG industry is a crucial pillar of the country's economy, contributing significantly to employment and export revenues. In 2022, Bangladesh secured the second position in global garment exports as a single country (BGMEA, 2024). Although RMG has immense potential, the sector faces significant challenges, including disruptions in the supply chain (SC) (Haider, 2007; Islam, 2008). The Bangladeshi garment sector is experiencing substantial environmental disruptions, primarily due to the usage of hazardous materials, water pollution, greenhouse gas emissions and poor waste disposal standards (The Third Pole, 2023; Rupa et al., 2022; Sarkar et al., 2020). These disruptions along with Sustainable Supply Chain Management (SSCM) adoption challenges impact all stakeholders in the SC network. Given the critical state of the RMG supply chain, the development of sustainable practices becomes imperative.

Industries exhibit limited interest in enhancing sustainability within Supply Chain Management (SCM) without external motivations (Pagell and Shevchenko, 2014). The global economy sees a substantial contribution from the Small and medium-sized enterprises (SME) business sector, emphasizing the need for the adoption of environmentally friendly practices in SMEs. The RMG industry is among the most polluting industries in the world, right after the oil industry. Kruse and Storm Rasmussen (2012) highlight the fashion and Garments industries as crucial polluters across the entire production process. The fashion industry, a global and socially challenging sector faces significant environmental problems, particularly in the Garments sector due to chemical usage impacts human health and the natural environment (Pesticide Action Network, 2011). The rationale for analyzing issues and challenges in SSCM is twofold:

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https://doi.org/10.1016/j.jclepro.2024.143460
Received 27 February 2024; Received in revised form 26 July 2024; Accepted 21 August 2024
Available online 23 August 2024

- Because of limited resource availability, Bangladeshi companies are under significant pressure to focus on waste reduction, greenhouse gas emissions, energy consumption and environmental effects, as well as ensuring sustainable SC practices within the organization.
- As a result of government regulations and heightened environmental consciousness among customers, Bangladeshi RMG industries are pressured to embrace sustainability in their SC. This necessity arises from retaining customers and maintaining their positions in the industrial landscape.

Consequently, the adoption of sustainable concepts in traditional SCM becomes a strong motivator for reducing waste and working towards a sustainable environment. The present waste, environmental pollution, and greenhouse gas emissions crisis in RMG industries in Dhaka, Bangladesh, receives daily attention from the media and social networks, leading to stricter government regulations and heightened public awareness (The Daily Star, 2023). Industries now face pressure to upgrade their traditional SC practices. Nearly all Bangladeshi garment industries have initiated the adoption of SSCM to minimize waste, pollution, and greenhouse gas emissions in response to stringent government regulations.

Although industries can benefit greatly from the integration of sustainability into supply chain management, there are significant challenges to its actual implementation. Industries encounter obstacles such as the need for substantial investments, a scarcity of green resources, and the intricacies of supply chain processes (Rezaei Vandchali et al., 2021; Bastas and Liyanage, 2019). Additionally, the increasing expectations from customers for sustainable practices add another layer of concern. Achieving success in Sustainable Supply Chain Management necessitates robust collaboration among network partners. The process demands considerable effort from management regarding coordination, control, and evaluation to effectively implement SSCM practices (Delmonico et al., 2018). The subsequent steps advance by answering the following three research questions:

RQ1: What are the current SSCM adoption challenges in the RMG sector?

QR2: What are the strategies available to mitigate these challenges? And

RQ3: What is the optimal sustainable portfolio of strategies to address challenges within budget constraints?

In response to this challenging scenario, exploring strategies to enhance the resilience and sustainability of the RMG supply chain becomes crucial. Organizations need to implement sustainable practices across the sector to address the prevailing issues and challenges within Bangladeshi RMG industries. This research aims to develop optimization models to offer insightful and actionable strategies for the adoption of sustainable practices within organizations. In pursuit of elevating the sustainability performance of the RMG supply chain in Bangladesh, this study adopts the QFD methodology, drawing inspiration from established literature (Park and Kim, 1998; Wang and Hong, 2007). QFD is chosen for its effectiveness in proactively addressing challenges in mitigating sustainability issues, offering a proven technique for designing mitigation strategies (Faisal, 2013). The extensive literature on QFD is briefly reviewed in a subsequent section. Notably, QFD empowers organizations to take a proactive stance towards challenges rather than a reactive one. This study makes a unique methodological contribution by incorporating the Analytical Hierarchy Process (AHP) (Saaty, 1980) within the QFD framework for data analysis. This research selected AHP over the Best-Worst Method (BWM) to capture the relative importance of various sustainability challenges faced by the Bangladeshi RMG industries. AHP offers a more context-specific and practical prioritization, whereas BWM relies solely on mathematical calculations (Emamat et al., 2023; Yazdi et al., 2019). The combined application of AHP, QFD, and the MILP model offers a unique advantage. AHP ensures the most critical challenges, while QFD translates them into actionable solutions. Finally, the MILP model optimizes these solutions within Bangladeshi RMG industries' budget constraints, maximizing sustainability impact for their allocated resources.

The contribution of this research is that it successfully fits sustainable supply chain management adoption challenges and mitigation strategies within the QFD framework. This integration is further enhanced by developing a novel AHP integrated QFD-based Mixed Integer Linear Programming (MILP) optimization model with proper theoretical justification. This research employs an approach that integrates AHP to determine the priorities and challenges within the QFD methodology. The prioritization of these challenges sets the foundation for an effective mitigation strategy. Moreover, integrating AHP with QFD models facilitates the identification of the absolute importance of challenges, assessing both the absolute and relative importance of strategies and exploring the potential for simultaneous strategy implementation if applicable. Recognizing the imperative to address these challenges, this research presents a QFD-based optimization model tailored for the unique landscape of Bangladeshi RMG Industries, keeping implementation cost and budget into account. The data obtained from this QFD table was subsequently used as an input parameter of the proposed optimization model. The optimization model considers budget constraints for the implementation of sustainable strategies. In addressing the implementation cost specifics, the model focuses on aspects crucial for sustainable supply chain success in small and medium-sized RMG industries (Diabat et al., 2014). As the RMG industry faces budget constraints, the model advocates for a phased implementation approach, allowing organizations to initiate essential strategies and progressively expand based on initial achievements.

The paper is structured to focus on various aspects of SSCM adoption challenges and mitigation strategies within the context of the Bangladeshi RMG industry. Section 2 conducts a thorough literature review, focusing on the challenges faced in adopting SSCM practices and exploring potential mitigation strategies. Section 3 outlines the methodology, detailing the implementation of QFD methods and QFD-based optimization model formulation. Section 4 applies the model to the RMG industry in Bangladesh, offering practical insights into its real-world applicability. Section 5 offers the results and discussion, including an in-depth analysis of the findings and the sensitivity analysis performed. Finally, Section 6 summarizes the findings, highlighting managerial insights gained from the study and emphasizing the importance of the findings in developing sustainable practices in the RMG industry.

2. Literature review

The literature review in this study is structured into five key areas, beginning with an exploration of supply chain sustainability and its environmental implications. This is followed by examining the specific sustainable supply chain management adoption challenges encountered by RMG industries in Bangladesh. Subsequently, mitigation strategies to address these challenges are discussed, leading to an overview of QFD in sustainable supply chains. Lastly, the research gap and motivation for this study are outlined.

2.1. Sustainability in RMG supply chain

In the last 23 years, the concept of "sustainability" has gained significant prominence within the field of SCM, sparking extensive research and attention from researchers and practitioners. In the context of the global business environment, sustainability and business are highly interconnected. The Bangladeshi RMG industry has encountered numerous challenges since its inception, prompting continual transformation and enhancement to bolster resilience (BGMEA, 2020). They have been facing the challenge of balancing competitiveness with environmental and social responsibility (Uddin et al., 2023). Sustainable supply chain practices are crucial for long-term success, but challenges like slow return on investment for eco-friendly technologies persist (Uddin et al., 2023; Debnath et al., 2024). The global context of sustainability is also marked by distinct challenges encompassing market competition, energy constraints, limited access to raw materials, environmental conservation issues, and a steadily growing global population (Bajaj et al., 2013). Businesses are undeniably confronted with new challenges and opportunities in the adoption of environmentally responsible practices (Sezen and Turkkantos, 2013). In this regard, Hart and Milstein (2003) conducted an analysis of the worldwide challenges related to sustainable development. Their emphasis was on pinpointing strategies and practices that contribute to advancing a more sustainable global environment and bolstering shareholder value. Mota et al. (2015) explore supply chain sustainability through design and planning, emphasizing social, environmental, and economic aspects. In order to address the triple bottom line, the study looks at tactics that support environmentally friendly SC operations. The researcher suggests combining Industry 4.0 technologies with green practices to improve sustainability performance (Karmaker et al., 2023). Akter et al. (2022) emphasize the importance of a circular economy in minimizing textile waste, a significant environmental concern. Strategies for environmental sustainability in the context of a growing economy's supply chain are examined by Roy et al. (2020a). Through examining the intricacies of supply chain dynamics within the framework of a developing nation, the research offers significant perspectives on how businesses might synchronize their activities with sustainable practices.

2.2. Adoption challenges for sustainable supply chain management

Sustainable practices in the RMG supply chain ensure long-term economical, environmental, technological, managerial and social viability. However, adopting sustainable supply chain management poses several challenges. These include high initial costs and investment in sustainable technologies, inadequate infrastructure, and organizational resistance to change. Limited access to necessary data and the complexity of integrating sustainability into existing processes further complicate adoption (Feng et al., 2022; Baig et al., 2020). Additionally, regulatory compliance, supplier collaboration, and maintaining transparency while ensuring data security and privacy are critical challenges (Munir et al., 2022; Luthra et al., 2018). This research identified 25 SSCM adoption challenges through a comprehensive literature review and expert consultations. These challenges are adapted from Karim et al. (2021) with necessary modifications based on brainstorming sessions with 5 experts, as shown in Table 1.

Table 1
SSCM adoption challenges.

Challenge Type	Challenge Name	Reference
Economical	C1: High cost of sustainability adoption	Walker et al. (2008)
	C2: Limited resource and capability	Zhu and Geng (2013)
	C3: High cost of disposing hazardous wastes	Govindan et al. (2014)
	C4: Cost of environmentally friendly packaging	Govindan et al. (2014)
	C5: Insignificant financial gains	Zhu and Geng (2013)
Environmental	C6: Lack of reverse logistics	Diabat and Govindan (2011)
	C7: Compliance with certifications and standards	Chkanikova et al. (2021)
	C8: Market competition and uncertainty	Sarker et al. (2018)
	C9: Weak regulatory environment	Sajjad et al. (2015)
	C10: Complexity in measuring and monitoring the environmental practice	(Govindan et al., 2014; Mathiyazhagan et al., 2013)
	C11: Unaware of the environmental benefits	Walker et al. (2008)
Technological	C12: Lack of information technology	Luthra et al. (2011)
	C13: Lack of adoption of advanced technology and processes	Gandhi et al. (2015)
	C14: Integration of advanced technology and processes	Kamble et al. (2023)
	C15: Lack of collaboration with research institute	Xia et al. (2015)
Managerial	C16: Lack of top management commitment	Luthra et al. (2011)
	C17: Lack of stakeholder involvement	Luthra et al. (2016)
	C18: Lack of supply chain integration	Jalalifar et al. (2013)
	C20: Collaboration challenges	Diabat and Govindan (2011)
	C21: Human factors and safety challenges	Koberg and Longoni (2019)
Societal	Ch22: Absence of Govt. support and policies	(Luthra et al., 2016; Zhu et al., 2006)
	Ch23: Lack of corporate social responsibility	Govindan et al. (2014)
	Ch24: Insufficient society pressure	(Govindan et al., 2015; Wang et al., 2016)
	C24: Lack of employee motivation	Karim et al. (2021)
	C25: Political pressure	Jadallah and Bhatti (2020); Silvestre et al. (2018)

2.3. Mitigation strategies for SSCM adoption challenges

To effectively address the diverse challenges associated with SSCM, it is essential to implement a range of targeted strategies. These strategies not only help in overcoming specific challenges but also promote overall sustainability within the supply chain. The following Table 2 presents the different sustainability performance roles of the strategies.

2.4. QFD in sustainable supply chain management

QFD in sustainable supply chain involves a systematic methodology that translates customer requirements into design characteristics while considering environmental and social factors, ensuring the alignment of supply chain practices with sustainability goals (Karuppiah et al., 2023; Wu et al., 2018). Originally developed in the manufacturing sector, QFD has been adapted for sustainable supply chains to systematically prioritize and align strategies with environmental and social considerations. QFD in sustainable supply chain management is a strategic methodology that integrates customer requirements with product or service development to enhance sustainability practices (Wu et al., 2018; Karuppiah et al., 2023).

Numerous researchers have underscored the advantages of the QFD model. The research by Koppiahraj et al. (2023) supports the integrated approach using fuzzy Delphi, AHP, and quality function deployment for designing a resilient and sustainable supply chain, considering both customers' requirements and technical capabilities. Chan and Wu (2002) acknowledge its effectiveness in product development, customer needs analysis, and decision-making. QFD's adaptability across various research methods is emphasized by Carnevalli and Miguel (2008), including action research, experimental methodology, modeling, and theoretical-conceptual approaches. The broad applicability of QFD extends to areas such as customer needs determination, priority setting, and addressing challenges in logistics and SCM (Xie et al., 2023; Bevilacqua et al., 2006; Bottani et al., 2006). QFD has also proven effective in identifying and mitigating supply chain risks (He et al., 2021; Faisal, 2013; Pujawan and Geraldin, 2009). By involving cross-functional teams, QFD facilitates the identification of sustainability challenges, aligns them with customer needs, and guides the development of efficient strategies, contributing to the overall success of sustainable supply chain initiatives (Xie et al., 2023; Karuppiah et al., 2023). Consistent

Table 2
Sustainable supply chain management strategies.

SSC Strategies (HOW's)	Role in Sustainability Performance	Reference
S1: Supplier Collaboration	Foster strong relationships with suppliers, encouraging them to adopt sustainable practices. Collaborate on environmental and social responsibility initiatives and ensure transparency in the SC.	(Alzoubi et al., 2020; Andalib et al., 2023)
S2: Sustainable Sourcing	Sustainable sourcing entails choosing suppliers and materials based on eco-friendly and ethical criteria, fostering a resilient supply chain and improving overall sustainability performance.	(Agrawal et al., 2019; Akhavan et al., 2017)
S3: Circular Economy Practices	Design products and packaging focusing on recyclability, reusability, and reduced waste. Implement circular economy principles to extend product life cycles and minimize the use of virgin resources.	(Mirzaei et al., 2023; Genovese et al., 2017)
S4: Energy-Efficient Technology and Renewable Energy	Invest in energy-efficient technologies within operations and logistics. Transition to renewable energy sources to reduce carbon emissions and overall environmental impact.	Centobelli et al. (2018)
S5: Green Logistics and Transportation	Optimize transportation routes to minimize emissions and fuel consumption. Utilize eco-friendly transportation modes, consolidate shipments, and implement efficient warehouse practices.	Fahimnia et al. (2015)
S6: Waste Reduction and Recycling	Implement recycling initiatives and waste reduction plans throughout the supply chain. Reduce the use of single-use packaging and promote material recycling across the SC.	(Khan et al., 2020; Akter et al., 2022)
S7: Ethical Labor Practices	Ensure fair labor practices, worker well-being, and adherence to ethical standards throughout the SC, aligning with the social responsibility aspect of LSCM.	Carlson et al. (2018)
S8: Life Cycle Assessment	An LCA helps to optimize environmental performance by assessing the entire life cycle from raw material extraction to end-of-life disposal.	(Atik et al., 2020; Mahiat et al., 2023)
S9: Waste and Pollution Management	Implement water-efficient practices in manufacturing processes and supply chain operations. Monitor and manage water usage, considering the impact on local ecosystems and communities.	(Chowdhury et al., 2013; Chowdhury and Yasmin, 2018)
S10: SC Resilience and Risk Management	Develop resilience strategies to address potential disruptions due to climate change, natural disasters, or geopolitical events. Build redundancy into the supply chain to mitigate risks.	(Ali et al., 2021; Chowdhury et al., 2018)
S11: Certifications and Standards	Certifications and standards, like ISO and industry-specific labels, are instrumental in enhancing sustainability performance. They provide clear guidelines, foster transparency, and build credibility, helping companies demonstrate and improve their commitment to responsible practices.	(Rahman and Dey, 2021; Ashadujjaman, 2019)
S12: Technology Integration	Technology integration enhances sustainability by streamlining processes, reducing environmental impact, improving resource efficiency, and fostering a resilient and eco-friendly supply chain.	(Shahadat et al., 2023; Razzak, 2023)
S13: Collaboration with Stakeholders	Engage with customers, government agencies, NGOs, and other stakeholders to understand expectations and collaborate on sustainable initiatives. Publicize sustainable practices to enhance brand reputation.	(Shajahan et al., 2024; Chowdhury et al., 2018)
S14: Continuous Improvement and Innovation	Continuous Improvement and Innovation drive perpetual process enhancement through tech integration and human-machine collaboration. This dynamic approach cultivates agility, efficiency, and sustainability, fostering an innovative culture.	(Shan et al., 2020; Lee, 2019)
S15: Education and Training Programs	Provide ongoing training and awareness programs for workers and management on sustainability practices. Encourage a culture of environmental and social responsibility within the industry.	(Chowdhury et al., 2018; Tramarico et al., 2017)
S16: Supply Chain Transparency	Enhances sustainability performance by providing real-time visibility into supply chain processes, fostering trust, and enabling timely identification of environmental, ethical, and operational issues.	(Karmaker et al., 2023; Uddin et al., 2023)

with existing literature, this study employs the QFD methodology to identify and address sustainable supply chain challenges through the development of optimal and efficient SSCM strategies.

2.5. MCDM integrated QFD based optimization

The integration of MCDM techniques with QFD for optimization purposes has emerged as a robust approach in addressing complex decision-making scenarios, particularly in sustainable supply chain management. This methodology combines the systematic prioritization capabilities of MCDM with the structured planning and deployment strengths of QFD, enabling organizations to make more informed and data-driven decisions (Torkayesh et al., 2022; Chen et al., 2021). In prior studies, researchers have frequently integrated various MCDM tools with QFD to improve decision-making processes by incorporating multiple criteria, ensuring a thorough evaluation of alternatives (Goker et al., 2022). AHP is frequently integrated into the QFD process, as seen in works such as (Kamvysi et al., 2014; Bhattacharya et al., 2005; Chan and Wu, 2002; Park and Kim, 1998). Hsu et al. (2017) integrated QFD with fuzzy TOPSIS to assess key performance factors for sustainable development. Employing a similar approach, He et al. (2021) analyzed risks within the SSC process using an integrated Kano-QFD-DEMATEL approach. Yazdani et al. (2020) combined QFD with the DEMATEL technique to assess barriers in the SSC process. However, to ascertain the relative importance of WHATs within the QFD framework, the authors plan to employ the AHP. A comprehensive description of the AHP process, although beyond the scope of this paper, can be found in the literature (Saaty, 1980). This combined framework allows for a more comprehensive analysis of the trade-offs between sustainability initiatives and their associated costs and benefits.

An optimization method is also essential to identify the most desirable HOWs that satisfy the WHATs under specific constraints (Delice and Güngör, 2011; Karsak, 2004b). To meet this demand, some researchers have used optimization techniques. To determine the most desirable design requirements (HOWs) within budgetary constraints, Wasserman (1993) and Park and Kim (1998) developed linear programming models, while Zhou (1998) proposed a MILP approach. Multiple objective optimization techniques have also been used to ascertain the HOWs (Deb, 2014; Köksalan, 2011). A 0–1 goal program incorporating analytical network procedures in a QFD application for product planning was developed by Karsak et al. (2002). A mixed-integer goal program was proposed by Delice and Güngör (2011), in which the target functions (cost, technical problems, and customer satisfaction) are transformed into objectives. Different target program modifications are among the other QFD applications based on multiple objectives optimization; they may be found in the works of Büyüközkan and Berkol (2011), Karsak and Özogul (2009), Chen and Weng (2006), and Lee et al. (2010). Multiple objective optimizations were used in QFD by Allehashemi et al. (2022) and Karsak (2004a, 2004b) to identify the non-dominated solutions of HOWs.

2.6. Research gap

The literature review indicates that both Multinational Corporations and Small and Medium-sized Enterprises worldwide have recognized the issue of industrial waste (Karmaker et al., 2023; Habib et al., 2022; Sarkar et al., 2020), Greenhouse Gas emissions (Rupa and Saif, 2022; Sarkar et al., 2020), industrial pollution (Junior et al., 2014), negative environmental impact (Karmaker et al., 2023; Habib et al., 2022; Sarkar et al., 2020) and have initiated the adoption of SSCM in their Traditional SCM practices. This shift is propelled by a heightened environmental consciousness, regulatory demands, and the realization that adopting sustainable practices can yield enduring benefits for both businesses and the larger ecosystem (Hariharasudan et al., 2021; Roy et al., 2020b). The long-term sustainability of the RMG supply chain is crucial due to its immense economic, environmental and social significance in Bangladesh (Chowdhury et al., 2013). While previous research has examined SSCM performance and various aspects of this transition (Dehghanian et al., 2011; Hussain, 2011; Faisal, 2010; Vinodh, 2010; Zheng, 2010), limited attention has been given to investigating the challenges and mitigation strategies related to SSCM adoption within the context of Bangladesh. Comparable studies have been conducted in countries like China (Zhuo et al., 2019; Wu et al., 2018), India (Vishwakarma et al., 2022; Nayak, 2018; Diabat et al., 2014), Poland and Canada (Grzybowska, 2012; Hussain, 2011). Although few studies in Bangladesh (Junayed et al., 2023; Chowdhury et al., 2015) provide some insights regarding challenges and vulnerabilities in RMG supply chain. However, these studies have not sufficiently addressed the specific strategies and quantitative models needed for effective SSCM adoption in the Bangladeshi RMG sector. This paper addresses the research gap by focusing on developing and implementing optimization models for SSCM strategies specifically tailored to the small and medium-sized RMG industries in Bangladesh. The aim is to provide a data-driven approach to overcoming SSCM challenges, including the selection of appropriate strategies and decision-making methods that can be effectively applied within this context.

3. Methodology

This research investigates the QFD methodology, detailing its basic framework and further focuses on formulating a QFD-based optimization model.

3.1. QFD methodology

In the QFD model, the customer requirements (existing organizational problems), such as challenges, vulnerabilities, and disruptions, are denoted as WHATs, while the methods for fulfilling customer requirements are identified as HOWs. The fundamental QFD framework, depicted in Fig. 1, utilizes CRi for WHATs and DRj for HOWs, where CRi represents challenges in RMG sustainable supply chains, and DRj signifies SSCM strategies or performance to mitigate challenges. The relationship matrix R_{ij} in Fig. 1 depicts the utilization of specific HOWs to fulfill given WHATs. Consistent with QFD literature (Faisal, 2013; Pujawan and Geraldin, 2009; Chan and Wu, 2002), R_{ij} is measured on a scale of (9 = strong mitigation, 3 = moderate mitigation, 1 = little mitigation, and 0 = no mitigation). The AI and RI represent the absolute and relative importance of HOWs, computed using the approach outlined by Park and Kim (1998).

$$AI_j = \sum_{i=1}^{m} w_i R_{ij} \quad j = 1, \ldots.., n$$

Here, AI_j represents the absolute importance of the jth design requirement (SSCM strategy), Wi is the weight of the ith supply chain challenge. R_{ij} denotes the relationship value, indicating the extent to which the jth SSCM strategy mitigates the ith challenge. The parameters include n for the number of SSCM strategies and m for the number of sustainable supply chain adoption challenges. In our context, AI_j is represented as the 'total sustainability' of the jth sustainability strategy for mitigating challenges. The relative importance of sustainability strategy j is expressed as

$$RI_j = \frac{AI_j}{\sum_{i=1}^{n} AI_i} \quad j = 1, \ldots.., n$$

The significance of the correlation between DRjs (HOWs) is evident in diverse QFD applications, illustrating the level of similarity when implementing two HOWs as shown in Fig. 1. Previous studies indicate a certain degree of interdependence among HOWs in practical applications (Park and Kim, 1998; Wasserman, 1993). If HOWi and HOWj are correlated, there are cost savings denoted as s_{ij} in their implementation (Park and Kim, 1998). Estimations for these s_{ij} values need to be provided by decision-makers. In this case, some HOWs are correlated and can be implemented together.

3.2. QFD-based optimization model formulation

The definition of "Sustainability Performance" encompasses two critical components: (i) Resource efficiency, emphasizing the need for minimal implementation costs. (ii) Optimization perspective, indicating that sustainable supply chain strategies should be efficient and optimal. Drawing inspiration from (Vugrin et al., 2011; Chowdhury et al., 2015), who discussed the efficiency of system resilience in terms of utilizing the "lowest possible amount of resources," this research aligns with their approach and defines "Sustainability Performance (SPj)" as AIj/ICj, where ICj represents the cost of implementing the jth SSCM strategy. Importantly, the parameters in the objective functions of our QFD optimization problem correspond to SPj. This ensures that our definition satisfies condition (i) of resource efficiency for sustainability performance. To fulfill condition (ii) of optimal sustainable supply chain strategies, this research ensures that the solution derived from the QFD-based optimization problem is efficient.

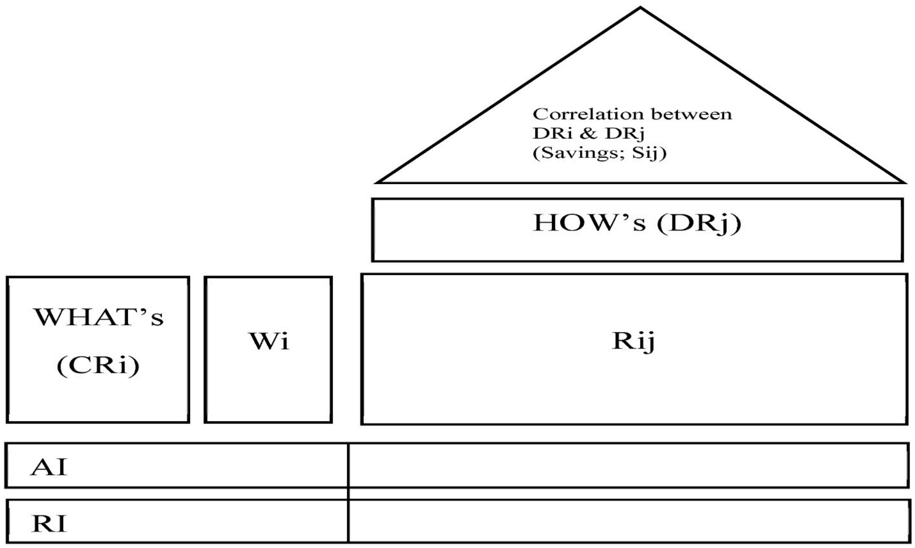


Fig. 1. Basic QFD framework.

The main goal of this study is to develop a QFD-based optimization problem to identify an efficient portfolio of strategies for SSCM to mitigate challenges effectively. The optimization problem is articulated as follows:

Input parameters

n: number of sustainable supply chain management strategies indexed by j;

SP_j: sustainability performance of SSCM strategy j;

IC_j: Implementation cost (expected) of SSCM strategy j;

S_{ij}: savings cost (if SSCM strategies i and j are implemented together);

B: available budget.

Decision variables

y_j: binary variable equal to one if the strategy j is selected; 0 otherwise.

Objective function

$$Max\, f(\mathbf{y}) = \sum_{j=1}^{n} SP_j y_j \tag{1}$$

Subject to,

$$\sum\nolimits_{j=1}^{n} IC_j y_j - \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=i+1}^{n} s_{ij} \left(y_i y_j \right) \leq B \tag{2}$$

$$y_j \in \{0, 1\}, j = 1, .., n \tag{3}$$

To linearize constraint (2), for strategies i and j, $j > i$, this research introduces a new binary variable z_{ij} equal to 1 if strategies i and j are implemented together, 0 otherwise (Asghari et al., 2022):

$$\sum_{j=1}^{n} IC_j y_j - \sum_{i=1}^{n} \sum_{j=i+1}^{n} s_{ij} z_{ij} \leq B \tag{5}$$

$$z_{ij} \leq y_i \quad i = 1, .., n-1, \quad j = i+1, .., n \tag{6}$$

$$z_{ij} \leq y_j \quad i = 1, .., n-1, \quad j = i+1, .., n \tag{7}$$

$$z_{ij} \geq y_i + y_j - 1 \quad i = 1, .., n-1, \quad j = i+1, .., n \tag{8}$$

$$y_i \in \{0, 1\} \quad i = 1, .., n \tag{9}$$

$$z_{ij} \in \{0, 1\} \quad i = 1, .., n-1, \quad j = i+1, .., n \tag{10}$$

4. Implementation of the model in small and medium-sized RMG industries of Bangladesh

This research focuses on small and medium-sized RMG industries in Bangladesh, given that over 70 percent of garment factories fall within this category (Textile Today, 2021). These enterprises play a pivotal role in the country's thriving RMG sector, producing diverse clothing items that cater to domestic and international markets. With a notable presence on the global stage, these industries export their products to more than 25 countries, contributing significantly to Bangladesh's position in the international garment trade. The scale of operations in these establishments is characterized by a workforce ranging from 1500 to 2500 employees, reflecting a substantial employment base (ACD Online, 2020). Operating within the constraints of an expected budget of USD 600,000, these enterprises typically navigate financial considerations while striving to maintain competitiveness and sustainability. This budgetary range, spanning from USD 500,000 to USD 1000,000, underscores the diverse economic landscape in which these small and medium-sized RMG industries. By addressing the unique characteristics of these smaller and medium-sized entities, this research aims to provide insights tailored to the challenges they face in adopting SSCM strategies, ultimately contributing to advancing the broader RMG industry in Bangladesh.

In recent times, there has been a growing preference for mixed methods, combining qualitative and quantitative approaches in research (Bryman, 2006). This trend is attributed to the advantages it offers, such as enhanced data quality, accuracy, validity, and reliability (Chan and Wu, 2002; Creswell and Clark, 2007). The aim of this study is to develop efficient SSCM strategies for the RMG supply chain in Bangladesh, addressing SSCM adoption challenges. To achieve this objective, we have chosen a mixed-methods approach, aligning with the principles of both qualitative and quantitative methodologies. This approach is particularly fitting with this research methodology QFD, which incorporates elements of both qualitative and quantitative methods (Park and Kim, 1998; Wang and Hong, 2007), thus aligning seamlessly with the objectives of this research.

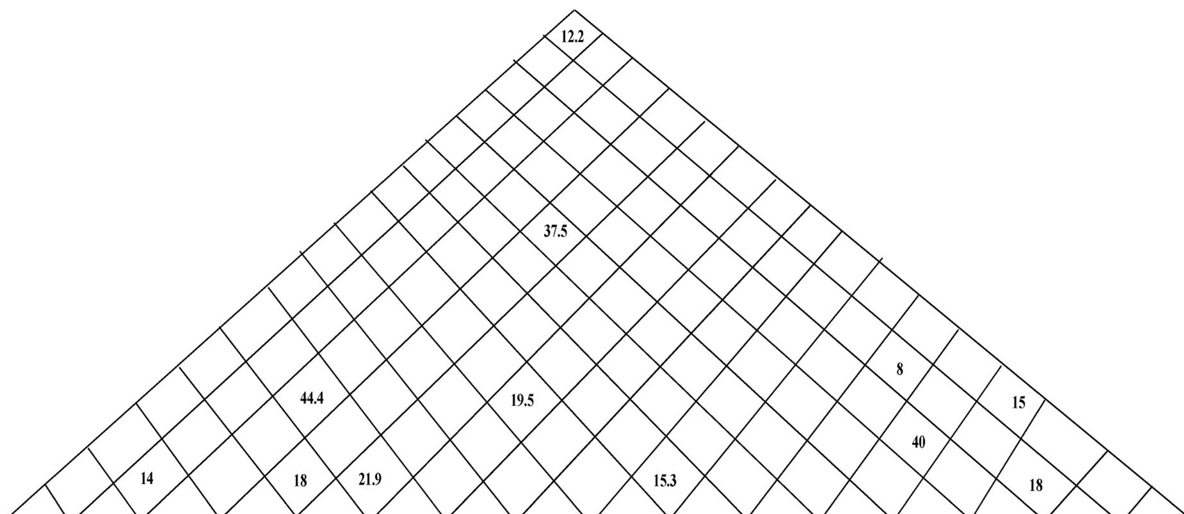
The implementation of the model in the RMG industry of Bangladesh is conducted in four phases as follows:

In the **initial phase**, to finalize the adoption challenges and select mitigation strategies, this research engaged a panel of five experts from both academic and professional backgrounds. These experts unanimously supported the identified 25 challenges and 16 strategies, although a few were excluded based on their collective evaluation.

Through expert primary evaluation, this study strategically excluded three challenges: Lack of worker skill development (Wang et al., 2016), Ineffective supplier selection strategies (Moktadir et al., 2018), and poor customer awareness and demand (Wang et al., 2016) due to their lower impact based on the context and sustainability performance in RMG supply chain. Additionally, the experts recommended excluding two strategies: traceability (Kraisintu et al., 2011) and data security and privacy (Ogbuke et al., 2022), from the initial list, as the experts believed these features were already embedded within the remaining 16 strategies. According to the expert consensus, among the initially outlined 16 strategies, they categorized S1, S6, S7, and S15 under Lean Supply Chain Management (LSCM), S2, S3, S4, S5, S8, S9, and S10 under Green Supply Chain Management (GSCM), S11, S13, and S16 under Blockchain Technology (BT), and S12 and S14 under Industry 5.0 (I5.0) categories. Additionally, there was some divergence in opinions, with some experts suggesting that S3 could fall under both GSCM and LSCM, S12 could be classified under BT and I5.0, and S14 could fall under both LSCM and I5.0.

This research used the AHP method to weightage the challenges in the **second phase**. Questionnaires were distributed to 33 experts, encompassing professionals and academicians intimately connected to the field; 20 responses were collected to prioritize the challenges for subsequent investigation. This research used an Excel solver to calculate the priority weights and ranking of the SSCM adoption challenges. The detailed calculations are not highlighted in this article to reduce the length of the article. However, the results of this prioritization process are crucial for our subsequent analysis and are reflected in the weightings assigned to each challenge throughout the research. This research have got the priority order as C3> C13 > C14 > C16 > C1 > C2 > C4 > C5 > C12 > C15 > C18 > C21> C6 > C9 > C10 > C11 > C19 > C20 > C7 > C8 > C17 > C22 > C23 > C24 > C25. Based on the AHP weight and relationship matrix between challenges and strategies obtained from the QFD framework, this research also calculated the absolute importance of the challenges. The prioritization of challenges, based on absolute importance obtained from expert surveys, revealed the top five challenges: High cost of disposing of hazardous wastes, lack of adoption of advanced technology and processes, integration of advanced technology and processes, Lack of top management commitment, and Human factor and safety challenges.

The **third phase** involved the careful integration of challenges and



Ci	Wi	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	AIi
C1	0.07	0	0	0	0.35	0.0469	0.1169	0	0.0469	0.1169	0.1638	0	0.49	0.35	0	0	0.1638	1.8452
C2	0.06	0	0	0	0	0	0.0204	0	0	0.0402	0	0	0.1002	0.0402	0.54	0.42	0.1404	1.3014
C3	0.1	0	0.234	0.234	0.5	0.167	0.7	0	0.5	0.5	0.234	0.1	0.167	0.067	0.5	0	0.067	3.97
C4	0.055	0	0	0.03685	0	0.275	0	0	0.275	0.1287	0.09185	0.09185	0.09185	0.03685	0.09185	0	0	1.1198
C5	0.05	0	0	0	0	0	0	0	0	0	0	0.117	0.117	0	0.0335	0.25	0.25	0.7675
C6	0.035	0.0819	0.035	0.245	0.0819	0.245	0.05845	0	0.02345	0.02345	0.05845	0.0819	0.175	0.05845	0	0.0119	0.05845	1.2383
C7	0.02	0	0.1	0.0468	0.0468	0.1	0.0134	0.02	0	0.06	0.1	0.14	0.0468	0	0.0134	0.14	0.0334	0.8606
C8	0.02	0.0134	0	0	0	0	0	0	0.0334	0.0134	0.18	0.06	0.1	0.0134	0.0334	0	0.0468	0.4938
C9	0.03	0	0.03	0.03	0	0.0702	0.0501	0.0501	0.0201	0.0702	0.15	0.21	0.0201	0.0702	0.0201	0.0702	0.15	1.0113
C10	0.03	0	0	0.0702	0	0.03	0	0.0201	0.15	0.0501	0.0702	0.0702	0.21	0.0501	0.0501	0.15	0.21	1.131
C11	0.03	0	0	0	0.03	0	0.0501	0.03	0.0501	0.0702	0.0501	0.15	0	0	0	0.15	0.0702	0.6507
C12	0.05	0	0	0	0.0835	0.0335	0	0	0	0	0.25	0	0.35	0	0.35	0	0.0335	1.1005
C13	0.08	0	0	0	0.56	0.0536	0	0	0.0536	0.1336	0.56	0	0.56	0	0.56	0.56	0.24	3.2808
C14	0.08	0	0	0.1336	0.4	0.0536	0.0536	0	0.1872	0.1336	0.56	0	0.72	0	0.56	0.56	0.4	3.7616
C15	0.04	0.0268	0	0	0	0	0	0	0.0268	0	0	0.0936	0.0268	0.0668	0.2	0.28	0.0668	0.7876
C16	0.06	0	0	0	0	0	0	0.1002	0	0.1002	0.1404	0.42	0.0402	0.3	0.42	0.42	0.3	2.241
C17	0.015	0.0351	0	0	0	0	0	0.0351	0.0351	0.0351	0.045	0.045	0.0351	0.135	0.045	0.105	0.045	0.5955
C18	0.04	0.0668	0	0.0936	0	0.04	0.0668	0	0.2	0.0668	0.0936	0.0268	0.2	0.2	0.2	0.2	0.36	1.8144
C19	0.025	0.225	0	0.01675	0	0	0	0.01675	0.0585	0	0.075	0.04175	0.04175	0.175	0.125	0.125	0.125	1.0255
C20	0.025	0	0.175	0.075	0.175	0.075	0.175	0.125	0.175	0.225	0.175	0.075	0.04175	0.04175	0.175	0.125	0.125	1.9585
C21	0.04	0.04	0.04	0.04	0.0936	0.12	0.12	0.12	0.04	0.0668	0.2	0.28	0.0268	0.0936	0.0936	0.2	0.0936	1.668
C22	0.015	0.0100	0.0100	0.0351	0.0351	0.02505	0.02505	0.105	0.015	0.045	0.045	0.045	0	0.105	0.01005	0.105	0.02505	0.6405
C23	0.01	0.0067	0	0.0067	0.0067	0.01	0.0167	0.05	0	0.01	0.0234	0.05	0	0.05	0.01	0.05	0.0067	0.2969
C24	0.01	0.01	0.0167	0.0234	0.0234	0.0234	0.0234	0.07	0	0.0234	0.0234	0.03	0	0.05	0.03	0.07	0.0234	0.4405
C25	0.01	0	0	0	0	0	0	0.05	0.0167	0.0067	0.07	0.03	0	0.0234	0	0.0167	0.01	0.2235
AIj		0.5157	0.6407	1.087	2.386	1.36825	1.4899	0.79225	1.90685	1.91935	3.3592	2.1581	3.56035	1.92675	4.061	4.0088	3.0441	
RIj		0.0151	0.0187	0.0318	0.0697	0.040	0.0435	0.0231	0.0557	0.0561	0.0981	0.0630	0.1040	0.0563	0.1186	0.1171	0.0889	
ICj		54	53.33	83.33	101.67	81.67	65	48.33	64.17	68.33	85	48.33	148.33	46.67	85	42.5	61.67	
SPj		0.0096	0.0120	0.0130	0.0235	0.0168	0.0229	0.0164	0.0297	0.0281	0.0395	0.0447	0.0240	0.0413	0.0478	0.0943	0.0494	

Fig. 2. QFD model (Note: Ci = Challenges, Wi = Weight, Sj = Strategies).

strategies within the established QFD framework. To determine the values of Rij, respondents were requested to express their opinions on the 'extent of mitigating the challenges i by SSCM strategy j' using the commonly accepted 9, 3, 1, and 0 scales (Chan and Wu, 2002; Faisal, 2013; Pujawan and Geraldin, 2009). The Rij values were then averaged across three respondents. Fig. 2 illustrates the Wi*Rij values in the central part of the matrix, along with the AIjs and the RIjs for different SSCM strategies. SSCM strategies S14 (continuous improvement and innovation), S15 (education and training programs) and S12 (technology integration) exhibited the highest AIs, scoring 4.06, 4.0 and 3.56, respectively. SSCM strategy S14, in particular, demonstrated the highest RE of 0.1186, followed closely by SSCM strategy S15 with an RE of 0.1171 and S12 with a RE of 0.1040. The implementation cost (ICj) of SSCM strategies was assessed comprehensively. Respondents provided estimates for the optimistic, most likely, and pessimistic costs of ICj. The expected cost (Ce) was then calculated using the formula $Ce = (Co + 4Cm + Cp)/6$, where Ce, Co, Cm, and Cp represent the expected, optimistic, most likely, and pessimistic cost estimates respectively (Collier et al., 2018; Chowdhury et al., 2015). These costs were averaged across three respondents and are presented alongside the ICj's and sustainability performances SPjs in Fig. 2. The cost figures are denominated in thousands of dollars. Furthermore, the savings (Sij) were calculated by aggregating respondents' views on which SSCM strategies can be implemented simultaneously and evaluating the resulting savings. Fig. 2's top section illustrates these savings data, such as the simultaneous implementation of SSCM strategies 1 and 16 with an estimated savings of 12.2 thousand USD. This research considers the average expected budget for small and medium-sized RMG industries in Bangladesh to implement SSCM strategies.

In the **final phase**, the optimization model is formulated to maximize the implementation of SSCM strategies, considering sustainability performance while minimizing the implementation costs and staying within the constraints of the allocated budget. Input data extracted from Fig. 2 was utilized, and the model was solved using equations (1)–(10) with an initial expected budget set at USD 600,000. The model was systematically solved using the OPL Cplex solver, and a comprehensive sensitivity analysis was conducted to offer valuable insights into the robustness of the proposed approach.

5. Results and discussion

The concept of "sustainability performance" is introduced, evaluating the effectiveness of implementing strategies relative to their associated implementation costs. A higher sustainability performance value indicated a greater impact relative to implementation costs. Conversely, a lower value suggested a less cost-effective strategy in addressing sustainable supply chain challenges, providing decision-makers valuable insights. Implementation costs are determined for small and medium-sized RMG industries, considering optimistic, pessimistic, and most likely values. With an expected budget of USD 600,000, the study illustrated that RMG industries could successfully implement 11 of the 16 identified strategies. These strategies encompass Green Logistics and Transportation (S5), Waste Reduction and Recycling (S6), Ethical Labor Practices (S7), Life Cycle Assessment (S8), Waste and Pollution Management (S9), SC Resilience and Risk Management (S10), Certifications and Standards (S11), Collaboration with Stakeholders (S13), Continuous Improvement and Innovation (S14), Education and Training Programs (S15), and Supply Chain Transparency (S16). This implementation resulted in a remarkable sustainability performance of 0.4309. However, it was highlighted that while experts consider the integration of technology crucial, budget constraints pose challenges in realizing this strategy. With a slight increase in the budget to $650,000, Technology Integration (S12) becomes feasible, demonstrating the critical role of financial resources in strategy implementation and sustainability performance. So, the new expected budget has been set as $650,000 with a sustainability performance of 0.4511 based on the decision-maker's recommendations. With the proposed expected budget, there is an opportunity to implement 12 out of the 16 identified mitigation strategies effectively. This optimal cost allocation ensures the incorporation of advanced technology-related strategies, addressing key challenges in the SSCM for RMG industries.

Despite the strategies of Supplier Collaboration (S1), Sustainable Sourcing (S2), Energy Efficient Technology and Renewable Energy (S4), and Green Logistics and Transportation (S5) not being selected within the proposed expected budget, the QFD analysis reveals relationships and opportunities for their implementation. The synergies identified through QFD highlight the potential for the simultaneous implementation of specific strategies. For instance, the collaboration between Supplier Collaboration (S1) and Supply Chain Transparency (S16) indicates that maintaining transparency throughout the supply chain could mitigate challenges related to supplier collaboration. Similarly, the relationship between Sustainable Sourcing (S2) and Circular Economy Practices (S3) suggests that successfully implementing circular economy practices within RMG industries, achievable within the proposed budget, may contribute to sustainable sourcing objectives. Moreover, the budget allocated for "Continuous Improvement and Innovation" could be extended to cover aspects of green logistics and transportation, showcasing the interconnectedness and strategic opportunities within the spectrum of sustainable supply chain strategies. This distinct understanding derived from the QFD analysis provides insights for decision-makers to optimize strategy selection and allocation, ensuring a more holistic and interconnected approach to sustainable practices in the RMG industry.

This research categorized 16 sustainable strategies into Lean, Green, Blockchain Technology, and Industry 5.0 related strategies. The analysis revealed that green strategies exert the highest impact on adopting sustainable supply chain practices in Bangladeshi RMG industries. Considering the challenges posed by technology in the current era, the research recommends the implementation of Blockchain or Industry 5.0 technologies alongside green strategies. Remarkably, this multi-faceted approach is achievable within the expected budget, demonstrating the feasibility of comprehensive sustainability initiatives. The sensitivity analysis conducted **[See section 5.1 for details]** provides detailed insights into the relationship between budget allocation, strategy implementation, and corresponding sustainability performance. These findings underscore the complex interplay between financial considerations and strategic priorities in advancing sustainable practices within RMG industries, highlighting the need for careful planning and resource management to achieve optimal outcomes.

5.1. Sensitivity analysis

This research conducted a sensitivity analysis to outline the effect on sustainability performance (SP) with the budget (B) change, as shown in Table 3 and Fig. 3.

The sensitivity analysis conducted on the implementation of SSCM strategies in small and medium-sized RMG industries in Bangladesh reveals insightful findings. Fig. 3 illustrates a linear relationship between the budget allocated and sustainability performance, providing a clear understanding of the impact of financial resources on the adoption of strategies. At the initial expected budget of (USD 600,000), the sustainability performance stands at 0.4309, allowing for the implementation of 11 out of 16 strategies. This underscores the impact of financial constraints on the practical implementation of strategies. With a slight budget increase to (USD 650,000), as recommended by decision-makers, sustainability performance improves to 0.4511, facilitating the implementation of 12 strategies. Notably, this adjustment enables the inclusion of a specific strategy related to technology integration (S12), illustrating the influence of budget flexibility on strategy selection. At the maximum budget of (USD 900,000), sustainability performance reaches its peak at 0.5130, accommodating the implementation of all 16 identified strategies. Conversely, no strategies can be implemented

Table 3
Sensitivity analysis.

B	SP	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12	s13	s14	s15	s16
900	0.513	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
850	0.5034	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
800	0.4914	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
750	0.4799	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
700	0.4635	0	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1
650	**0.4511**	**0**	**0**	**1**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
600	**0.4309**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**1**	**1**	**1**	**1**
550	0.4141	0	0	0	0	0	1	1	1	1	1	1	0	1	1	1	1
500	0.3977	0	0	0	0	0	1	0	1	1	1	1	0	1	1	1	1
450	0.3748	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	1
400	0.3467	0	0	0	0	0	0	0	1	0	1	1	0	1	1	1	1
300	0.2939	0	0	0	0	0	0	1	0	0	0	1	0	1	1	1	1
100	0.139	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
50	0.0943	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

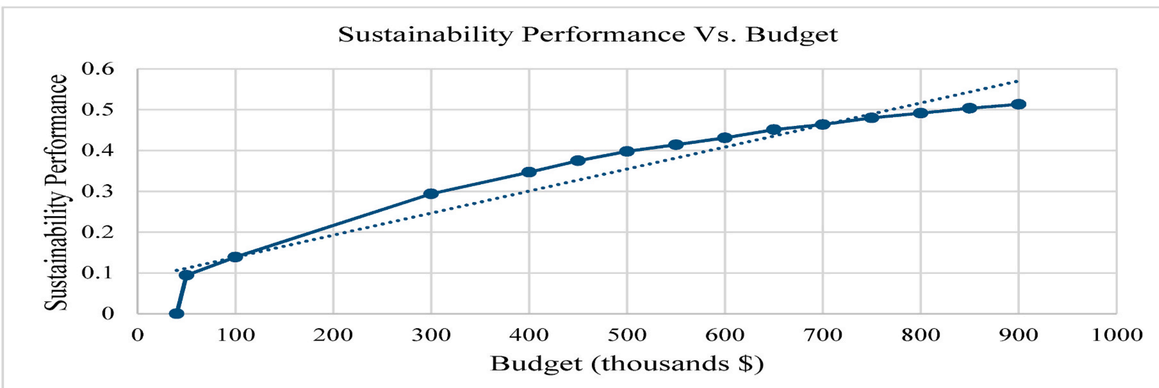


Fig. 3. Sensitivity analysis.

below a budget of (USD 50,000), resulting in a minimal sustainability performance of 0.0943. This highlights the crucial threshold for initiating sustainable practices and the significance of adequate financial resources. Between budgets of (USD 50,000) and (USD 900,000), there is flexibility in implementing any number of strategies based on organizational needs, emphasizing the adaptability of the model to different budget scenarios and organizational priorities.

While the analysis prioritizes strategies based on their cost-effectiveness (sustainability performance), it's crucial to recognize the influence of weight changes within the AHP criteria on this ranking. These criteria likely include environmental impact, economic viability, and social responsibility. Exploring different weight scenarios could impact the ranking of challenges hindering SSCM adoption and potentially lead to the selection of different optimal mitigation strategies within the QFD framework. For instance, increasing the weight of "environmental impact" could elevate the importance of strategies such as "Waste Reduction and Recycling (S6)" or "Life Cycle Assessment (S8)". As a result, the QFD analysis might prioritize these strategies differently, potentially leading to their inclusion within the budget constraints. The sensitivity analysis offers practical benefits beyond simply understanding the impact of the budget. It empowers companies to allocate resources strategically, prioritizing high-impact options within their budget. Companies can develop flexible plans by analyzing different budget scenarios, like having a core set of essential practices for tighter budgets and integrating advanced strategies as finances improve. This data also facilitates cost-effective decision-making, allowing companies to choose the optimal strategy mix for maximizing environmental impact within their financial constraints.

5.2. *Comparison with similar studies*

This research distinctly focuses on mitigating challenges in adopting sustainable supply chain practices, while the primary focus of Chowdhury and Quaddus (2015) was managing SC disruptions. This research employs a single-objective MILP model, contrasting with the non-fuzzy multi-objective formulation adopted by Chowdhury and Quaddus (2015). Furthermore, their approach utilizes an interactive method to find an initial solution and then explore various efficient solutions, while this research focuses on finding an optimal solution through a single-objective model. Similar to our findings, several studies have highlighted the critical role of financial resources in implementing sustainable practices. For example, Ramanathan and Yunfeng (2009) and Lin et al. (2011) demonstrated the impact of budget limitations on the adoption of sustainability initiatives in different industries. Our research further substantiates this by illustrating that with an expected budget of USD 600,000, Bangladeshi RMG industries can implement 11 out of 16 identified strategies, achieving a sustainability performance of 0.4309. This aligns with the insights of Aydin et al. (2023), who emphasized the need for a structured framework to manage financial constraints while fulfilling customer expectations and enhancing sustainability.

Moreover, our study's focus on the integration of advanced technologies, such as Blockchain and Industry 5.0, resonates with recent literature advocating for technological advancements to bolster sustainability efforts. The inclusion of technology integration within our proposed budget framework ($650,000) underscores the findings of Hsu et al. (2017) and Yazdani et al. (2020), who incorporated advanced decision-making tools to enhance the efficiency and effectiveness of sustainability practices. The critical role of technology in achieving comprehensive sustainability objectives is further highlighted by Allehashemi et al. (2022), who utilized fuzzy QFD and weighted-sum methods to address CO2 emissions and quality aspects in a closed-loop supply chain network. Additionally, our research offers a nuanced understanding of strategy interrelationships by applying QFD analysis to identify synergies between strategies such as Supplier Collaboration (S1) and Supply Chain Transparency (S16). This interconnected approach mirrors the findings of He et al. (2021), who integrated Kano-QFD-DEMATEL to analyze risks and identify strategic linkages within sustainable supply chains. However, our research addresses the practical challenges of adopting sustainability and provides strategic insights that align with and extend the findings of prior studies. This comparative discussion underscores the evolving landscape of sustainable supply chain management and the critical role of innovative methodologies in achieving sustainability goals.

5.3. Strategic action plan

The strategic action plan for enhancing sustainable supply chain adoption in Bangladeshi RMG industries involves a comprehensive approach that integrates research findings with current industry initiatives spearheaded by BGMEA (2020). Commencing with a SWOT analysis, the plan leverages internal strengths, addresses weaknesses, explores external opportunities, and mitigates potential threats. Integrating AHP with QFD methodology prioritizes challenges and strategies, providing a targeted framework for intervention. The decision-makers can merge results obtained from this research with their current initiatives (BGMEA, 2020): (i) Aligning Sustainable Development Goals (SDGs: 3, 5, 6, 12, and 17) with National Priority Indicators (NPIs: NPI 5 & 6, 17 & 18, and 13) intending to impact 10% of the Bangladeshi population (ii) The commitment to Decarbonization, reducing industry GHG emissions by 30% by 2030. (iii) “Green Button Initiative” reflects the commitment to a holistic sustainability seal for apparel products. (iv) SWITCH to circular economy value chains to achieve circularity in the RMG sector. (v) Partnership for Cleaner Textile (PaCT), with its focus on water footprint reduction, energy efficiency, and chemical management. To enhance the practicality of the model, consultations with supply chain experts through cost analyses should be suggested that are aligned with organizational goals.

The strategic action plan is adaptable to various scenarios, with budget allocations offering financial flexibility for effective strategy implementation. Innovative financing models and collaborations with governments and NGOs can be explored to overcome budget constraints and facilitate technology integration. Stakeholder collaboration, training programs, and key performance indicators contribute to a comprehensive and measurable sustainability initiative. A robust risk management plan can be built around strengthening resilience and ensuring continual improvement. Communication strategies and benchmarking global best practices can promote transparency, awareness, and the incorporation of cutting-edge sustainable methods. Decision-makers in Bangladeshi RMG industries could set the way for a sustainable and resilient future by aligning their green policy, water resource management, and waste management programs with our research findings.

6. Conclusion

This research presents a comprehensive approach to addressing SSCM adoption challenges in Bangladeshi small and medium-sized RMG industries. The study employs a mixed-methods approach to formulate a MILP optimization model within the QFD framework, integrating qualitative and quantitative methodologies. The research identifies 25 SSCM adoption challenges and 16 mitigation strategies, offering a systematic methodology to prioritize and optimize their implementation. The proposed QFD-based optimization model, integrated with the AHP, provides a strategic tool for decision-makers in RMG industries. The model considers the sustainability performance of strategies relative to their implementation costs, highlighting the importance of budget allocation in achieving optimal sustainability outcomes. The research recommends a phased implementation approach, aligning strategies with the expected budget, and emphasizes the critical role of financial resources in enhancing sustainability performance.

The results indicate that relying solely on GSCM may not effectively address all challenges associated with the adoption of sustainable supply chains, given the rapid advancements in technology and processes. Consequently, this study proposes two viable solutions: either integrating GSCM with Blockchain technology or combining it with Industry 5.0 for more efficient mitigation of challenges. Additionally, the research observes opportunities to implement certain strategies simultaneously across LSCM, GSCM, BT and I5.0, allowing organizations to leverage cost savings. The optimization model already accounts for savings costs, identifying efficient and sustainable strategies.

In conclusion, this research successfully addressed the initial inquiries. It identified and prioritized 25 challenges faced by Bangladeshi RMG industries in adopting sustainable supply chains (RQ1). Subsequently, 16 mitigation strategies were proposed to address these challenges (RQ2). Finally, by employing a QFD-based optimization model, the study identified an optimal set of 12 strategies that maximize sustainability performance within a constrained budget (RQ3). This study’s impact could extend beyond Bangladesh. Providing a practical model for optimizing sustainable supply chain management adoption offers a roadmap for garment industries in other developing nations. This can lead to a domino effect, pushing the global fashion industry towards more sustainable practices and reducing its environmental footprint.

6.1. Research contributions

This research contributes to Bangladeshi RMG industries from a sustainability perspective. This research offers optimization models that help to provide more insightful actionable strategies along with qualitative studies. Developing an AHP integrated QFD-based optimization model to select optimal mitigation strategies is a significant contribution to SSCM. This combined approach offers a more comprehensive and data-driven decision-making framework compared to existing methodologies. The study enhances the traditional MILP models by linearizing nonlinear constraints, offering a new technique that can be applied to various optimization problems in supply chain management and beyond. The outcomes promote environmental practices and highlight the importance of integrating green technologies. The detailed sensitivity analysis **[See section 5.1 for details]** conducted in the study provides insights into the complex interplay between budget allocation, strategy implementation, and sustainability performance, guiding decision-makers in optimal resource management. This following Table 4 summarizes the academic and scientific contributions of this research, highlighting the specific applications and methods employed.

6.2. Managerial implications

The research outcomes offer crucial insights for managers in Bangladeshi small and medium-sized RMG industries seeking to enhance sustainability within their supply chains. The optimal sustainable portfolio, composed of 12 selected mitigation strategies, is a viable option achievable within an expected budget of USD 650,000, resulting in a sustainability performance of 0.4511. This information aids managers in making informed decisions on strategy selection and resource allocation. Additionally, the research emphasizes the pivotal role of financial resources in implementing sustainable practices, highlighting the need for proper budget planning to achieve optimal sustainability performance. Managers are urged to consider a phased approach, prioritizing strategies based on their impact and aligning them with the available budget.

Organizations must cultivate sustainability performance to address

Table 4
Contributions of this research.

Method	Application	Contribution
AHP	Enables targeted focus on the most impactful areas for improvement.	Prioritization of key challenges hindering SSCM adoption in the Bangladeshi RMG industry
QFD	Facilitates the development of actionable plans to address specific challenges.	Selection of optimal mitigation strategies for prioritized challenges
Integration of AHP and QFD	Provides a structured approach for RMG companies to make informed decisions regarding SSCM implementation.	Data-driven decision-making framework for sustainable supply chain management
Extensive survey and interview process with academic and industry experts	Offers a valuable reference point for other companies striving to improve their environmental performance.	Establishment of a benchmark for sustainable practices within the Dhaka region's garment industry
Novel MILP Optimization Model	Contributes to a more environmentally responsible and sustainable future for the Bangladeshi garment sector.	Promotion of SSCM adoption and enhancement of the overall sustainability performance of the RMG industry

the challenges associated with adopting sustainable supply chain practices. This research offers valuable insights for managers, particularly in the RMG sector in Bangladesh, aiding them in addressing three pivotal elements: (i) Identifying the current sustainable supply chain management adoption challenges in the RMG sector, (ii) Understanding the strategies available to mitigate these challenges, and (iii) Determining the optimal sustainable portfolio of strategies to address challenges within budget constraints. Specifically, the "optimal sustainable portfolio" is delineated by the 12 selected strategies, strategically chosen based on their effectiveness and alignment with the budget constraints. This portfolio represents a balanced mix of selected strategies. The outcomes of this study serve as a guide for RMG managers, offering a comprehensive understanding of efficient sustainable strategies tailored to their specific context.

6.3. Limitations and future directions

Despite the valuable insights provided, the study has certain limitations. The research relies on expert opinions and averages, which might introduce subjectivity and potential bias. The expected budget of $650,000 is proposed based on decision-maker recommendations, and variations in budget assumptions could impact the results. The study focuses on small and medium-sized RMG industries in Bangladesh, limiting the generalizability of findings to other industries or larger enterprises. The sensitivity analysis provides insights within the defined budget constraints, but external factors influencing budget availability have not been extensively explored.

To advance the research in this domain, future studies could focus deeper on specific factors influencing budget allocation for sustainable supply chain practices. Exploring external influences such as government incentives, industry collaborations, or financial support programs could provide a more comprehensive understanding of budget dynamics. Additionally, incorporating real-world data and case studies from diverse industries and regions would enhance the generalizability of findings. Future research could also explore integrating emerging technologies, such as blockchain and Industry 5.0, in greater detail, considering their unique challenges and opportunities. Finally, longitudinal studies tracking the actual implementation and outcomes of suggested strategies would contribute to the evolving body of knowledge in sustainable supply chain management.

Funding

The Open Access Funding Provided by the Qatar National Library.

CRediT authorship contribution statement

Md Al Amin: Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Roberto Baldacci:** Writing – review & editing, Supervision.

Declaration of competing interest

We are confirming the authenticity and originality of the work "**QFD-Based Optimization Model for Mitigating Sustainable Supply Chain Management Adoption Challenges for Bangladeshi RMG Industries**" and declaring that this article has not been published elsewhere. We have no conflict of interest to disclose.

Data availability

No data was used for the research described in the article.

Acknowledgments

Authors use AI-assisted technologies (Quillbot and Grammarly) in the writing process to improve readability and language.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143460.

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