

Quantitative evaluation of material waste and its root causes in bridge construction using pareto and fishbone framework

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ABSTRACT

Material waste is one of the most persistent issues affecting the efficiency, cost, and sustainability of construction projects. In large-scale bridge construction, excessive waste not only escalates project costs but also undermines environmental performance and resource utilization. This study quantitatively evaluates the types, magnitude, and root causes of material waste in the construction of the Main Bridge (MB) STA 6+876, part of the Sigli-Banda Aceh Toll Road project in Indonesia. A descriptive quantitative approach utilised primary data from 70 respondents (owners, contractors, and consultants) and secondary data from project documentation and cost estimates (BoQ). The analysis employed the Pareto method to identify dominant waste contributors, a Fishbone Diagram to determine causal factors, and the Statistical Package for the Social Sciences (SPSS) to validate the descriptive results. The Pareto analysis revealed that deformed steel bars (BJTD 40) accounted for 84.17% of total material waste costs, followed by structural concrete class B-1-1a at 14.78%. The Fishbone analysis identified unexpected site conditions (weather and soil), errors in ordering and delivery, and inadequate material storage as the primary causes of waste generation. SPSS analysis confirmed the statistical dominance of these factors, supporting the reliability and validity of the findings. The results emphasized the need for enhanced accuracy in material planning, procurement, supervision, workforce training, and risk mitigation. This integrated framework is recommended as a practical reference for improving material efficiency and reducing waste in future infrastructure projects.

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1. INTRODUCTION

The construction industry is globally known as one of the largest consumers of natural resources, and material waste remains a persistent challenge undermining cost efficiency, project timelines, and environmental performance (Aftab et al., 2025; Shajidha and Mortula, 2025). Material waste in construction, especially in large-scale infrastructure projects, not only leads to cost overruns and schedule delays but also to CO₂ emissions, resource depletion, and landfill burdens (Ferriz-Papi et al., 2024; Karaca et al., 2024). Recent systematic reviews highlighted that this sector continues to exhibit high volumes of waste generation, limited source-reduction practices, and weak integration of circular-economy principles, despite strong regulatory and sustainability pressures (Swarnakar and Khalfan, 2024; Kannan et al., 2024). These findings underscore an urgent need for enhanced material-waste assessment frameworks that address not just end-of-pipe recycling but also upstream planning, procurement, and monitoring stages (Anggraini et al., 2022).

Material waste is increasingly framed not only as an operational inefficiency but also as a sustainability risk across the life cycle of construction projects. Stakeholder studies indicate that strategies such as design for disassembly, prefabrication, and material reuse can substantially reduce waste generation, yet their adoption remains inconsistent due to technical, economic, and organizational barriers (Karaca et al., 2024; Rani et al., 2023). Recent research also shows that waste behavior varies significantly depending on project type, with residential and commercial buildings generating multiple waste streams compared to large infrastructure projects (Viswalekshmi and Bendi, 2023; Zheng et al., 2024). To prioritize interventions, scholars have applied the Pareto principle to identify the vital few waste components that account for the majority of project losses, providing a more targeted approach to waste reduction (Naji et al., 2022; Aftab et al., 2025). However, these studies often stop at cost identification without systematically mapping underlying causal mechanisms, reducing their value for managerial decision-making.

In the Indonesian context, prior studies have primarily focused on small-scale or medium-scale projects such as housing, schools, and office buildings, identifying causes of waste such as inaccurate material estimation, inadequate storage, design changes, and weak coordination among stakeholders (Rani et al., 2023; Rani et al., 2024). Although valuable, these studies lack comprehensive integration between quantitative cost-based assessments and root-cause diagnostic frameworks. There is a scarcity of empirical work examining waste in large-scale bridge projects, which are characterized by complex logistics, exposure to environmental factors, and high sensitivity to design and specification changes (Anggraini et al., 2022; Aftab et al., 2025). Furthermore, statistical validation of identified causes is seldom applied, leaving a methodological gap in linking stakeholder perceptions with cost-based evidence.

Bridges are among the most critical components of transportation infrastructure, serving as vital connectors that ensure accessibility, mobility, and economic integration. Unlike building projects, bridge construction involves large volumes of structural concrete, reinforcement steel, and specialized materials such as elastomeric bearings and prestressed girders. These materials are often high in unit cost, which magnifies the financial impact of any waste. Previous research suggests that the highest total of waste proportions in infrastructure projects are frequently concentrated in a few material categories, particularly reinforcement

steel and concrete (Viswalekshmi and Bendi, 2023; Zheng et al., 2024). Mismanagement of these materials not only raises project costs but also undermines structural performance and sustainability objectives.

To address these challenges, the present study adopts a mixed methodological framework integrating Pareto analysis, Fishbone diagramming, and statistical validation. The Pareto method is applied to identify the dominant contributors to material waste by cost, allowing prioritization of interventions according to the 80/20 rule. The Fishbone diagram (also known as the Ishikawa cause-and-effect diagram) is then used to categorize the root causes of waste into systematic groups such as manpower, methods, materials, machinery, measurements, and environment (Anaç et al., 2024). This structured diagnosis is complemented by statistical analysis using SPSS, which validates the reliability of survey responses and quantifies the relative influence of identified factors (Rani and Arlianti, 2024). While these methods have individually been employed in prior studies, their integration in the context of large-scale bridge construction remains limited in current literature.

The case study chosen for this research, the Main Bridge (MB) STA 6+876 on the Sigli-Banda Aceh Toll Road, provides an ideal empirical context for applying this integrated framework. The project represents a large-scale, complex infrastructure development in Indonesia involving multiple stakeholders (owners, consultants, contractors, and field workers), high-cost materials, and significant logistical challenges. Preliminary observations indicated high levels of reinforcement steel and concrete waste. However, without a systematic evaluation, the magnitude and root causes could not be clearly identified. Addressing this gap is critical not only for cost reduction but also for enhancing sustainability and ensuring that infrastructure projects align with national goals for efficient resource use and climate resilience.

Therefore, the objectives of this study are fourfold: (1) to measure the magnitude and types of material waste (by category and cost) in a major bridge construction project; (2) to identify and categorize the root causes of the most dominant waste contributors using Fishbone analysis; (3) to statistically validate which factors are most significant from stakeholder perspectives; and (4) to propose actionable managerial and operational strategies for reducing material waste in similar infrastructure projects. By achieving these objectives, this study contributes to both academic knowledge and professional practice. From an academic standpoint, it extends existing waste-management research by integrating cost-based prioritization, root-cause analysis, and statistical validation in a single methodological framework. From a practical perspective, it provides project managers, contractors, and policy makers with evidence-based recommendations to enhance efficiency, reduce unnecessary expenditure, and align infrastructure development with the principles of sustainability, with particular emphasis on prioritizing avoidance and minimization over treatment strategies (Heffernan and Kempton, 2025).

2. LITERATURE REVIEW

2.1 Material Waste in a Construction Project

Material waste has been increasingly recognized as a major obstacle to achieving efficiency and sustainability in the construction industry. Defined broadly, it refers to any construction material that is not utilized as intended during a project, leading to economic loss, inefficiency, and environmental burden

(Swarnakar and Khalfan, 2024). The construction sector generates approximately 30-40% of global solid waste, making it one of the largest contributors to unsustainable resource use (Aftab et al., 2025; Kannan et al., 2024). Large-scale infrastructure projects such as bridges exacerbate this challenge, as they involve high-cost materials and complex logistics where even minor inefficiencies could possibly lead to significant waste (Zheng et al., 2024).

While material waste is sometimes unavoidable, recent research emphasizes that a substantial portion can be avoided with improved planning, monitoring, and management practices. Previous studies confirm that reinforcement steel and structural concrete represent the largest share of waste costs, reflecting both their high usage and their susceptibility to errors in estimation, delivery, and handling (Viswalekshmi and Bendi, 2023; Naji et al., 2022). As a result, material waste is not only a technical issue but also a managerial concern that influences productivity, profitability, and sustainability (Anggraini et al., 2022).

2.2 Classification of Construction Material Waste

Efforts to understand and control waste generation have led to various classifications of material waste. One common categorization distinguishes between direct waste (unused or damaged materials), indirect waste (losses caused by rework or design changes), and process waste (inefficiencies caused by poor labor or equipment use) (Naji et al., 2022; Aftab et al., 2025). Another perspective differentiates on-site waste, such as breakage, spillage, and mishandling, from off-site waste, which includes over-ordering, delivery delays, and procurement errors (Karaca et al., 2024). These classifications are important because they enable targeted interventions: on-site waste can be mitigated through supervision and training, but off-site waste requires procurement and improvements in the supply chain.

To provide a clearer comparison of construction material waste types reported in previous studies, Table 1 summarises the main classifications of construction material waste and their characteristics.

Table 1: Classification of Construction Material Waste

Classification	Description	Typical Examples	Key References
Direct waste	Materials that are damaged, unused, or discarded during construction activities	Broken concrete, cut-off reinforcement steel, spilled materials	Naji et al. (2022); Aftab et al. (2025)
Indirect waste	Material losses resulting from rework, design changes, or corrective actions	Demolition due to redesign, rework of structural elements	Aftab et al. (2025); Moradi (2023)
Process waste	Waste caused by inefficiencies in construction processes, labour, or equipment usage	Over-mixing of concrete, idle time, improper sequencing	Swarnakar and Khalfan (2024)
On-site waste	Waste generated directly at the construction site during handling, storage, and installation	Material breakage, poor storage, and mishandling	Karaca et al. (2024); Zheng et al. (2024)

Off-site waste	Waste is generated before materials reach the site due to procurement and logistics issues.	Over-ordering, delivery errors, and damaged materials in transport	Karaca et al. (2024); Zheng et al. (2024)
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Source: Authors

Recent studies have also highlighted project-specific classifications, particularly in infrastructure projects where materials such as elastomeric bearings, prestressed girders, and specialized concrete mixes are used. Such materials are expensive and highly customized, making waste particularly costly (Zheng et al., 2024). Understanding the distinct categories of waste in these contexts is critical for prioritizing managerial attention and developing effective mitigation strategies tailored to project type and scale (Viswalekshmi and Bendi, 2023). Moreover, systematic reviews of construction waste estimation methods have proven that classification frameworks form the foundation for quantifying and managing waste effectively in diverse project contexts (Tong et al., 2023). Recycling-oriented classifications have also been proposed, emphasising that waste categories should be linked directly to opportunities for the reuse and recovery of resources in construction projects (Patil et al., 2024)

2.3 Causes of Material Waste

The causes of material waste are complex, multifactorial, and vary across projects. Internal causes include inaccurate estimation, poor design documentation, inadequate storage facilities, and insufficient supervision of workers (Moradi, 2023; Rani et al., 2024). External causes often relate to weather conditions, soil instability, or supply chain disruptions, which are particularly relevant in large-scale bridge projects (Naji et al., 2022; Aftab et al., 2025). Combined, these factors highlight the need for both project-level and systemic interventions to reduce waste.

In developing countries, structural challenges further aggravate the problem. Limited adoption of digital tools, fragmented governance structures, and reliance on informal or low-skilled labor create an environment where waste becomes more likely (Anggraini et al., 2022; Abulebdah et al., 2024). Recent studies further emphasise that the absence of structured best-practice frameworks and systematic waste minimisation strategies contributes significantly to persistent material waste in construction projects (Ishak and Mahayuddin, 2025). These findings underline the importance of diagnosing waste not just as isolated incidents but as outcomes of interconnected managerial, technical, and environmental shortcomings.

2.4 Role of Statistical Analysis in Waste Studies

To complement qualitative methods, statistical tools such as the Statistical Package for the Social Sciences (SPSS) have been increasingly employed in construction waste research. SPSS enables researchers to perform descriptive statistics, test reliability (e.g., Cronbach's alpha), and validate the significance of survey results. For example, studies in infrastructure projects have applied statistical modeling to quantify stakeholder perceptions of waste causes, thereby enhancing the reliability and generalizability of their findings (Naji et al., 2022; Viswalekshmi and Bendi, 2023). Similarly, research in the Indonesian context emphasizes the importance of integrating statistical validation to ensure the robustness of construction waste studies (Rani and Arlianti, 2024). Systematic reviews also highlight that

statistical approaches are increasingly combined with waste estimation methods to improve empirical reliability in construction research (Tong et al., 2023).

By combining SPSS with Pareto and Fishbone methods, researchers can triangulate their findings, ensuring that dominant waste contributors are not only identified and mapped but also statistically confirmed (Aftab et al., 2025). Moreover, effective minimisation of construction waste requires strategies applied consistently across all project stages, from planning to execution and closure, which reinforces the value of integrating statistical analysis with management practices (Mohammad, 2025). This integration strengthens both academic rigor and managerial applicability, providing actionable evidence for waste reduction strategies.

2.5 Research Gap and Contribution

Although Pareto, Fishbone, and statistical methods have been individually applied in construction waste research, their integration remains limited, especially in the context of large-scale infrastructure projects. Most existing studies are concentrated on residential, commercial, or educational buildings, while large bridge and toll road projects are underrepresented (Alotaibi and Alnuaim, 2025; Rani et al., 2023). Moreover, many studies measure waste in terms of quantity rather than cost, although cost is the most relevant metric for project stakeholders (Aftab et al., 2025). Recent reviews also emphasise that avoidance and minimisation strategies should be prioritised over treatment to maximise economic and environmental benefits (Heffernan, Kempton et al., 2025). Similarly, life cycle perspectives have been proposed to better capture the long-term sustainability implications of waste management, yet such approaches remain rarely applied in large infrastructure projects (Balasbaneh et al., 2025).

The present study addresses these gaps by applying an integrated Pareto-Fishbone-SPSS framework to evaluate material waste in a toll road bridge project in Indonesia. By combining cost-based prioritization, systematic root-cause analysis, and statistical validation, this study contributes to a more comprehensive understanding of material waste in infrastructure projects. It provides both theoretical contributions to construction waste literature and practical recommendations for enhancing material efficiency, reducing unnecessary expenditure, and promoting sustainability in large-scale infrastructure development (Zheng et al., 2024).

3. RESEARCH METHODOLOGY

3.1 Research Design

This study employed a descriptive quantitative research design supported by a single case study to assess material waste and its underlying causes in large-scale bridge construction. The approach enabled systematic measurement of waste quantities and costs, combined with statistical validation to ensure rigor and comparability across projects (Naji et al., 2022; Viswalekshmi and Bendi, 2023). The selected case, the Main Bridge (MB) STA 6+876 of the Sigli-Banda Aceh Toll Road Project, represents a complex infrastructure development ideal for examining cost-based waste prioritization and root-cause analysis (Rani and Arlianti, 2024; Aftab et al., 2025).

Primary data were obtained through structured questionnaires from 70 stakeholders (owners, contractors, consultants, and site supervisors), capturing perceptions of waste causes such as design changes, procurement errors, and handling inefficiencies. Secondary data included project documentation: BoQs, progress reports, and as-built drawings to compare planned versus actual material use and compute waste costs (Rani et al., 2023; Rani et al., 2024).

Data analysis was conducted in three stages. First, material waste volumes and costs were quantified and ranked using Pareto analysis to identify dominant waste contributors (Aftab et al., 2025). Second, a Fishbone diagram categorizes root causes into manpower, methods, materials, machinery, measurement, and environmental factors (Anaç et al., 2024). Finally, SPSS software was used for reliability testing (Cronbach's α) and descriptive statistics, ensuring triangulated and statistically validated results for managerial application (Naji et al., 2022; Rani and Arlianti, 2024).

To enhance clarity and provide an overall overview of the research process, a methodological framework was developed to illustrate the sequence of data collection and analysis employed in this study, as shown in Fig. 1. The framework integrates quantitative assessment of material waste, Pareto analysis for prioritising dominant waste contributors, Fishbone analysis for identifying root causes, and statistical validation using SPSS.

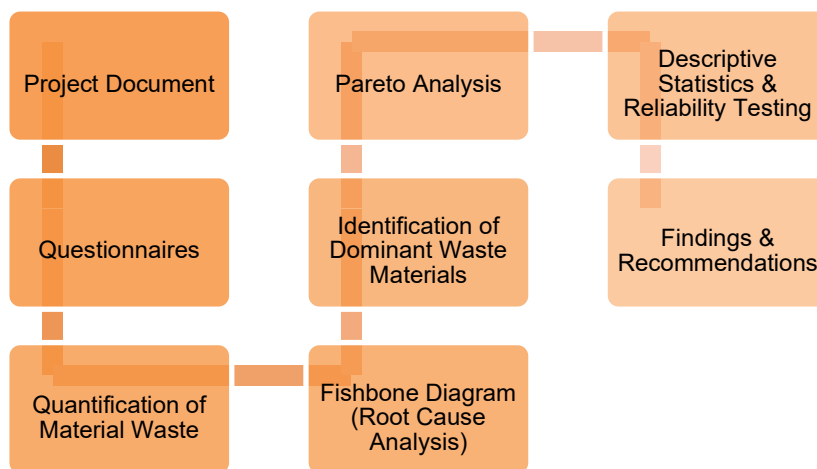


Fig. 1. Research Framework of the Study
Source: Authors

4. RESULT AND DISCUSSION

4.1 Pareto Analysis of Material Waste

The analysis of material waste in the Main Bridge (MB) STA 6+876 project revealed that six major material categories contributed to the total waste cost. Table 1 presents the calculation of waste volume, unit prices, waste costs, and their respective contributions to overall project waste. The results show that reinforcement steel (BJTD 40) mainly comprised waste costs, amounting to IDR 5,480,111,924 or 84.17%

of total waste. Structural concrete class B-1-1a was the second most significant contributor, representing IDR 962,038,003 or 14.78% of the total. Together, these two materials accounted for more than 98% of waste costs, while other materials, such as structural concrete class E, concrete diaphragms, pier columns, and pier heads, contributed marginally.

This finding is consistent with prior studies proving that steel reinforcement and concrete are typically the most waste-prone materials in construction projects, both in terms of cost and volume (Viswalekshmi and Bendi, 2023; Zheng et al., 2024). To further visualise the distribution of material waste costs and cumulative contributions, a Pareto chart was developed, as shown in Fig. 2.

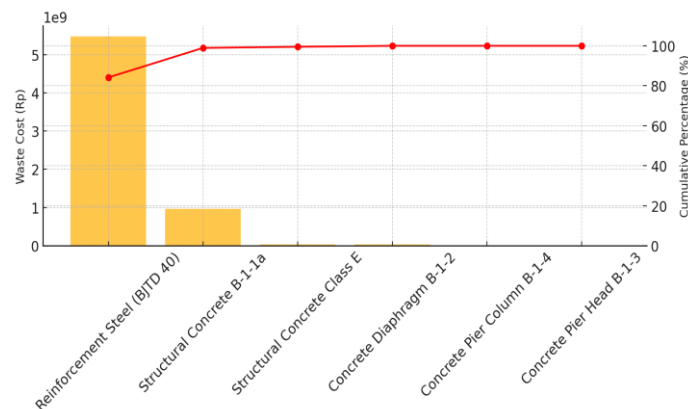


Fig. 2. Pareto Analysis of Material Waste

Source: Authors

Fig. 2 illustrates the Pareto distribution of material waste costs, highlighting the dominant role of reinforcement steel and structural concrete. The bar chart represents waste costs, while the cumulative line indicates that the first two material categories already surpass the 80% threshold, validating the Pareto principle and demonstrating that waste reduction efforts should prioritize these materials.

This aligns with the broader understanding that a small number of materials usually account for the majority of waste, confirming the applicability of Pareto analysis in construction waste management (Aftab et al., 2025; Naji et al., 2022).

4.2 Fishbone Diagram of Waste Causes

To systematically identify the root causes of material waste associated with reinforcement steel and concrete, a Fishbone (Ishikawa) diagram was developed, as presented in Fig. 3.

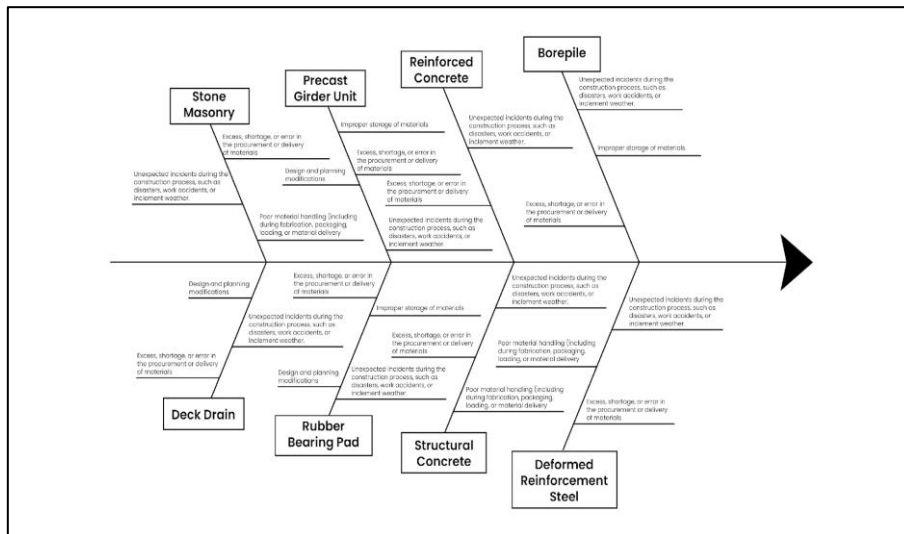


Fig. 3. Fishbone Diagram of Material Waste Causes

Source: Authors

The diagram shows that manpower-related causes included insufficient worker skills, lack of training, and poor on-site supervision. Method-related causes were linked to ineffective scheduling, errors in cutting and bending of reinforcement, and suboptimal concreting techniques. Material-related issues encompassed poor quality control at delivery, damage during handling, and excessive safety stock. Machinery problems involved equipment breakdowns, delays in crane operations, and improper storage of machinery. Measurement-related factors were associated with errors in estimating material requirements and inaccuracies in BoQ documentation. Environmental factors such as unexpected rainfall, fluctuating soil conditions, and inadequate site drainage further exacerbated material losses.

This analysis reveals that material waste in bridge construction is not driven by a single factor but rather by an interplay of managerial, technical, and environmental conditions. Reinforcement steel waste, which comprised the largest cost proportion, was strongly linked to cutting errors, storage deficiencies, and poor supervision. Concrete waste, on the other hand, was primarily caused by inaccurate estimation, poor curing conditions, and weather-related disruptions. These findings are consistent with previous studies that emphasize the multifactorial nature of waste in infrastructure projects (Rani et al., 2023; Rani et al., 2024; Naji et al., 2022; Aftab et al., 2025).

4.3 Descriptive Analysis of Waste Factors

Before conducting statistical validation, descriptive analysis was performed on the questionnaire responses from 70 participants, consisting of project owners, contractors, consultants, and site supervisors. The respondent profile showed that 55% of participants had more than 10 years of experience in bridge or infrastructure projects, while 30% had between 5 and 10 years, and only 15% had less than 5 years of experience. This indicates that the majority of respondents possessed sufficient expertise to provide reliable insights into material waste issues.

Table 2 presents the descriptive statistics of perceived waste causes across six categories. The results indicate that inaccurate material estimation (mean = 4.35, SD = 0.62) and ineffective supervision (mean = 4.28, SD = 0.57) were rated as the most dominant factors contributing to reinforcement steel waste. For concrete waste, weather-related disruptions (mean = 4.12, SD = 0.68) and errors in mixing and placement (mean = 3.97, SD = 0.74) were considered significant. Factors such as machinery breakdown (mean = 3.21) and procurement delays (mean = 3.08) were perceived as less influential. These results reinforce the Fishbone analysis by showing that managerial and environmental causes outweigh equipment-related factors.

Table 2: Descriptive Statistics of Waste Factors

Category	Waste factor	Mean	Std. dev.	Interpretation
Measurement	Inaccurate material estimation	4.35	0.62	Very significant
Manpower	Ineffective supervision	4.28	0.57	Very significant
Environment	Weather-related disruptions	4.12	0.68	Significant
Methods	Errors in mixing and placement	3.97	0.74	Significant
Machinery	Equipment breakdowns	3.21	0.83	Moderate
Procurement	Delays in material delivery	3.08	0.91	Moderate

Source: Authors

The descriptive results highlight that human and planning-related issues remain the most critical drivers of material waste in bridge construction, while technical machinery issues and procurement delays play a secondary role. This finding is consistent with previous research emphasizing that errors in estimation, supervision, and site planning contribute disproportionately to waste in large-scale infrastructure projects (Rani et al., 2023; Rani et al., 2024; Naji et al., 2022; Aftab et al., 2025).

4.4 Statistical Validation

Statistical validation was conducted using SPSS to ensure the reliability and validity of the survey findings. The reliability test using Cronbach's Alpha produced a coefficient of 0.873, exceeding the acceptable threshold of 0.70, indicating strong internal consistency of the measurement items (Naji et al., 2022; Rani and Arlianti, 2024). Validity testing through the Kaiser-Meyer-Olkin (KMO) measure yielded a value of 0.812, supported by Bartlett's Test of Sphericity ($p < 0.001$), confirming the suitability of the dataset for factor analysis (Viswalekshmi and Bendi, 2023; Aftab et al., 2025).

Factor analysis grouped the waste causes into three dominant clusters, explaining 86.4% of the total variance: (1) managerial deficiencies such as inaccurate estimation and weak supervision, (2) environmental disruptions and storage issues, and (3) logistical issues including procurement delays and machinery breakdowns. These results reinforce that material waste in bridge construction is primarily

influenced by managerial and planning-related factors rather than technical issues, supporting the findings from the Pareto and Fishbone analyses (Naji et al., 2022; Rani and Arlianti, 2024).

5. DISCUSSION

This study confirms that reinforcement steel and structural concrete are the dominant contributors to material waste in bridge construction, accounting for more than 98% of total waste costs. This aligns with previous research showing that high-cost, high-volume materials such as steel and concrete consistently generate the majority of waste in large-scale infrastructure projects (Viswalekshmi and Bendi, 2023; Zheng et al., 2024), emphasizing the need to prioritize waste reduction efforts of these materials.

The Fishbone analysis showed that waste is primarily driven by managerial and planning-related deficiencies: particularly inaccurate estimation, ineffective supervision, and design changes, consistent with earlier studies that identified poor planning and site management as major contributors to waste (Rani et al., 2023; Naji et al., 2022). Environmental factors such as heavy rainfall and unstable soil conditions were also found to significantly influence waste generation, supporting the findings that environmental and logistical challenges present a growing importance in developing-country infrastructure contexts (Moradi, 2023; Rani et al., 2024).

Statistical validation using SPSS strengthened the credibility of these findings. High reliability (Cronbach's Alpha = 0.873) and factor analysis results identified three dominant clusters of waste drivers: managerial deficiencies, environmental conditions, and logistical issues, reinforcing the value of combining quantitative and analytical tools in construction waste research (Naji et al., 2022; Rani and Arlianti, 2024). The integration of Pareto, Fishbone, and SPSS methods provides a more comprehensive understanding of waste mechanisms than studies relying solely on qualitative or cost-focused analyses (Aftab et al., 2025).

Unlike previous research that predominantly examined smaller-scale building projects such as residential and commercial structures (Rani et al., 2023; Rani et al., 2024), this study contributes new insight by focusing on a large-scale toll road bridge project, where complexity, environmental exposure, and heavy logistics intensify waste generation risks (Alotaibi and Alnuaim, 2025). The results highlighted the need for targeted, context-specific strategies in mega-projects, combining managerial improvements with proactive environmental risk management. This aligns with circular economy principles, where waste prevention through planning, supervision, and digital monitoring should take precedence over treatment and disposal (Angraini et al., 2022; Karaca et al., 2024). Overall, the findings reinforce the importance of adopting evidence-based and proactive waste management practices to enhance efficiency and sustainability in infrastructure development.

6. CONCLUSION

This study evaluated material waste in the Main Bridge (MB) STA 6+876 of the Sigli-Banda Aceh Toll Road using an integrated Pareto-Fishbone-SPSS framework. The findings showed that reinforcement steel and structural concrete were the main waste producers, accounting for more than 98% of total waste costs.

Fishbone analysis revealed that managerial and planning-related deficiencies, particularly inaccurate estimation, ineffective supervision, and design changes, were the primary drivers of waste. However, environmental disruptions such as heavy rainfall and soil instability played secondary but significant roles. Statistical validation using SPSS confirmed the robustness of these results, grouping waste causes into three clusters: managerial deficiencies, environmental disruptions, and logistical issues. This research demonstrates that waste generation in bridge construction is multifactorial, with managerial shortcomings having a greater impact than machinery or technical factors. Strategies recommended to reduce waste include improving estimation accuracy through digital tools such as BIM, strengthening site supervision and workforce training, implementing efficient procurement and storage practices, and applying proactive environmental risk management. Integrating analytical tools like Pareto, Fishbone, and statistical validation into routine project management can enhance decision-making and material efficiency. Future studies are encouraged to apply this framework to other infrastructure types and investigate advanced technologies such as IoT-based monitoring to support sustainable construction waste reduction.

7. ACKNOWLEDGEMENTS/FUNDING

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8. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

9. AUTHORS' CONTRIBUTIONS

Hafnidar A. Rani led the research design, coordinated the study framework, and prepared the initial draft of the manuscript; Tamalkhani Syammaun conducted data collection, performed statistical validation using SPSS, and assisted in quantitative interpretation; Firmansyah Rachman contributed to the case study investigation, field observations, and analysis of project documentation; Iswan Bahagia assisted in data verification, visualization (Pareto and Fishbone analysis), and refinement of the final manuscript.

10. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

AI tools (e.g, ChatGPT, Grammarly) were used for drafting, assistance, paraphrasing and grammar checking. All content was critically reviewed and edited by researchers.

11. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during this study are available from the corresponding author upon reasonable request.

12. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects.

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