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Evaluation of challenges to marine plastic waste management with an integrated multiple-criteria decision-making approach

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Introduction: Overdependence on plastic and negligence in plastic waste management are the major reasons for marine plastic pollution. Besides several global initiatives, marine plastic waste management is still affected by several challenges. Thus, marine plastic waste management has become a global environmental threat, and overcoming these challenges is essential for reducing plastic contamination of water bodies. This study assesses the challenges to identify key areas that need attention for effective marine plastic waste management.

Methods: Challenges in marine plastic waste management were identified through a literature review and verified through a Delphi analysis based on experts' input. An integrated multi-criteria decision-making framework, consisting of Fermatean Fuzzy Sets - Analytic Hierarchy Process - Decision-Making Trial and Evaluation Laboratory, was used to evaluate weight significance and causal interrelationship of the challenges. A sensitivity analysis was performed to measure the robustness of the results.

Results: Lack of real-time marine plastic data, absence of social consciousness, Rapid coastal urbanization, Lack of science advice, and Frail enforcement mechanisms were identified as major challenges to marine plastic waste management.

Discussion: Outcomes may provide valuable insight for policymakers and industrial practitioners in devising strategies for effective marine plastic waste management. Also, it could help in lowering marine pollution and attaining Sustainable Development Goal 14.

KEYWORDS
Delphi analysis, FFS-AHP, FFS-DEMATEL, marine plastic waste management, sustainable development goals

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1 Introduction

Every year, nearly 8–10 million tonnes of plastic waste enter water bodies in various ways and 80% - 90% of plastic waste is municipal waste. The quantity of this plastic entering water bodies is estimated to double by 2030 and even quadruple by 2050 (Wu, 2022). Thus, marine plastic pollution has become one of the most significant environmental challenges of the twenty-first century (Courtene-Jones et al., 2022). Plastic consumption and production systems offer significant societal and economic benefits due to their low cost, long lifespan, and flexibility as materials. However, the same characteristics that have led to the benefits associated with plastic production and consumption lead to plastic accumulation (as waste) in water bodies. When plastic materials enter the marine environment, they can remain for a long period of time, travel thousands of miles from their source (de Deus et al., 2024; Bel Hassen et al., 2025), and create environmental, economic, and social impacts that are felt long after a product leaves its source. Marine plastic pollution is thus a serious concern for governments, industries, environmental organizations, and international institutions that wish to achieve long-lasting environmental sustainability.

Many initiatives have been implemented to address the serious nature of this issue and to reduce plastic leakage into marine environments. International agreements, national regulations, waste-management programs, circular economy programs, extended producer responsibility programmes, public awareness campaigns and technological innovations for monitoring and recovering waste are all examples of these initiatives. Together, they indicate an increasing commitment at the global level to tackling marine plastic pollution, both through preventive measures and the correction of past damage (Courtene-Jones et al., 2022; Fonseca et al., 2024; Chang and Saqib, 2025). However, despite these efforts, plastic pollution in many aquatic ecosystems is still increasing, indicating that the presence of policies, technologies, and management initiatives may not be enough for achieving successful outcomes.

Due to a lack of collection and disposal methods, plastic waste in the oceans continues to pose serious ecosystem challenges that can only be solved through collaboration by all stakeholders involved in managing marine plastics, including all levels of government, industry, communities, researchers, non-profit organizations and other governing bodies at the local, state, national, and international levels. Marine plastic waste management must address the interplay of numerous governance, social, operational, and information challenges that contribute to the success or failure of current management solutions. Although much research has already been done on understanding the impact of plastic pollution on the environment and possible mitigation solutions, not enough research has focused on how management issues interact with each other to discourage or support effective implementation (Bertolazzi et al., 2024; Fonseca et al., 2024).

Marine plastic governance faces many limitations, such as weak enforcement, poor coordination between stakeholders, operational constraints, and a lack of information (Bank et al., 2021; Mofokeng et al., 2024; Luo et al., 2025). These challenges have been investigated in isolation, which has led to a limited understanding of marine plastic governance as a whole. Additionally, limited research exists on how these different challenges may interact with one another, essentially, which ones may act as the primary drivers of marine plastic governance issues, and which challenges may result from more general marine plastic governance conditions. This gap is particularly important given the resource constraints faced by policymakers and practitioners; therefore, they need to know where to intervene to maximise their impact. Exploring the causal structure of marine plastic governance challenges can help inform effective and coordinated governance strategies.

In order to fill this gap, a systems-based analytical approach has been utilized in the current study to evaluate the challenges associated with managing marine plastic waste. In particular, the study will focus on identifying those challenges that have the most significant effect on marine plastics management, investigating the relationships of these challenges with one another, and determining the causal forces having the maximum impact on the overall management system. An integrated framework will be utilized in order to achieve these objectives. This framework will consist of Fermatean Fuzzy Sets, the Analytic Hierarchy Process (AHP) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method.

Accordingly, the study addresses the following research questions:

RQ1. What are the most critical challenges affecting effective marine plastic waste management?

RQ2. How do these challenges influence one another within the broader marine plastic management system?

RQ3. Which challenges act as primary causal drivers and therefore represent strategic leverage points for intervention?

This research provides various significant contributions. First, from a policy standpoint, it identifies high-priority issues and leverage points that support the development of improved marine plastic management strategies. Second, managers can utilize the findings to allocate resources effectively and create collaborative actions for regulators, waste management entities, and industry participants. Third, with respect to theory, the study creates a new understanding of marine plastic management by conceptualizing marine plastic management challenges as interconnected components of a broader system rather than isolated obstacles. Fourth, from a methodological standpoint, the combination of Fermatean Fuzzy Sets and AHP/DEMATEL provides a sound basis for prioritizing challenges and determining cause-and-effect links in environments of uncertainty. Finally, using an analysis of the critical drivers for marine plastic management issues will assist in creating better, harmonized, and sustainable approaches for reducing plastics in marine ecosystems.

2 Literature review

2.1 Impact of plastic waste on water bodies

Plastic pollution is a global challenge and threatens all types of aquatic ecosystems. Plastics are extremely durable and take a long time to break down. Therefore, plastic waste that enters the ocean, rivers, lakes, and other aquatic environments will remain there for a long time and cause significant environmental harm (Bertolazzi et al., 2024; Bel Hassen et al., 2025). In marine environments, plastics can adversely affect species through ingestion, entanglement, habitat loss, and/or changes in ecological processes. Concerns about the impacts of microplastics have increased as microplastics can enter aquatic systems relatively easily and become part of the aquatic food web, accumulate in marine animals, and persist in aquatic environments for a long time. Thus, it is becoming evident that plastic pollution represents a significant threat to biodiversity, resilience, and the long-term sustainability of our aquatic ecosystems (Chanda et al., 2024; Jeong et al., 2024; Bagavathsingh et al., 2025).

Plastic pollution goes beyond environmental harm (McMullen et al., 2023). There are substantial costs associated with the impacts of plastic across fisheries, tourism, shipping and local communities. In addition to these costs, many governments and businesses incur high costs in cleaning efforts, waste disposal, and restoration of the environment. More recent scientific studies have demonstrated additional potential for negative impacts on human health by way of microplastics entering the food chain (Jeong et al., 2024). Due to the environmental, economic and social implications of plastic pollution, researchers are increasingly extending their attention beyond investigating the effects of plastic pollution on marine environments toward identifying effective management strategies capable of preventing plastic from entering aquatic ecosystems.

2.2 Challenges to marine plastic waste management

Various global policy frameworks do not have the capability to effectively manage plastic pollution that crosses international boundaries (Bel Hassen et al., 2025; Hui et al., 2025). Ineffective regulatory frameworks at the national level and disorganized leadership structures limit the effectiveness of the current policies (Ahmed et al., 2025). There is no cohesive policy framework due to the lack of integration of scientific knowledge into policymaking, the lack of effective enforcement mechanisms, and the lack of internationally recognized standards (Hui et al., 2025; Suazo-Galdames et al., 2025). The governance deficiencies also limit policymakers and regulatory agencies from creating and implementing long-term solutions. Marine plastic management efforts can be hindered by complications related to stakeholders and social challenges that exist within communities. Public awareness and environmental consciousness have significant impacts on the plastic consumption and disposal behaviours of individuals, but many communities are still unaware of the environmental impact of improper plastic disposal (Miguel et al., 2024). Because marine plastic pollution is a transboundary issue and involves a number of stakeholders across borders, the lack of adequate collaboration will negatively affect the effectiveness of management interventions (Heath and Cotton, 2022; Lampitt et al., 2023; Mofokeng et al., 2024).

Marine plastic management is also hampered by operational and technical barriers. Microplastics are especially problematic due to the challenges associated with detecting, monitoring, and removing these very small plastic particles from aquatic environments (Mohsin and Abd zaid, 2025). Plastic waste generated by ports, fisheries, shipping, and coastal operations contributes to marine debris accumulation (Apete et al., 2024). Illegally discarding plastics is primarily the result of poor waste management systems and limited enforcement, and is continually leading to more plastics leaking into the waters (Gómez-Sanabria and Lindl, 2024). The heterogeneous nature of the plastic complicates the recycling and recovery process as different polymers have different processing requirements (Mager et al., 2026). The increasing number of people living on the coast increases the amount of waste generated in ecologically sensitive coastal areas, further compounding these operational challenges (Chen et al., 2023). Another major challenge to effective management is inadequate access to quality information and monitoring systems (Bank et al., 2021). There is a notable lack of monitoring systems in many areas, particularly in remote coastal regions, which allows for illegal dumping and disposals to occur unnoticed. The presence of unreliable and outdated data concerning plastics in the marine environment will impede evidence-based policymaking and adaptive management processes (Rilov et al., 2020). Although advances in remote sensing, artificial intelligence, and environmental monitoring technologies are likely to help overcome these obstacles, their ongoing success will depend on having strong institutional support, coordination mechanisms, and data-sharing agreements in place (Hussain et al., 2024). These marine plastic management challenges represent an interconnected network of socio-institutional issues, governance systems, stakeholder networks, operational processes and information infrastructure, rather than just a waste management problem (Heath and Cotton, 2022; Fonseca et al., 2024). These challenges are highly interrelated, implying that improvements made to one challenge will have some effect on many other challenges within the management system. It is vital to understand how these challenges relate to each other to create successful intervention strategies (Tong et al., 2023). Table 1 displays the list of challenges to marine plastic waste management collected through literature review.

2.3 Research gaps and contributions

Despite previous research identifying many obstacles to managing marine plastics, there are still large gaps in our knowledge. Firstly, most current research examines governance, stakeholders, operations, and information barriers separately and therefore results in a fragmented understanding of how these barriers collectively influence marine plastic management (Bertolazzi et al., 2024; Fonseca et al., 2024). Secondly, while marine plastics management clearly involves complex interactions between institutions, society, technical and information barriers, there is limited research into the nature of these relationships (Heath and Cotton, 2022). Lastly, little attention has been paid by researchers to distinguishing between root causes of challenges and the resultant challenges for practitioners and policymakers, which limits their ability to determine high-leverage intervention points.

To fill these gaps, this study will take a systems-wide view of marine plastic management challenges. The study will use a combination of Fermatean Fuzzy Sets, AHP, and DEMATEL to prioritize the challenges and explore causal relationships among those challenges. It is anticipated that the results of this study will

TABLE 1 Challenges to marine plastic waste management.

Challenges	Description	References
Ineffective global policy framework (C1)	Existing global policies fail to control plastic contamination in water bodies.	(Ferraro and Failler, 2020; Bel Hassen et al., 2025)
Weak national policies (C2)	Policies framed by individual nations are insufficient to control marine plastic pollution.	(Ferraro and Failler, 2020; Bel Hassen et al., 2025)
Non-existence of global leadership (C3)	Multiple global bodies result in diversified opinions.	(Ferraro and Failler, 2020)
Lack of scientific advice (C4)	Failure to incorporate scientific advice to control marine plastic pollution.	(Ferraro and Failler, 2020)
Absence of social consciousness (C5)	People were unaware of the consequences of throwing plastic into water bodies.	(Nelms et al., 2022)
Frail enforcement mechanisms (C6)	Although several policy frameworks exist, it has not been enforced effectively.	(Hui et al., 2025; Leal Filho et al., 2025)
Deficit of standardized guidelines (C7)	Different laws in different countries weaken marine plastic contamination control.	(Hui et al., 2025; Leal Filho et al., 2025)
Inadequate cooperation among business partners (C8)	Differences regarding plastic management among business partners result in a lack of cooperation.	(Hui et al., 2025)
Microplastic contamination (C9)	Micro-level plastic bypasses the segregation process and enters the water body.	(Casella et al., 2024; Bhattacharjee et al., 2025)
Port and fishing gear debris contamination (C10)	End-of-use plastic materials are thrown into water bodies.	(Mohite and Mathew, 2025; Kanhai et al., 2026)
Illegal plastic waste disposal (C11)	Due to a lack of proper waste management, plastic is disposed of near water bodies.	(Liu, 2025)
Plastic heterogeneity (C12)	Variation in chemical composition poses a difficulty in plastic waste management.	(Leal Filho et al., 2025; Liu, 2025)
Rapid coastal urbanization (C13)	A growing population has resulted in rapid urbanization in coastal areas.	(Zhai et al., 2020)
Lack of surveillance in remote coastal areas (C14)	Failure in monitoring remote areas allows illegal dumping of plastic waste.	(Riaz and Gharbia, 2026)
Lack of real-time marine Plastic Data (C15)	Difficulty in quantifying the amount of marine plastic waste.	(Leal Filho et al., 2025; Liu, 2025)

assist policymakers, regulators, and industry stakeholders in developing improved marine plastic management strategies and reducing plastic pollution in marine environments.

3 Methodology

This study uses the FSS-AHP-DEMATEL technique to evaluate the challenges to marine plastic waste management.

3.1 Fermatean fuzzy sets

FFS, an extension of classical fuzzy set theory, offers more flexibility in handling uncertainty and expert hesitation (Senapati and Yager, 2020). It evaluates membership, non-membership, and hesitation degrees under a cubic constraint (Zenginoğlu and Kuvvetli, 2026). The cubic constraint of FFS permits experts to make a more realistic assessment, whereas intuitionistic and Pythagorean fuzzy sets under linear and quadratic constraints limit the combined evaluation of membership and non-membership degrees. FFS offers a large decision space for modelling expert hesitancy when compared with intuitionistic and Pythagorean fuzzy sets (Al-kuwari et al., 2026). Also, FFS provides higher flexibility as the sum of cubes of membership and non-membership functions is less than or equal to one (Liu et al., 2025). This flexibility enhances the illustration of uncertainty without burdening the experts. Furthermore, it improves interpretability and computational efficiency. The fundamental steps in FFS are explained below:

Consider a global set X, and the common form of FFS is represented as follow:

$$f = \left\{\left(x,\ \mu_f^F(x),\ v_f^F\right) : x \in X\right\} \tag{1}$$

Calculate the indeterminacy degree (π_f^F) using Equation 2.

$$\pi_f^F(x) = \sqrt[3]{1 - \left(\mu_f^F(x)\right)^3 - \left(v_f^F(x)\right)^3} \tag{2}$$

Estimate Fermatean fuzzy weighted average (FFWA) with Equation 3.

$$FFWA(f_1,\ f_2,\ \ldots .f_n) = \left(\sum_{i=1}^n w_i \mu_f^F,\ \sum_{i=1}^n w_i v_f^F\right) \tag{3}$$

FFS score is measured using Equation 4.

$$S^F(f) = \frac{1}{2}\left[\left((\mu_f^F)^3 - (v_f^F)^3 - \ln\left(1 + \pi_f^F 3\right)\right)\right] \tag{4}$$

3.2 Analytic hierarchy process

AHP, the most popular MCDM method, was proposed by (Saaty, 1980). It is a structured method for solving complex decision-making problems. It is a hierarchical decision-making method that exhibits the associations between goals and alternatives (Sivrikaya and Küçük, 2022). Pairwise comparisons are made among the factors and its accuracy is measured using consistency ratio. It follows the principles of reciprocal condition, homogeneity, dependency, and expectations to rank each factor (Islam et al., 2025). The advantages of AHP include observance of hierarchical structure in problem solving, assessment of quantitative and qualitative problems, capable of measuring interdependency of factors, and examination of consistency in ranks (Tavana et al., 2023). The steps in the AHP technique are as follows:

Step 1: Construct a pairwise comparison matrix (A).

$$A = \begin{bmatrix} a_{11} & \cdots & \cdots & a_{1j} \\ \vdots & \ddots & \iddots & \vdots \\ \vdots & \iddots & \ddots & \vdots \\ a_{i1} & \cdots & \cdots & a_{ij} \end{bmatrix} \tag{5}$$

where a_{ij} denotes the impact of challenge (i) over challenge (j).

Step 2: Analyze the consistency of the pairwise comparison matrix (A).

To measure the consistency, W' has to be estimated. Before that, the weight of the criteria (W) has to be calculated.

$$W = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix} \text{ and } W_i = \frac{\sum_{i-1}^{n} \alpha_{ij}}{n} \tag{6}$$

$$W' = AW = \begin{bmatrix} W_1' \\ W_2' \\ \vdots \\ W_n' \end{bmatrix} \tag{7}$$

$$\lambda = \frac{1}{n}\left(\frac{W_1'}{W_1} + \cdots + \frac{W_n'}{W_n}\right)_{max} \tag{8}$$

$$ConsistencyIndex(CI) = \frac{\lambda_{max}}{n-1} \tag{9}$$

where λ_{max}- highest eigenvalue and n - size of the matrix.

$$ConsistencyRatio(CR) = \frac{CI}{RandomIndex(RI)} \tag{10}$$

Step 3: Estimate the weights of the challenges.

$$W = (w_1, \ldots, w_n) \tag{11}$$

where W is the weight of the drivers.

3.3 Decision making trial and evaluation laboratory

DEMATEL, a combination of graph theory and matrix tool, introduced by (Gabus and Fontela, 1972), is used to solve critical problems. It depicts the complicated causal interrelationships among the factors via digraphs (Shi et al., 2024). DEMATEL converts qualitative evaluation of relationships into quantitative metrics to examine causal interrelationship among the factors. In DEMATEL, the factors are grouped under the cause-and-effect groups, which helps in understanding of their influence and interdependencies. It further helps in determining the relationship strength among the factors. The following are the steps involved in the DEMATEL technique:

Step 1: Establish a direct-relation matrix (B).

Step 2: Normalized matrix (N)

The direct-relation matrix (B), was normalized with Equation 12 and Equation 13 and normalized matrix (N) was established.

$$N = c^{-1}B \tag{12}$$

$$C = max\left(\max_{1\le i\le n}\sum_{j=1}^{n} a_{ij}, \max_{1\le i\le n}\sum_{i=1}^{n} a_{ij}\right) \tag{13}$$

Step 3: Construct a total relation matrix (T).

Total-relation matrix (T) was established using Equation 14.

$$T = N(I-N)^{-1} \tag{14}$$

where 'I' is the identity matrix.

Step 4: Calculate influence and prominence values

The sum of rows (P_i) and columns (Q_j) of the total-relation matrix (T) are measured with Equation 15 and Equation 16.

$$P_i = \left(\sum_{i=1}^{n} t_{ij}\right)_{n\times 1} = (t_i)_{n\times 1} \tag{15}$$

$$Q_j = \left(\sum_{j=1}^{n} t_{ij}\right)_{1\times n} = (t_i)_{1\times n} \tag{16}$$

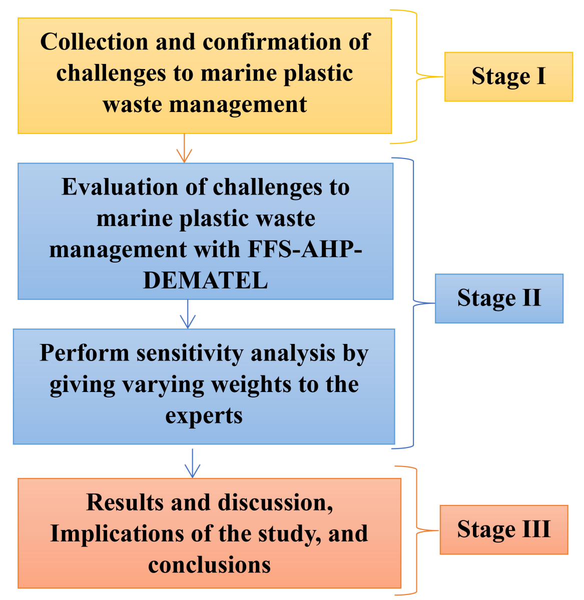

FIGURE 1
Research framework.

4 Real-time application of the methodology

The research framework shown in Figure 1 was used in this study to evaluate the challenges in marine plastic waste management. As depicted in Figure 1, the study was carried out in three stages. The first stage focuses on the collection and confirmation of the challenges to marine plastic waste management, while in the second stage, the challenges were evaluated. In the third stage, a discussion on the outcomes and implications of the study is provided.

4.1 Collection and confirmation of challenges to marine plastic waste management

The study begins with the collection of challenges to marine plastic waste management. In the pursuit of collecting relevant challenges, a systematic literature review was conducted on the Scopus database. The Scopus database has been preferred as it covers a wider domain, including engineering, management studies, and environmental sciences. The following search strings, formed using the Boolean operators, have been used to identify relevant articles on the Scopus database: 'Marine' OR 'Sea' OR 'Water bodies AND 'Plastic' AND 'Challenges' OR 'Barriers' OR 'Impediments'. The literature search was conducted between February 2026 and April 2026. Initial search yielded 669 articles. Then, articles published in languages (Chinese – 19, Russian – 3, Italian – 2, Portuguese – 2, Thai – 1, Polish – 1, Persian – 1, Korean – 1, and German - 1) other than English were rejected. Next, only original research articles were selected, and other documents (Review – 133, Book chapter – 76, Conference paper – 67, Conference review – 10, Book – 5, Short Survey – 2, Retracted – 1, and Note - 1) were excluded. Further, articles published between 2021 and 2026 have been filtered, and this results in 261 articles. Title screening was done for these 261 articles to confirm their relevance to this study. During this phase, 112 articles were omitted. Then, abstract reading was carried out, and 68 articles were neglected. Finally, full paper reading was performed to ensure that the article answers the research questions this study intends to address. At last, 72 articles that match the scope of this study have been selected, and from these articles, the challenges given in Table 1 have been collected.

To verify the relevance of the challenges collected from the literature, opinions from the domain experts were used. For this, an expert panel consisting of 15 domain experts was formed. These 15 domain experts possessed sufficient working experience in marine plastic waste management, working in different capacities (port manager, Oceanographer, Marine Campaigner, and Compliance Officer) related to the marine environment. The average working experience of the expert panel was 6 years. Apart from working experience, educational qualifications, and demonstrated expertise in marine plastic waste management were taken into consideration while selecting the domain experts. Accordingly, the expert panel includes domain experts with substantial domain-specific knowledge despite variations in working experience. The opinions of the domain experts were collected using the Delphi analysis. Here, the Delphi analysis was conducted at two different time to ensure robustness and reliability. A questionnaire (Table A1 of Appendix - I) containing a five-point Likert scale was given to the domain experts to gather their responses. The threshold value set for confirming the challenges was three. The reason for setting three as the threshold value is that it is the average of the minimum value (1 – strongly disagree) and maximum value (5 – strongly agree) (O'Neill, 2017). During the first Delphi round, all fifteen challenges received the threshold value. The degree of consensus among the domain experts in the first round of Delphi analysis was estimated using Kendall's Coefficient of Concordance (W) analysis. The analysis yielded W = 0.358 (χ^2 = 75.113, df = 14, p< 0.001), indicating a moderate and statistically significant level of consensus among the 15 domain experts (Table B1 of Appendix – II). Again, Kendall's Coefficient of Concordance (W) analysis was conducted during second round of the Delphi analysis. Now, the obtained value was W = 0.523 (χ^2 = 109.884, df = 14, p< 0.001), indicating a strong and statistically significant level of agreement among the 15 domain experts (Table B2 of Appendix – II). It confirms the reliability of the domain expert judgments and support the retention of the challenges for subsequent analysis. Thus, all fifteen challenges were considered for further evaluation with FFS-AHP-DEMATEL.

4.2 Evaluation of challenges to marine plastic waste management with FFS-AHP-DEMATEL

In this stage, the challenges were evaluated with FFS-AHP-DEMATEL. First, the weight significance of the challenges was evaluated with FFS-AHP. For this, the experts were asked to make pairwise comparisons between the challenges using the linguistic scale provided in Table 2. A questionnaire (Table C1 of Appendix - III) was used to get experts' opinions. With the response of experts for the questionnaire (Table C1 of Appendix - III), a pairwise comparison matrix (A) as represented in Equation 5 was constructed. Then, the linguistic response of the experts was transformed into FFS numbers. These FFS numbers are converted into crisp numbers with Equations 1–4. Then, the CR of the matrix (A) was assessed with Equations 6–10. The obtained CR of the matrix (A) was 0.067, which was within the acceptable range (Frish et al., 2025). Next, the weight significance of the challenges was estimated with Equation 11 and is given in Table 3.

The causal interrelationship among the challenges was examined using FFS-DEMATEL. A questionnaire (Table C2 of Appendix - III) was used to get experts' opinions. Based on the experts'

TABLE 2 Linguistic scale.

Linguistic terms	Linguistic scale	FFS numbers
No Influence (NO)	0	(0,1)
Very low Influence (VL)	1	(0.1, 0.75)
Low Influence (L)	2	(0.4, 0.5)
High Influence (H)	3	(0.7, 0.2)
Very high Influence (VH)	4	(0.9, 0.1)

TABLE 3 Rank of challenges.

Challenges	P_i	Q_j	$P_i + Q_j$	Rank	P_i - Q_j	Cause/effect	Weight	Rank
C1	0.62	1.03	1.648	8	-0.414	Effect	0.168	7
C2	0.59	0.93	1.522	13	-0.332	Effect	0.162	9
C3	0.59	1.13	1.716	6	-0.538	Effect	0.155	10
C4	1.79	0.90	2.697	4	0.888	Cause	0.502	4
C5	1.84	0.98	2.819	2	0.858	Cause	0.526	2
C6	1.77	0.86	2.629	5	0.908	Cause	0.491	5
C7	0.53	0.99	1.520	14	-0.453	Effect	0.149	12
C8	0.53	1.05	1.576	10	-0.515	Effect	0.147	13
C9	0.59	1.05	1.646	9	-0.459	Effect	0.165	8
C10	0.62	1.05	1.677	7	-0.431	Effect	0.168	6
C11	0.55	0.98	1.532	12	-0.424	Effect	0.152	11
C12	0.53	0.98	1.506	15	-0.448	Effect	0.146	14
C13	1.87	0.95	2.815	3	0.923	Cause	0.512	3
C14	0.49	1.06	1.546	11	-0.570	Effect	0.133	15
C15	1.94	0.93	2.866	1	1.007	Cause	0.539	1

opinions, the direct relationship matrix (B) is constructed. The direct-relationship matrix (B) was normalized using Equations 12 and 13, and the normalized matrix (N) was obtained. With normalized matrix (N), the total-relationship (T) using Equation 14. The sum of rows (P_i) and columns (Q_j) of the total-relation matrix (T) are measured with Equation 15 and Equation 16. With this, the prominence ($P_i + Q_j$) and influence (P_i - Q_j) values of the challenges are calculated and are given in Table 3. The causal interrelationship among the challenges is depicted in Figure 2.

A sensitivity analysis was conducted to measure the robustness and reliability of the outcomes. In this study, the sensitivity analysis was conducted by assigning various weights to the experts (see Table D1 in Appendix - IV). Such a sensitivity analysis was also carried out in earlier studies (Li et al., 2025; Novoa-Hernández et al., 2025). The outcome of the sensitivity analysis is given in Table 4 and displayed in Figure 3.

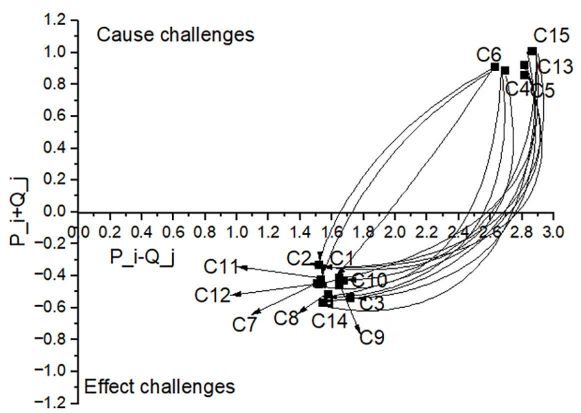

FIGURE 2
Cause and effect relationships among the challenges.

5 Discussion

According to the weight significance calculated with the FFS-AHP method, the challenges are ranked as follows: C15 > C5 > C13 > C4 > C6 > C10 > C1 > C9 > C2 > C3 > C11 > C7 > C12 > C8 > C14. “Lack of real-time marine plastic data (C15)” is the most significant marine plastic waste management challenge, as effective quantification is impossible to perform for the plastic waste amount, and proper effective measures cannot be initiated unless the responsible authority and research bodies get real-time data for different sorts of marine plastic (Leal Filho et al., 2025). also identified the absence of real-time data in the case of marine plastic waste to better understand the current scenario and generate corrective measures for preparedness and maintenance as a continuous course of management. “Absence of social consciousness (C5)” is the next critical challenge, implying that plastic waste generation is ultimately triggered by unaware handling and throwing of plastic waste into the water bodies by people (Nelms et al., 2022). This can be more elucidated that, due to the absence of proper social awareness and lack of knowledge of the consequences of marine plastic waste, people just think that the plastic waste is just a negligible part in comparison to the vast ocean, which eventually generates massive havoc for the marine living bodies, including both plants and fishes moreover the water bodies (Bhattacharjee et al., 2025; Hui et al., 2025). The third important challenge is “Rapid coastal urbanization (C13)”. Densely populated cities are increasingly choosing to settle in the coastal areas rather than in towns and other dense zones. This phenomenon is also occurring due to good communication with towns and low-cost living in coastal areas (Horton et al., 2025). This new and unwanted urbanization process has a great negative impact on the environment of the coastal areas and is very much tempting to plastic material usage as well as disposal in coastal water bodies due to the

TABLE 4 Rank of challenges in sensitivity analysis.

Challenges	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5		Trial 6		Trial 7		Trial 8	
	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
C1	0.160	6	0.161	7	0.163	7	0.167	6	0.160	7	0.166	6	0.164	7	0.164	7
C2	0.153	8	0.160	8	0.160	9	0.161	8	0.159	8	0.162	8	0.157	9	0.159	8
C3	0.147	12	0.156	9	0.151	11	0.155	10	0.151	10	0.152	10	0.155	10	0.149	10
C4	0.506	2	0.487	4	0.498	4	0.497	4	0.495	4	0.498	4	0.500	4	0.497	4
C5	0.504	3	0.502	3	0.522	2	0.522	2	0.526	2	0.519	2	0.527	2	0.523	2
C6	0.483	5	0.483	5	0.487	5	0.487	5	0.487	5	0.477	5	0.487	5	0.487	5
C7	0.140	13	0.144	13	0.149	13	0.148	11	0.146	12	0.152	11	0.144	12	0.148	11
C8	0.138	14	0.139	14	0.145	14	0.145	13	0.144	13	0.142	14	0.141	14	0.142	13
C9	0.159	7	0.156	10	0.162	8	0.159	9	0.159	9	0.159	9	0.159	8	0.157	9
C10	0.151	10	0.170	6	0.171	6	0.164	7	0.164	6	0.164	7	0.164	6	0.164	6
C11	0.149	11	0.145	12	0.153	10	0.147	12	0.147	11	0.147	12	0.147	11	0.145	12
C12	0.153	9	0.149	11	0.150	12	0.142	14	0.142	14	0.142	13	0.142	13	0.141	14
C13	0.513	1	0.508	2	0.510	3	0.509	3	0.511	3	0.511	3	0.509	3	0.510	3
C14	0.132	15	0.133	15	0.134	15	0.129	15	0.128	15	0.128	15	0.129	15	0.129	15
C15	0.500	4	0.534	1	0.537	1	0.536	1	0.540	1	0.536	1	0.536	1	0.541	1

Challenges	Trial 9		Trial 10		Trial 11		Trial 12		Trial 13		Trial 14		Trial 15	
	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
C1	0.162	8	0.152	9	0.154	8	0.159	7	0.155	9	0.161	8	0.169	6
C2	0.157	9	0.155	7	0.153	9	0.152	9	0.158	7	0.155	9	0.158	9
C3	0.153	10	0.150	10	0.149	10	0.149	10	0.152	10	0.155	10	0.157	10
C4	0.499	4	0.497	4	0.499	4	0.497	4	0.497	4	0.497	4	0.497	4
C5	0.526	2	0.524	2	0.524	2	0.522	2	0.522	2	0.522	2	0.522	2
C6	0.487	5	0.488	5	0.487	5	0.487	5	0.487	5	0.487	5	0.489	5
C7	0.147	14	0.142	13	0.144	12	0.140	14	0.144	12	0.147	13	0.148	12
C8	0.149	13	0.140	14	0.140	13	0.140	13	0.142	13	0.147	11	0.154	11
C9	0.170	7	0.154	8	0.157	7	0.157	8	0.156	8	0.164	7	0.164	8
C10	0.170	6	0.160	6	0.158	6	0.161	6	0.160	6	0.166	6	0.164	7
C11	0.151	11	0.143	12	0.146	11	0.141	11	0.151	11	0.147	12	0.147	13
C12	0.149	12	0.149	11	0.139	14	0.141	12	0.140	14	0.142	14	0.142	14
C13	0.508	3	0.508	3	0.509	3	0.508	3	0.508	3	0.508	3	0.508	3
C14	0.129	15	0.128	15	0.133	15	0.131	15	0.133	15	0.129	15	0.125	15
C15	0.536	1	0.534	1	0.536	1	0.534	1	0.534	1	0.536	1	0.536	1

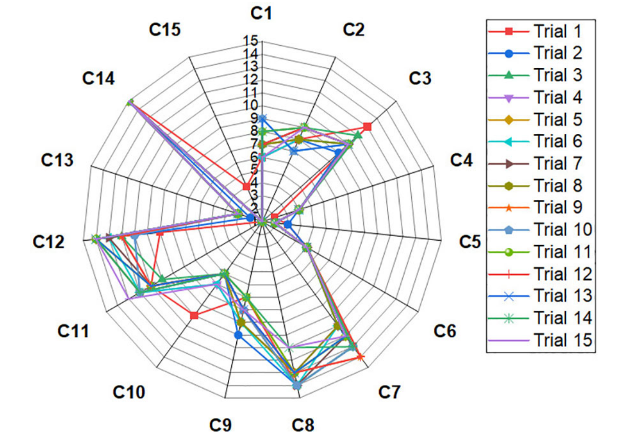

FIGURE 3
Sensitivity analysis.

course of garbage mismanagement by local or coastal authorities (Zhai et al., 2020).

Another critical challenge to marine plastic waste management is "Lack of science advice (C4)". Although scientists and researchers are largely interested in conducting their research on the sustainability and environmental issues of urban and industrial areas, there is an evident lack of research on marine sustainability and environmental concerns. However, some fruitful scientific research and discoveries have provided effective guidelines to favor the marine plastic control process, but in most of the cases, the actual control mechanism practitioners lack scientific knowledge and are reluctant to modify the existing policies and working procedures (Ferraro and Failler, 2020; Krishnaraja et al., 2026). The fifth important challenge is "Frail enforcement mechanisms (C6)". Although some strict rules and regulations have been enforced in the last decade by some prominent authorities in popular coastal areas to effectively set and maintain control mechanisms for marine plastic pollution, these are not exercised effectively in actual practice, both by the concerned authority and the coastal visitors, as well as local dwellers (Hui et al., 2025; Leal Filho et al., 2025). "Port and fishing gear debris contamination (C10)" is the sixth important challenge in marine plastic waste management, contributing to a serious marine plastic pollution problem. Such a type of pollution gets boosted by the unconscious fisherman throwing their damaged plastic parts of fishing nets or broken plastic fishing equipment directly into the water bodies, which eventually turns into an artificial cave for fish and other coastal animals (Aransiola et al., 2025; Mohite and Mathew, 2025).

With FFS-DEMATEL, the fifteen challenges have been grouped into cause-and-effect groups, with 5 challenges in the cause group and the remaining 10 challenges in the effect group. Among the cause group challenges, this study found "Lack of real-time marine Plastic Data (C15)" as the most prominent one. Absence of real-time marine data collection, generation, and transmission can be treated as a serious cause of marine plastic pollution, as this can trigger the postponement of other onward pollution control mechanisms (Leal Filho et al., 2025; Luo et al., 2025). The next important challenge in the cause group is "Rapid coastal urbanization (C13)". The consistently increasing accommodation tendency of the people in the coastal areas acts as a vital cause of marine plastic waste contamination in the coastal water bodies, as well as the rapid growth of local markets, restaurants and small factories, which is also responsible for this happening (Zhai et al., 2020). “Frail enforcement mechanisms (C6)” is the next important challenge, causing marine plastic pollution. This challenge is so remarkable that unless the concerned local and coastal authorities can effectively enforce the control measures for marine plastic waste contamination, other onward protective and monitoring actions become meaningless, denoting just a fruitless financial investment for the entire management (Hui et al., 2025; Leal Filho et al., 2025).

In the effect group, “Lack of surveillance in remote coastal areas (C14)” has been identified as the most significant challenge, indicating that due to irregular monitoring in remote areas, far from port observation, marine plastic pollution occurs more severely with uncontrolled plastic waste dumping. It can be so realistic when the well-enforced marine environment conservation laws and policies are not in actual practice, through continuous monitoring directed by the marine surveillance authority in many coastal areas (Krishnaraja et al., 2026; Riaz and Gharbia, 2026). “Non-existence of global leadership (C3)” has been noted as the second most severe effect challenge. This phenomenon comes up with the variations in setting up marine environment management laws and orders, mostly by the governments of the adjacent countries. Since seas have no practical or geographical borders or limitations, pollutant materials in one ocean area can conveniently spread over a long distance, creating a massive waste issue for another territory. Hence, for effective marine climate and water conservation, global leadership and coordination are badly needed to ensure the efficacy of the actionable measures (Ferraro and Failler, 2020; Chu and Xuan Chau, 2026). “Microplastic contamination (C9)” is the third most important challenge in the effect group. Since microplastic elements cannot be traced or restricted through the actual segregation process, they can easily be contaminated in water bodies, ultimately creating serious havoc for the normal living mechanism of the marine ecosystem (Casella et al., 2024; Aransiola et al., 2025; Bhattacharjee et al., 2025).

The ranking outcomes achieved from the integrated methodological approach were furthermore validated through sensitivity analysis. Although the radar chart, as illustrated in Figure 3, has designated the ranking results generated from different trial runs with some negligible deviations from the actual ranking, the prominent ranking results match the resultant ranking. Hence, the initial ranking outcomes can be considered as appropriate for effective implications in the reformation of a constructive national and cross-border maritime policy framework, as well as overall growth of social awareness.

6 Implications of the study

6.1 Policy implications

Marine plastic pollution has been considered a global concern for the marine environment in the last several decades and is catastrophic for the marine ecosystem in a broad sense. However, by being aware of such a serious issue, governments from different countries have enforced timely, relevant, and applicable laws and policies regarding effective marine plastic pollution control measures. Since the ocean has no visible boundary or border line among the territories of adjoining countries, plastic waste can conveniently get contaminated in water bodies in one territory and spread over long distances, making it untraceable to blame any government for their lack of enforced laws and practices, as well as ineffective marine surveillance. Hence, instead of distinctive actions and practices adopted by different governments, marine plastic contamination can be controlled by effective coordination among the conjoining nations. There should be a globally applicable general policy framework regarding marine plastic waste control in each country. Beyond these policies, specific adjacent nations can enforce some additional policies contemporary to their ocean control range, fishing activities, tourism, and shipping operations. However, such supplementary policies must be aligned with the global policy framework in enforcement and application to avoid apparent conflicts among the nations. Furthermore, the policy framework in both global aspects and territorial domains must be consistently upgraded with the discoveries and guidelines from the noble scientific research works to better realize the scenario, as well as ensuring more advanced control mechanisms. The responsible marine management authority from the government side must acquire real-time data for plastic pollution so that effective control measures can be initiated instantly and sustainable actions can be maintained. Lack of real-time data has been a major issue in marine plastic waste management. Meanwhile, rapid coastal urbanization increases plastic contamination of water bodies. With digital technologies like the Internet of Things, drones, and geographic information systems, it is possible to monitor the entry of plastics into water bodies and identify hotspots. In rapidly urbanizing coastal regions, these digital technologies can be used to streamline plastic waste management. Developing countries with limited financial constraints should invest in affordable digital monitoring systems for effective marine plastic waste management.

6.2 Social implications

Marine plastic contamination is not a natural occurrence, merely a human-generated issue that is detrimental to the marine environment to a large extent. Once the plastic materials are deposited in the ocean bed, it is quite impossible to pull them completely out of the ocean, especially for microplastics. In that case, already dispensed and deposited plastic materials are a serious and still unresolved problem for proper marine environmental management. Moreover, different chemical compositions in plastic compounds create difficulties in waste management for collection, sorting, and disposal. Such a serious marine ecosystem disturbance has been triggered by the continuous, unconscious dumping of plastic by humans in the deep ocean or at the seashore. Although several awareness-raising campaigns and social activities are being held in coastal areas specifically for sea beach tourists and ocean travellers, including fishing and shipping activities, people are not conscious of their casual plastic-dumping attitude, feeling like it is a

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normal activity, and that such small plastic material cannot support pollution purposes in the vast ocean as well. Furthermore, the rapid movement of people in the coastal areas to their new accommodations is also responsible for the increasing pattern of marine plastic pollution. People living alongside the port or coastal areas are very prone to dumping their used-up or damaged plastic materials in their nearest garbage. Unless effective garbage handling activities are carried out by the local municipal, coastal, or any other concerned authorities, these plastic waste materials can eventually be discharged into the marine water bodies by the local drainage system and thus stimulate marine pollution. Additionally, besides the coastal side dwellers, the employees of the shipping company, along with the fishermen, must act in attention of social responsibility in handling their plastic waste and restrict themselves from plastic dumping in marine water bodies. Shipping, tourism, and fishing industry authorities and unions must realize this serious fact and come up with more conscious guidelines for their people. They must also conduct training sessions for proper plastic waste management when they are in ocean transit or fishing work.

7 Conclusion

Plastic has been designated as a curse for environmental pollution due to its naturally impossible nature of decomposition. In this advanced age, plastic circularity has achieved a remarkable recognition, but such recycling is far from the actual consumption and disposal in a global sense. However, alongside general plastic pollution caused by humans, marine plastic pollution is not a newly discovered major ecosystem issue; it has been regarded as a crucial challenge for coastal environment management for the last several decades. Although the developed nations have already initiated various control mechanisms for marine plastic pollution, a simple activity can reduce and almost eradicate this serious marine ecosystem impact, and that is just conscious human behavior who are close to the coastal areas or marine water bodies and responsible disposal of the daily used-up plastic materials. Nevertheless, social campaign programs must be continued by the coastal authorities, and even more realistic demonstrations are needed for growing social awareness among all who are responsible for marine pollution. However, the government should act in both ways, including the extraction of the currently deposited plastics from the ocean bed, along with regular surveillance of the coastal areas. Moreover, coordination and collaboration among the adjacent nations can help conduct marine plastic pollution control effectively, and globally enforceable laws and policies can be framed with more actualization.

This study aimed to effectively analyze the prominent challenges of marine plastic pollution. However, this study identified several key limitations. Firstly, this study did not address the challenges for the local coastal authority and the central government for marine plastic pollution more specifically. Secondly, this study did not analyze the contribution of several industries like tourism, shipping, and fishing in the case of marine plastic pollution. Thirdly, this study did not focus on any specific areas, such as coastal tourism, shipping lines, and fishing areas, for a better realization of the study findings. Moreover, the research framework used in this study should be viewed as a decision-support tool rather than a policy prescription. Hence, caution should be exercised while implementing the outcome of this study as the social, economic, and technological conditions vary across the countries.

Future research works can be executed for more specific marine plastic waste management issues for local coastal authorities on a small scale and for the policy reforming government wings entirely. Further research can also be designated to industry-specific challenges and their contribution to controlling marine plastic pollution. Moreover, extensive case studies need to be performed in specific pollution-prone territorial domains to better delineate the actual portfolio. Regarding sensitivity analysis, Monte Carlo simulation or scenario-based sensitivity analysis should be conducted in future work.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

Author contributions

KK: Methodology, Conceptualization, Data curation, Writing – review & editing, Writing – original draft, Formal analysis. MR: Formal analysis, Data curation, Writing – review & editing, Conceptualization, Writing – original draft. AS: Writing – review & editing, Data curation, Writing – original draft, Formal analysis, Conceptualization. SK: Writing – review & editing, Formal analysis, Conceptualization, Writing – original draft. SP: Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

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