DEVELOPING CIRCULAR ECONOMY-BASED CONSTRUCTION WASTE MANAGEMENT STRATEGIES FOR SUSTAINABLE INFRASTRUCTURE DEVELOPMENT

Hamedoni Harita[1)], Ikhtiar Aronifati Daeli[2)], Arfin Telaumbanua[3)], Detamisteryomen Gea[4)], Apriaman Zega[5)]
[1)]Teknik Sipil, Fakultas Sains Dan Teknologi, Universitas Nias, Gunungsitoli, Indonesia
Email: hamedoniharita@gmail.com
[2)]Teknik Sipil, Fakultas Sains Dan Teknologi, Universitas Nias, Gunungsitoli, Indonesia
Email: daeliaroni_ikhtr@gmail.com
[3)]Teknik Sipil, Fakultas Sains Dan Teknologi, Universitas Nias, Gunungsitoli, Indonesia
Email: arfin99tela@gmail.com
[4)]Teknik Sipil, Fakultas Sains Dan Teknologi, Universitas Nias, Gunungsitoli, Indonesia
Email: detamsgea@gmail.com
[5)]Teknik Sipil, Fakultas Sains Dan Teknologi, Universitas Nias, Gunungsitoli, Indonesia
Email: apriaman80@gmail.com

Abstract
Construction waste management represents a significant challenge to sustainable infrastructure development due to extensive material consumption and waste generation during project implementation. This study aims to develop circular economy-based construction waste management strategies by applying the principles of reduction, reuse, and recycling to improve resource efficiency, minimize waste generation, and optimize management costs. A quantitative descriptive and comparative approach was employed using hypothetical simulations of four management scenarios: conventional waste management, waste reduction, combined reduction and reuse, and an integrated circular economy strategy. The evaluated parameters included waste composition, waste prevention, material recovery rates, net management costs, and reductions in final disposal. The simulation results indicate that, from an initial potential waste generation of 100 tons, the integrated strategy could prevent 15 tons of waste, reuse 25 tons, and recycle 40 tons of materials, reducing final disposal to 20 tons, equivalent to an 80% reduction. Furthermore, the integrated strategy resulted in potential net cost savings of 35.56%, decreasing management costs from IDR 45,000,000 to IDR 29,000,000, with a waste diversion rate of 76.47%. These findings suggest that circular economy principles can improve material efficiency and reduce construction waste management costs while supporting sustainable infrastructure development. However, the results are hypothetical and require validation using actual construction project data before practical implementation.
Keywords: Circular Economy; Construction Waste; Waste Management; Resource Efficiency; Sustainable Infrastructure.

INTRODUCTION

Infrastructure development is one of the essential factors supporting economic growth, improving regional connectivity, and providing public service facilities. The construction of roads, bridges, buildings, and various public facilities requires substantial quantities of construction materials and generates waste at every stage of project implementation. Increasing infrastructure demands without efficient resource management may place considerable pressure on the environment through raw material extraction, energy consumption, and growing volumes of construction waste. The United Nations Environment Programme (UNEP, 2025) highlighted that the building and construction sector plays a significant role in global resource consumption and emissions, emphasizing the need for a transition toward more resource-efficient and sustainable construction practices. This indicates that the success of infrastructure development should not be evaluated solely based on construction quality and budget compliance but should also consider environmental impacts throughout the project life cycle. Therefore, developing effective construction waste management systems is an important component of promoting sustainability-oriented infrastructure development.

Construction waste refers to residual materials generated during infrastructure construction, renovation, maintenance, and demolition activities. Such waste may include concrete, bricks, wood, steel, glass, plastics, excavated soil, and various other materials that are no longer used in construction processes. Some of these materials have the potential to be recovered through sorting, processing, reuse, and recycling. However, inadequate waste management practices may result in potentially valuable materials being disposed of in landfills. The European Commission (2024) reported that construction and demolition waste accounts for more than one-third of the total waste generated in the European Union, making this sector a priority in developing circular economy-based resource management. Furthermore, differences in material characteristics and handling methods contribute to variations in construction waste recovery rates across regions. These conditions demonstrate that waste management should be implemented according to material characteristics and recovery opportunities to minimize the quantity of materials requiring final disposal.

Construction waste management challenges are not limited to increasing volumes of residual materials but also involve the inefficient utilization of resources throughout construction activities. Inaccurate material quantity estimates, design modifications, damage resulting from improper storage, unplanned material cutting, and inadequate project

coordination can contribute to increased waste generation. Materials that retain potential value are frequently discarded because appropriate sorting and management mechanisms are unavailable. Ferriz-Papi et al. (2024) identified several barriers to implementing circular economy principles in construction and demolition waste management, including technical, organizational, economic, and institutional challenges. These barriers indicate that construction waste problems cannot be addressed solely through waste transportation or disposal activities. Instead, comprehensive strategies encompassing project planning, construction implementation, and material utilization control are required. Accordingly, management approaches capable of preventing waste generation from the initial stages of infrastructure development are necessary.

The circular economy approach is one of the concepts that can be implemented to address challenges associated with resource consumption and construction waste generation. This concept emphasizes preserving material value for as long as possible by reducing the use of virgin resources, promoting material reuse, facilitating repair and recovery, and encouraging recycling. Unlike the linear economic model, which relies on raw material extraction, production, consumption, and disposal, the circular economy seeks to establish a more efficient system of material utilization throughout the material life cycle. Papamichael et al. (2023) explained that implementing circular economy principles in construction waste management has the potential to reduce environmental impacts through resource recovery and the development of material recovery mechanisms. This approach creates opportunities to reduce dependence on virgin materials while minimizing the quantity of waste requiring disposal. Therefore, integrating circular economy principles into construction waste management can provide a foundation for developing more sustainable infrastructure development strategies.

Implementing circular economy principles in construction projects requires a shift from waste management systems focused primarily on end-of-process disposal toward approaches that prioritize waste prevention. During the planning stage, strategies may include design optimization, accurate material quantity estimation, selection of reusable materials, and adoption of construction methods that minimize material losses. During construction, circular economy principles can be implemented through controlled material procurement, waste segregation according to material type, appropriate storage practices, and the reuse of materials that meet technical requirements. During demolition, selective dismantling and material recovery processes can enhance recycling opportunities. Victar and Waidyasekara (2024) emphasized that circular economy strategies should be implemented throughout various stages of the project life cycle, including demolition, material reuse, resource recovery, and construction material production. This demonstrates that successful construction waste management is strongly influenced by the integration of strategies across different project implementation stages.

In addition to environmental benefits, circular economy-based construction waste management has the potential to improve project economic efficiency. Reducing material waste can decrease the need to procure new construction materials, while reusing technically suitable materials can reduce waste transportation and disposal costs. Nevertheless, implementing these strategies may require additional expenditures for sorting, storage, processing, quality testing, and transporting recovered materials. Therefore, economic benefits should be evaluated comprehensively by considering the balance between implementation costs and the economic value of retained resources. Soto-Paz et al. (2023), through a comparative study of developing and developed countries, demonstrated that circular economy implementation in construction waste management is influenced by waste management system characteristics, development conditions, and implementation readiness. Consequently, waste management strategies should be adapted to the characteristics of the construction industry and the availability of resources to generate both economic and environmental benefits.

In the context of infrastructure development in Indonesia, implementing sustainable construction waste management presents challenges related to construction practices, technological adoption, industry readiness, and policy support, as well as coordination among stakeholders. Material management in construction projects frequently prioritizes completing activities within established cost, quality, and time targets, whereas waste prevention and resource recovery require additional management and control mechanisms. Syifa et al. (2026), through a systematic review of construction waste management strategies in Indonesia, identified technological approaches, government policies, circular economy implementation, and stakeholder collaboration as important factors supporting more sustainable waste management. These findings indicate that responsibility for developing effective waste management strategies cannot be assigned exclusively to contractors. Instead, the involvement of designers, material suppliers, construction supervisors, facility managers, and government institutions is necessary. Such cooperation is essential to ensure that waste reduction becomes an integral component of project management systems from the preparation stage through construction completion.

The development of construction waste management strategies also requires consistent systems for identifying, measuring, and controlling material flows throughout project implementation. One of the primary challenges in evaluating waste management performance is the limited availability of reliable data concerning the types and quantities of waste generated, the proportion of materials recovered or reused, and the costs associated with waste handling. Without adequate recording and monitoring systems, the effectiveness of circular economy strategies is difficult to assess objectively. Swarnakar and Khalfan (2024), through a review of 212 scientific articles, identified research limitations concerning monitoring technologies, material traceability, decision-support systems, and performance measurement for circular economy implementation in construction waste management. Their findings highlighted the continued need to develop structured evaluation frameworks that support decision-making regarding resource utilization and waste control. Therefore, applying quantitative performance indicators is essential to ensure that waste management strategies can be assessed based on measurable outcomes.

Several previous studies have contributed to the development of circular economy concepts and strategies for construction waste management. Papamichael et al. (2023) discussed a construction waste management framework emphasizing material recovery and the identification of barriers to circular system implementation. Soto-Paz et al. (2023) conducted a comparative review of circular economy practices in construction waste management across developing and developed countries to understand implementation characteristics and development opportunities. Ferriz-Papi et al. (2024) identified various challenges influencing the successful implementation of circular economy principles in the construction and demolition sector. Meanwhile, Swarnakar and Khalfan (2024) highlighted the need for more integrated monitoring, decision-making, and performance measurement systems. Collectively, these studies demonstrate that circular economy approaches offer opportunities to improve construction waste management effectiveness. However, their implementation still requires comprehensive approaches that consider the interrelationships among technical, economic, environmental, and institutional factors.

Although previous research has addressed circular economy concepts, recycling technologies, implementation barriers, and construction material recovery, the development of strategies that can serve as operational frameworks at the project level requires further investigation. Waste management approaches focusing on a single activity, such as material recycling, may not produce optimal results unless integrated with procurement control, construction methods, material recording systems, and cost evaluation. Furthermore, the diverse characteristics of infrastructure projects require adaptable approaches that consider material types, construction quantities, processing facilities, and technical requirements for recovered materials. Swarnakar and Khalfan (2024) identified the need for more structured circular economy implementation frameworks, while Alhawamdeh et al. (2024) demonstrated that successful construction waste management requires supporting factors encompassing various implementation dimensions. These findings emphasize the importance of developing strategies that not only explain circular economy principles conceptually but also establish practical implementation mechanisms and performance indicators applicable to infrastructure construction activities.

Based on the preceding discussion, the research gap addressed in this study is the need to develop circular economy-based construction waste management strategies that integrate waste generation reduction, material reuse, recycling, cost efficiency, and environmental performance measurement within a unified management framework. The proposed novelty lies in developing an integrated evaluation approach that connects waste source identification, material handling prioritization, resource recovery potential analysis, and assessments of technical, economic, and environmental benefits at the infrastructure project level. This framework can be developed using indicators such as waste generation rates relative to construction quantities, percentages of reused materials, recycling rates, reductions in virgin material requirements, and changes in waste management costs. Through this approach, circular economy strategies are expected to be evaluated more systematically and provide a basis for selecting waste management measures appropriate to individual project characteristics. However, the proposed novelty must be further examined through comparisons with previous research frameworks and applications using verifiable project data.

Based on the aforementioned background, this study aims to develop circular economy-based construction waste management strategies to support sustainable infrastructure development. The research focuses on identifying the characteristics and sources of waste generated during construction activities, evaluating existing material management practices, analyzing opportunities to implement waste reduction, reuse, and recycling principles, and formulating alternative strategies based on technical, economic, environmental, and institutional considerations. Furthermore, the proposed strategies are evaluated using relevant performance indicators to assess their potential to reduce waste generation, increase material reuse, and improve construction resource efficiency. The findings are expected to contribute scientifically to the development of more integrated construction waste management approaches while providing practical references for contractors, design consultants, project managers, and government institutions in implementing circular economy principles for efficient, environmentally responsible, and sustainable infrastructure development.

RESEARCH METHODOLOGY

3.1. Research Design and Approach

This study was designed using a quantitative approach with descriptive and comparative methods to develop circular economy-based construction waste management strategies that support sustainable infrastructure development. The quantitative approach was employed to evaluate waste generation characteristics, material utilization rates, potential waste reduction, and cost efficiency in construction waste management. The descriptive method was applied to describe existing waste management conditions based on material types, sources of waste generation, and handling mechanisms implemented during project execution. Meanwhile, the comparative method was used to compare conventional waste management systems with several alternative circular economy strategies focused on reducing resource consumption, reusing materials, and recycling construction waste. Strategy development integrated technical, economic, and environmental considerations to ensure that the proposed alternatives could not only reduce the quantity of discarded materials but also offer practical implementation potential suited to the needs and characteristics of infrastructure projects.

3.2. Research Object and Scope

The research focused on managing waste materials generated during infrastructure development activities, particularly building construction, road construction, and other supporting infrastructure projects. The scope of the study

was limited to residual materials with potential for reduction, reuse, or recycling, including concrete, reinforcing steel, formwork timber, bricks, aggregates, and construction material packaging. Waste categories were selected based on material characteristics, quantities generated, potential for recovery, and the availability of processing methods that support circular economy principles. The units of analysis were defined according to material type and construction stage, covering procurement, storage, utilization, and residual material handling. The study also considered the influence of construction methods, storage conditions, material utilization control, and the involvement of stakeholders responsible for waste management. Hazardous and toxic waste was excluded from the scope of general reuse evaluation because such materials require specialized management procedures in accordance with applicable regulations.

3.3. Types and Sources of Data

The research data consisted of primary and secondary data related to construction material utilization, waste characteristics, and management systems implemented in infrastructure development projects. Primary data were planned to be obtained through direct observations of construction activities, records of material quantities used, measurements of generated waste, and observations of waste sorting, storage, transportation, and disposal processes. Data collection could also be supplemented by interviews with project contractors, site supervisors, construction workers, and material managers to identify existing waste management practices and barriers to implementing circular economy strategies. Secondary data were obtained from project design documents, construction cost estimates, bills of quantities, material utilization reports, procurement records, technical specifications, construction unit prices, and relevant scientific literature. All data were used to identify the relationships among material requirements, waste generation quantities, handling costs, and opportunities for recovering construction resources.

3.4. Data Collection Techniques

Data collection was conducted through field observations, construction material inventories, documentation of project activities, and waste flow recording at each stage of construction. Observations focused on identifying material receiving, storage, cutting, installation, and unused material handling processes. Material inventories were prepared by recording the quantities of materials delivered to the project site, materials incorporated into construction activities, materials remaining suitable for utilization, and waste materials designated for disposal. Waste data were classified according to material type and expressed in appropriate mass or volume units based on material characteristics. To ensure consistency in measurement units, conversions between volume and mass were performed using relevant material density values. Additionally, information regarding waste collection, sorting, storage, transportation, processing, and disposal costs was compiled to support economic evaluation. Documentation was used to identify waste generation sources and provide an overview of management practices implemented throughout construction activities.

3.5. Identification and Analysis of Construction Waste Generation

Construction waste generation was analyzed by identifying the types and quantities of residual materials produced during various construction activities. The analyzed materials included cutting remnants, damaged materials, excess procurement quantities, unusable materials, and demolition components entering the waste stream. Each waste category was classified according to its construction activity source and material characteristics to determine its contribution to total project waste generation. Waste generation rates were assessed by comparing the quantity of materials classified as waste with the total quantities of materials used or received during the same observation period. Calculations were conducted consistently using material mass to enable objective comparisons among different waste categories. Materials subsequently reused or recycled were still recorded as part of waste generation when they had previously entered the waste stream, allowing waste prevention to be distinguished from waste diversion through recovery processes. The analytical results were used to identify materials with the highest waste generation rates and establish priorities for waste reduction measures during both project planning and construction implementation.

3.6. Development of Circular Economy-Based Waste Management Strategies

Waste management strategies were developed by applying the principles of waste reduction, material reuse, and recycling as the foundation for alternative construction resource management approaches. Waste reduction strategies focused on optimizing material requirements, improving procurement accuracy, controlling cutting operations, enhancing storage systems, and implementing construction methods that minimize material damage. Material reuse strategies emphasized the utilization of materials that retained their technical functionality, such as formwork timber, certain construction components, and residual materials that continued to satisfy quality requirements. Recycling strategies were developed by identifying waste categories that could be processed into new materials or products, including demolished concrete with the potential to be processed into recycled aggregates following appropriate quality assessments. Each alternative strategy was evaluated based on technical suitability, equipment requirements, workforce capacity, implementation costs, and the availability of material recovery facilities. Strategy development also considered coordination among contractors, material suppliers, supervising consultants, waste management operators, and other relevant stakeholders to promote integrated circular economy implementation throughout the project life cycle.

3.7. Analysis of Material Reuse and Recycling

Material reuse and recycling were analyzed to evaluate the effectiveness of circular economy strategies in increasing the utilization of materials that had previously entered the waste stream. The material reuse rate was determined based on the proportion of waste materials that could be directly utilized without processing that substantially altered their original characteristics. Meanwhile, the recycling rate was assessed based on the quantity of waste successfully processed into new materials or products with practical value. Evaluations were conducted separately for each material category to clearly identify the respective contributions of reuse and recycling activities. Material accounting procedures ensured that materials recorded as reused were not subsequently counted again as recycled materials within the same evaluation period, thereby preventing double counting. The study also considered technical requirements for recovered materials, quality testing needs, and potential applications in construction activities. The analytical results were used to identify the extent of waste diversion from final disposal and determine which material categories made the greatest contribution to circular economy implementation.

3.8. Cost Efficiency Analysis of Waste Management

Cost efficiency was analyzed by comparing the financial requirements of conventional waste management systems with those associated with alternative circular economy strategies. Under conventional management practices, costs included waste collection, loading, transportation, and final disposal. In contrast, circular economy implementation required evaluation of additional expenditures related to sorting, storage, processing, quality inspection, transportation, and other supporting activities. The analysis also considered potential economic benefits arising from reduced purchases of virgin construction materials, lower disposal costs, and possible revenue from selling recovered materials. Cost calculations were based on work quantities and unit prices applied consistently across all management alternatives. The resulting net costs were subsequently compared to determine changes in expenditure associated with circular economy implementation. The evaluation was intended to identify strategies capable of generating potential cost savings without compromising technical requirements or construction material quality. Therefore, economic efficiency was assessed not merely through reduced disposal expenses but also through the ability to preserve material value and minimize dependence on new construction resources.

3.9. Environmental Impact and Sustainability Assessment

Environmental impact assessment was conducted by analyzing changes in waste disposal quantities, improvements in material utilization, and reductions in virgin material requirements resulting from circular economy strategy implementation. The analysis focused on comparing conventional waste management conditions with alternative strategies emphasizing waste reduction, reuse, and recycling. The evaluation indicators included quantities of waste diverted from final disposal, proportions of materials successfully recovered, and the potential replacement of virgin materials with reused or recycled resources. Consistent system boundaries and observation periods were maintained to prevent discrepancies arising from differences in analytical scope. Reductions in waste disposal quantities were considered indicators of improved material management performance but were not automatically interpreted as evidence of reduced carbon emissions. Where supporting information on energy consumption, transportation distances, emission factors, and material processing activities was available, the assessment could be extended using a Life Cycle Assessment (LCA) approach. This method would enable a more comprehensive evaluation of environmental benefits based on resource consumption and changes in environmental impacts throughout the various stages of material management.

3.10. Comparative Analysis of Alternative Strategies

Comparative analysis was conducted by evaluating conventional waste management practices alongside several alternative circular economy-based strategies. The conventional system served as the baseline condition, representing material management practices before the implementation of additional improvement measures. The first alternative focused on reducing waste generation by improving material requirement planning and strengthening material control during construction activities. The second alternative integrated waste reduction measures with the reuse of materials that continued to satisfy technical requirements. The third alternative combined waste reduction, material reuse, and recycling within a unified waste management system. Each alternative was compared based on waste quantities generated, material recovery rates, volumes of waste disposed of, virgin material requirements, and net management costs. Comparisons were conducted using consistent baseline conditions and analytical boundaries to ensure that observed performance changes could be attributed to the proposed management strategies. The evaluation results were used to identify the alternative with the greatest potential benefits based on the balance among technical effectiveness, cost efficiency, and environmental sustainability.

3.11. Prioritization of Waste Management Strategies

The prioritization of waste management strategies was conducted by evaluating the technical, economic, and environmental assessment results for each alternative. The evaluation focused on the ability of each strategy to reduce waste generation, improve material utilization, minimize management costs, and decrease dependence on virgin resources. Implementation feasibility was also considered an important criterion because infrastructure projects differ in construction

characteristics, equipment availability, workforce capabilities, and access to material processing facilities. Waste prevention strategies were prioritized when technically and economically feasible, while reuse and recycling approaches were developed to manage unavoidable residual materials. Strategy prioritization was based on comparisons of performance indicators across alternatives while considering their respective benefits and limitations. The resulting assessment provided the basis for formulating waste management recommendations suited to project requirements and supporting the sustainable implementation of circular economy principles.

3.12. Data Processing and Interpretation Techniques

Data obtained from field observations, material inventories, and cost calculations were processed using descriptive and comparative quantitative analysis techniques. Initial data processing involved verifying information completeness, categorizing waste materials, and preparing material flow balances to identify the relationships among materials received, utilized, reused, recycled, and disposed of. The data were subsequently analyzed to determine waste generation rates, the effectiveness of waste reduction measures, material recovery rates, and changes in management costs under each alternative strategy. The analytical results could be presented through comparative tables, graphs illustrating changes in waste quantities, and material flow diagrams to clarify differences in waste management performance. Interpretation considered construction activity characteristics, material categories, technical feasibility, and the resulting economic and environmental benefits. Research conclusions were developed based on comparisons of alternative strategy performance, ensuring that the recommended approaches were supported by measurable analytical indicators and could serve as a reference for advancing circular economy-based construction waste management in infrastructure projects.

RESULTS AND DISCUSSION

4.1. Characteristics of Construction Waste Generation

The identification of construction waste characteristics was conducted by classifying materials based on their types, sources of generation, and recovery potential. The research model represented an infrastructure construction project with an initial waste generation of 100 tons, consisting of concrete, bricks, formwork timber, reinforcing steel, aggregates, and packaging materials. These material categories were selected based on common construction waste characteristics and their potential for management through reduction, reuse, and recycling. Concrete and bricks may be considered for recycling after satisfying relevant technical requirements, while reinforcing steel has potential for recovery through recycling processes. Formwork timber and certain aggregates may also be reused when their physical conditions remain suitable.

Table 1. Composition of construction waste generation under baseline conditions

Waste Type	Mass (tons)	Percentage
Concrete	40	40%
Bricks	20	20%
Formwork timber	15	15%
Reinforcing steel	10	10%
Aggregates	10	10%
Packaging materials	5	5%
Total	100	100%

Source: Hypothetical simulation data, 2026.

The simulation results presented in Table 1 indicated that concrete constituted the largest waste component, accounting for 40% of total waste generation, followed by bricks at 20% and formwork timber at 15%. These three materials collectively contributed 75% of the total construction waste. This composition suggested that management strategies targeting dominant waste materials could substantially influence the quantity of waste requiring final treatment or disposal. Meanwhile, reinforcing steel and aggregates each accounted for 10%, while packaging materials represented the smallest proportion at 5%.

Conceptually, the substantial contributions of concrete and masonry waste emphasize the importance of controlling material requirements during the construction planning stage. Concrete waste may result from inaccurate estimates of concrete quantities, while brick waste may arise from cutting activities, transportation damage, and inadequate material handling. Formwork timber may become waste when damaged or when repeated utilization is not incorporated into construction planning. These conditions demonstrate that construction waste generation is influenced not only by material characteristics but also by decisions related to planning, procurement, and construction methods.

Ferriz-Papi et al. (2024) identified technical, organizational, economic, and institutional barriers to implementing circular economy principles in construction waste management. Their findings support the importance of developing management strategies that address waste generation at its source rather than focusing exclusively on handling materials after disposal.

4.2. Evaluation of Conventional Waste Management Conditions

Under the conventional waste management scenario, all 100 tons of generated waste were assumed to be collected

and transported to disposal facilities without specific measures for waste prevention, material reuse, or recycling. This system served as the baseline condition for comparing the effectiveness of circular economy-based strategies. The selection of this baseline was a simplification for simulation purposes and did not imply that all actual construction projects dispose of their entire residual material quantities.

In the assumed conventional management system, waste materials were recorded according to the total quantities removed from the project site, while the potential value of materials was not considered a primary factor in waste handling decisions. Consequently, all materials classified as waste entered the disposal stream. This condition resulted in relatively high transportation and final disposal requirements, while opportunities for material recovery remained unutilized.

This baseline provided a foundation for evaluating potential changes in waste management through circular economy strategies. The European Commission has explained that construction and demolition waste comprises various materials, including concrete, bricks, timber, metals, glass, and plastics, each possessing different recovery potential. Source segregation is particularly important because mixed waste streams, especially those contaminated with hazardous substances, may hinder effective recycling processes.

4.3. Development of Alternative Circular Economy Strategies

Construction waste management strategies were developed by comparing four scenarios: conventional management, waste generation reduction, waste reduction combined with material reuse, and an integrated system incorporating reduction, reuse, and recycling. Each scenario was designed to illustrate changes in material flows resulting from the introduction of additional waste management measures.

Table 2. Alternative construction waste management strategies

Scenario	Strategy	Characteristics
S0	Conventional management	Waste collection and disposal
S1	Reduce	Control of material requirements and utilization
S2	Reduce + Reuse	Waste reduction and material reuse
S3	Reduce + Reuse + Recycle	Integrated circular waste management

Source: Research simulation scenario design, 2026.

Scenario S1 focused on preventing waste generation by improving the accuracy of material quantity estimates, controlling procurement, optimizing cutting methods, and enhancing material handling during storage. Scenario S2 expanded these measures by incorporating the reuse of materials that continued to satisfy technical requirements. Meanwhile, Scenario S3 represented an integrated management system that added recycling processes for materials that could not be directly reused.

In the simulation model, waste reduction measures were assumed to prevent the generation of 15 tons of waste from the initial potential quantity of 100 tons. Following waste prevention measures, the remaining waste generation was reduced to 85 tons. Under Scenario S2, 25 tons of the remaining waste were allocated for direct reuse. Under Scenario S3, an additional 40 tons were recovered through recycling, reducing the quantity of waste requiring final disposal to 20 tons.

Table 3. Comparison of material flows under each management strategy

Component	S0 (tons)	S1 (tons)	S2 (tons)	S3 (tons)
Initial potential waste	100	100	100	100
Waste prevented	0	15	15	15
Waste generated	100	85	85	85
Material reused	0	0	25	25
Material recycled	0	0	0	40
Waste disposed of	100	85	60	20

Source: Hypothetical scenario calculations, 2026. Generated waste equals the combined quantities of reused, recycled, and disposed materials.

The results presented in Table 3 indicated that implementing Scenario S1 reduced the quantity of waste requiring disposal by 15% compared with conventional management. Scenario S2 further reduced waste disposal to 60 tons, while Scenario S3 achieved the lowest disposal quantity of 20 tons. Consequently, Scenario S3 resulted in an 80% reduction in disposed waste mass compared with Scenario S0. This reduction comprised 15 tons of prevented waste and 65 tons diverted from final disposal through reuse and recycling.

These findings illustrated that progressively implementing circular economy principles could increase the proportion of materials retained within productive use cycles. Nevertheless, the effectiveness of each strategy in actual construction

projects would depend on material conditions, quality testing requirements, processing facility availability, and the existence of markets or users capable of accepting recovered materials.

4.4. Analysis of Material Reuse and Recycling Potential

The analysis of material reuse and recycling was conducted to identify the contribution of individual waste categories to circular economy implementation. Under Scenario S3, the quantity of waste generated after prevention measures was 85 tons. Of this amount, 25 tons were allocated for reuse and 40 tons for recycling. The remaining 20 tons were assumed to be unsuitable for recovery through the available strategies and therefore required final disposal.

Table 4. Simulated material balance under the integrated circular economy strategy (S3)
All quantities are expressed in tons.

Material	Initial Waste	Prevented	Reused	Recycled	Disposed
Concrete	40	6	4	20	10
Bricks	20	3	4	8	5
Formwork timber	15	2	10	2	1
Reinforcing steel	10	1	2	6	1
Aggregates	10	2	5	2	1
Packaging materials	5	1	0	2	2
Total	100	15	25	40	20

Source: Simulated material balance, 2026. Prevented materials were not counted as generated waste.

Table 4 demonstrated that concrete contributed the largest quantity of recycled materials, reaching 20 tons. Formwork timber exhibited the greatest reuse potential at 10 tons, while reinforcing steel contributed 6 tons to recycling. These findings indicated that material recovery strategies should be adapted to the physical characteristics, functional properties, and technical requirements of each waste category.

Concrete waste can potentially be recycled by crushing and processing it into recycled aggregates. However, the use of recycled aggregates must consider gradation, water absorption, cleanliness, and quality requirements associated with their intended construction applications. Formwork timber may be reused when it retains adequate strength and dimensional integrity, while reinforcing steel must undergo appropriate condition assessments before direct reuse. Recovered materials should not automatically be considered compliant with construction requirements merely because they are available for utilization.

Based on the simulation results, the material reuse rate reached 29.41% of the 85 tons of waste generated after prevention measures, while the recycling rate reached 47.06%. Consequently, the overall waste diversion rate reached 76.47%. This value differed from the 80% reduction in disposal relative to the initial baseline because the diversion rate used the actual waste generated after prevention as its denominator, whereas the reduction in disposal was calculated relative to the conventional baseline of 100 tons.

Swarnakar and Khalfan (2024) emphasized that implementing circular economy principles in construction waste management requires improved monitoring systems, material traceability, and decision-support mechanisms. This perspective aligns with the importance of maintaining material balance records in the present study, as waste diversion performance should not be assessed solely based on the quantities of materials collected but should also consider the amounts successfully reused or processed into usable products.

4.5. Evaluation of Construction Waste Management Cost Efficiency

Cost efficiency was evaluated by comparing the economic implications of implementing each waste management strategy. In the simulation model, conventional management costs were assumed to include waste collection, handling, transportation, and disposal. Circular economy strategies required additional expenditures for waste prevention, segregation, reuse preparation, recycling processes, quality testing, and transportation of recovered materials. However, these additional expenditures were assumed to be partially offset by reduced disposal costs, savings from purchasing fewer new materials, and potential revenues from recovered materials.

To maintain consistency across the scenarios, a uniform disposal cost of IDR 350,000 per ton was applied. Other cost components were based on hypothetical assumptions designed to illustrate differences in operational requirements among the strategies. These values were not intended to represent official regional construction or waste management unit prices.

Table 5. Simulated waste management costs by alternative strategy
All values are expressed in million Indonesian rupiah (IDR million).

Cost Component	S0	S1	S2	S3
Waste disposal	35.00	29.75	21.00	7.00

Collection and handling	10.00	9.00	8.00	7.00
Waste reduction program	0	4.00	4.00	4.00
Material segregation	0	0	7.00	9.00
Reuse preparation	0	0	5.00	5.00
Recycling processing	0	0	0	12.00
Quality testing	0	0	0	3.00
Additional transportation	0	0	0	4.00
Total expenditure	45.00	42.75	45.00	51.00
Economic benefits from materials	0	0	−12.00	−22.00
Net cost	45.00	42.75	33.00	29.00

Source: Hypothetical cost calculation assumptions, 2026. The economic benefits under Scenario S3 consist of IDR 16 million in material savings and IDR 6 million in revenue from recovered material sales. Materials sold were not counted again as procurement savings.

The results indicated that conventional waste management generated a net cost of IDR 45,000,000. Implementing Scenario S1 reduced the net cost to IDR 42,750,000, corresponding to a 5.00% saving. Scenario S2 achieved a further reduction to IDR 33,000,000, representing cost savings of 26.67%. Meanwhile, Scenario S3 produced the lowest net cost of IDR 29,000,000, equivalent to a 35.56% reduction compared with conventional management.

The simulation demonstrated that circular economy-based management systems could potentially generate cost savings despite requiring additional expenditure for segregation, processing, testing, and transportation. Under Scenario S3, total operational expenditure reached IDR 51,000,000, exceeding the IDR 45,000,000 expenditure associated with conventional management. However, after accounting for the hypothetical economic benefits of reused and recovered materials, the net cost of Scenario S3 decreased to IDR 29,000,000.

These findings highlighted the importance of distinguishing between operational expenditure and net waste management costs. Strategies requiring greater initial expenditure are not necessarily more expensive overall if they generate economic value from materials that would otherwise be discarded. Nevertheless, the hypothetical economic benefits did not account for uncertainties in recycled material market prices, material rejection risks, processing facility investment requirements, or equipment maintenance expenses. Therefore, the economic advantages of Scenario S3 require validation using actual project cost data before practical implementation.

4.6. Evaluation of Environmental Impacts and Infrastructure Sustainability

Environmental performance was evaluated by comparing the quantities of waste disposed of and the potential for resource recovery under each management strategy. Under conventional management, all 100 tons of generated waste were assumed to require final disposal. Implementing waste prevention measures reduced disposed waste to 85 tons, while combining waste prevention and material reuse reduced the quantity to 60 tons. Under the integrated circular economy strategy, waste requiring disposal decreased to 20 tons. These reductions illustrated the potential improvement in resource management performance when prevention, reuse, and recycling strategies are implemented collectively.

Table 6. Comparison of environmental performance indicators across strategies

Indicator	S0	S1	S2	S3
Waste disposed of (tons)	100	85	60	20
Waste prevented (tons)	0	15	15	15
Materials recovered (tons)	0	0	25	65
Disposal reduction relative to S0	0%	15%	40%	80%
Diversion rate of generated waste	0%	0%	29.41%	76.47%

Source: Hypothetical simulation scenario calculations, 2026.

The results showed that Scenario S3 achieved a potential 80% reduction in waste disposal compared with the baseline condition. This reduction consisted of 15 tons of prevented waste and 65 tons of materials diverted from final disposal

through reuse and recycling. Consequently, the integrated circular economy approach could reduce dependence on final disposal facilities while retaining a substantial proportion of materials within productive utilization cycles.

These simulated findings were consistent with the direction of resource management transformation discussed by the United Nations Environment Programme (2025), which emphasized the importance of circular construction practices and low-carbon materials in supporting sustainable development. Nevertheless, reductions in disposed waste quantities should not automatically be interpreted as equivalent reductions in carbon emissions or overall environmental impacts. Recycling activities may also require additional energy, transportation, and processing operations that generate environmental impacts.

Therefore, a more comprehensive environmental assessment would require a Life Cycle Assessment (LCA) that considers energy consumption, material transportation, processing-related emissions, and the actual quantities of virgin materials replaced by recovered resources. Such an approach would enable a more accurate evaluation of the environmental implications of circular economy implementation throughout the material life cycle.

4.7. Effectiveness Analysis of Construction Waste Management Strategies

The effectiveness of construction waste management strategies was evaluated based on each alternative's ability to reduce waste disposal, preserve material value, and minimize net management costs. The simulation results indicated that expanding the scope of circular economy measures produced different levels of performance improvement across the evaluated indicators. Scenario S1 primarily contributed to preventing waste generation, while Scenario S2 provided additional benefits through material reuse. Scenario S3 integrated all three approaches and achieved the greatest reduction in waste disposal and the lowest net management cost within the analyzed scenarios.

Table 7. Comparative evaluation of circular economy strategy effectiveness

Evaluation Indicator	S0	S1	S2	S3
Waste prevention (tons)	0	15	15	15
Material reuse (tons)	0	0	25	25
Recycling (tons)	0	0	0	40
Final waste disposal (tons)	100	85	60	20
Net cost (IDR million)	45.00	42.75	33.00	29.00
Cost savings	0%	5.00%	26.67%	35.56%

Source: Summary of hypothetical simulation calculations, 2026.

The comparative evaluation indicated that Scenario S3 represented the most favorable alternative within the limitations of the research model. This strategy achieved the highest waste disposal reduction of 80%, a waste diversion rate of 76.47%, and net cost savings of 35.56%. These results demonstrated the potential for an integrated circular economy approach to generate environmental and economic benefits simultaneously.

Nevertheless, implementing Scenario S3 would require a more complex management system than the other alternatives. The availability of segregation facilities, the quality of recovered materials, investment requirements, and workforce capabilities could influence implementation success. Ferriz-Papi et al. (2024) identified technical, economic, organizational, and institutional barriers to implementing circular economy principles in construction waste management. Therefore, strategy selection should consider project readiness rather than relying exclusively on calculated cost savings and waste reduction performance.

Furthermore, Swarnakar and Khalfan (2024) emphasized the importance of developing monitoring and decision-support systems for circular economy implementation in construction waste management. This reinforces the need for systematic material flow recording as a foundation for performance evaluation, ensuring that reuse and recycling activities can be monitored quantitatively.

4.8. Recommended Priorities for Construction Waste Management Strategies

Based on the evaluation results, the development of circular economy-based construction waste management strategies should be implemented progressively according to resource availability and project conditions. Initial priorities should focus on preventing waste generation by improving material requirement planning, controlling procurement quantities, enhancing storage systems, and optimizing construction methods. These measures can often be implemented through improvements in project management practices without requiring complex processing technologies.

The subsequent stage should emphasize increasing the reuse of materials that continue to meet technical requirements. This can be achieved through source segregation, designated material storage areas, quality inspections, and the identification of potential applications in other construction activities. Within infrastructure projects, material reuse can improve resource efficiency when recovered materials possess suitable quality and do not compromise construction safety.

At a more advanced stage, recycling activities can be developed through collaboration with material processing facilities and suppliers. Recycling implementation should consider equipment requirements, transportation costs, final product quality, and market availability for processed materials. Accordingly, recycling activities should aim not only to reduce waste quantities but also to establish material utilization cycles that preserve economic value and technical functionality.

Operationally, circular economy principles can be integrated into project control systems through the preparation of waste management plans, recording of incoming and outgoing materials, periodic measurement of waste generation, and performance evaluations using consistent indicators. These strategies are expected to help project managers identify sources of material waste, control resource requirements, and promote more environmentally responsible construction practices.

4.9. Implications of the Findings for Sustainable Infrastructure Development

The development of circular economy-based construction waste management strategies has implications for improving material resource efficiency and reducing pressure on final disposal facilities. The simulation results indicated that waste management performance could be improved by combining waste generation prevention with material value recovery. This approach provides an alternative to conventional management systems that primarily focus on collecting and disposing of residual materials after construction activities have been performed.

From an economic perspective, circular economy strategies have the potential to generate savings through reduced disposal costs and improved material utilization. However, these benefits must be evaluated against investment requirements, segregation costs, processing expenditures, and material quality testing. From an environmental perspective, reductions in waste disposal can serve as an initial indicator of improved project sustainability, while broader environmental impact assessments require additional analysis of energy consumption, emissions, and resource utilization.

Overall, circular economy approaches can be developed as part of construction management systems that integrate technical, economic, and environmental considerations. The application of quantitative performance indicators enables project managers to compare alternative strategies based on measurable outcomes. Such a framework may also support the development of internal material management policies, strengthen coordination among project stakeholders, and promote the implementation of sustainable infrastructure development principles.

4.10. Research Limitations

This study has several limitations because the data were derived from hypothetical simulations rather than direct measurements conducted on a specific construction project. Waste composition, prevention rates, material reuse potential, recycling capacity, and management costs were established as assumptions to illustrate relationships among research variables. Consequently, the simulation results cannot be used to establish actual circular economy performance levels in infrastructure projects.

Furthermore, the analysis did not comprehensively account for variations in recycled material prices, transportation distances to processing facilities, secondary material market capacity, equipment investment requirements, or detailed material quality testing. The environmental assessment was also limited to changes in waste disposal quantities and material recovery rates, meaning that it did not represent the full range of environmental impacts throughout the material life cycle.

Future research should incorporate primary data from actual construction projects through measurements of incoming and outgoing materials, waste generation records, cost surveys, and observations of reuse and recycling processes. This would allow the proposed strategies to be validated under real project conditions and support the development of more accurate, practical, and scientifically defensible recommendations.

CONCLUSIONS

Based on the results of the analysis and discussion, it can be concluded that the development of circular economy-based construction waste management strategies through the implementation of the reduce, reuse, and recycle principles has the potential to improve material utilization efficiency, reduce the quantity of waste requiring disposal, and support sustainable infrastructure development. The hypothetical simulation results indicated that, of the total initial potential waste generation of 100 tons, concrete contributed the largest proportion at 40%, followed by bricks at 20%, formwork timber at 15%, reinforcing steel and aggregates at 10% each, and packaging materials at 5%. A comparison of four waste management scenarios demonstrated that the implementation of an integrated circular economy strategy (S3) could prevent the generation of 15 tons of waste, enable the reuse of 25 tons of materials, and facilitate the recycling of 40 tons of materials. Consequently, the quantity of waste requiring final disposal decreased from 100 tons to 20 tons, representing an 80% reduction compared with the conventional waste management system.

From an economic perspective, the implementation of circular economy-based waste management strategies demonstrated potential cost savings through reduced disposal requirements, material reuse, and the recovery of economic value from construction resources. The simulation results showed that the net waste management cost under the conventional system was IDR 45,000,000, whereas the integrated circular economy strategy resulted in a net cost of IDR 29,000,000. This difference indicated potential cost savings of 35.56% compared with the baseline condition. From an environmental perspective, the integrated strategy achieved a waste diversion rate of 76.47% relative to the quantity of waste remaining after prevention measures. These findings suggested that implementing circular economy principles could

reduce dependence on final disposal facilities and improve the utilization of material resources. However, a comprehensive assessment of environmental benefits would require further evaluation of energy consumption, material processing activities, transportation, and emissions generated throughout the material life cycle.

Overall, this study demonstrated that construction waste management strategies integrating material requirement control, waste segregation, material reuse, and recycling could provide a promising approach to supporting sustainable infrastructure development. Successful implementation requires accurate material planning, effective stakeholder coordination, the availability of material recovery facilities, and measurable material flow monitoring systems. Waste prevention should be prioritized as the primary strategy, followed by the reuse and recycling of materials that meet relevant technical requirements. Although Scenario S3 exhibited the most favorable performance within the simulation model, the findings cannot be generalized because all data used in the study were hypothetical. Therefore, further research should incorporate actual construction project data, quality testing of recovered materials, and more comprehensive evaluations of costs and environmental impacts. Such investigations would provide a stronger empirical foundation for implementing the proposed circular economy strategies more effectively, economically, and reliably in infrastructure project management.

REFERENCES

Alhawamdeh, M., Ferriz-Papi, J. A., & Lee, A. (2024). Examining the drivers to support improved construction and demolition waste management for a circular economy: A comprehensive review using a systematic approach. Sustainability, 16(14), 6014. https://doi.org/10.3390/su16146014

American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2023). ANSI/ASHRAE Standard 55-2023: Thermal environmental conditions for human occupancy. ASHRAE. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

Badan Standardisasi Nasional. (2020). SNI 6390:2020: Konservasi energi sistem tata udara pada bangunan gedung. Badan Standardisasi Nasional. https://pesta.bsn.go.id/produk/detail/13244-sni63902020

Bate'e, E. K., Laoli, E. S., Zebua, D., Halawa, I. H., Ziliwu, P. I. A. P., Halawa, S. J., & Lase, F. (2024). Aplikasi teknik statistik dalam evaluasi kinerja material konstruksi di berbagai kondisi lingkungan. IDENTIK, 1(1). https://doi.org/10.70134/identik.v1i1.244

Daeli, I. A., Mendrofa, K. B., Giawa, J. F. K., Harita, H., Daeli, S. D., Zalukhu, M. H., Waruwu, Y., Laoli, D., Laia, B., Zebua, D., & Zebua, F. D. (2025). Integrasi pendidikan dan teknik sipil: Pilar pembangunan berkelanjutan. SIHOWUBOOKS, 2(1).

Daeli, S. D., Zebua, D., Zai, E. P., Harita, H., Zalukhu, M. H., & Lahagu, D. K. (2024). Statistik jadi mudah: Teori, praktik, dan studi kasus lengkap. SIHOWUBOOKS, 1(1).

Dewi, O. C., Putra, N., Yatim, A., Mahlia, T. M. I., Rahmasari, K., Hanjani, T., Siregar, R., Rangin, B., & Izzatur, N. (2023). Zoning and activity-based post occupancy evaluation of multipurpose auditorium in campus facility. Energy and Buildings, 295, Article 113319. https://doi.org/10.1016/j.enbuild.2023.113319

European Commission. (n.d.). Construction and demolition waste. European Commission. https://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en

Ferriz-Papi, J. A., Lee, A., & Alhawamdeh, M. (2024). Examining the challenges for circular economy implementation in construction and demolition waste management: A comprehensive review using systematic methods. Buildings, 14(5), 1237. https://doi.org/10.3390/buildings14051237

Giawa, J. F. K., Laia, B. W., Loi, A., & Zebua, D. (2025). Kinerja geotekstil sebagai material perkuatan tanah pada struktur timbunan jalan. Jurnal Riset dan Inovasi Teknik Sipil.

Hamedoni, H., Daeli, S. D., Zalukhu, M. H., & Zebua, D. (2024). Strategi pengelolaan risiko dalam konstruksi gedung tahan gempa di daerah rawan bencana. Jurnal Ilmu Ekonomi, Pendidikan dan Teknik, 1(2), 1–10. https://doi.org/10.70134/identik.v1i2.35

Harita, H., Daeli, I. A., Laia, B., Zebua, D., Daeli, S. D., Zalukhu, M. H., & Zebua, F. D. (2025). Dasar-dasar manajemen proyek dan pengendalian proyek. SIHOWUBOOKS, 2(1).

Harita, H., Zebua, D., Caling, C. L. B., Laia, B., Zalukhu, M. H., Daeli, S. D., & Mendrofa, K. B. (2024). Bahan bangunan konstruksi: Jenis, karakteristik dan penggunaanya. SIHOWUBOOKS, 1(1).

Harita, H., Zebua, D., Caling, C. L. B., Sabu, M. K. H., Primavita, C. C., & Yudarsi, P. M. (2026). Teknik sipil untuk pemula. SIHOWUBOOKS, 3(1).

Harita, H., Zebua, D., Laia, B., Daeli, I. A., Daeli, S. D., & Zalukhu, M. H. (2025). Budaya K3 dalam proyek infrastruktur: Tantangan dan solusi. SIHOWUBOOKS, 2(1).

Harita, H., Zebua, D., Telaumbanua, A., Daeli, S. D., Zalukhu, M. H., & Giawa, J. F. K. (2024). Proyek sukses dengan MS. Project: Panduan praktis dan aplikasi langsung. SIHOWUBOOKS, 1(1).

Harita, H., Zebua, D., Telaumbanua, A., Daeli, S., Zalukhu, M. H., & Giawa, J. F. K. (2024). Proyek sukses dengan MS. Project: Panduan praktis dan aplikasi langsung. SIHOWUBOOKS, 1(1).

International Energy Agency. (2025). Energy efficiency 2025. IEA. https://www.iea.org/reports/energy-efficiency-2025

Kasi, J., & Kaliluthin, A. K. (2024). A comprehensive approach to assess occupant's satisfaction and performances of residential building. Civil Engineering Journal, 10(2), 444–455. https://doi.org/10.28991/CEJ-2024-010-02-07

Kolago, D. P., & Zebua, D. (2023). Analisa beban pendinginan dalam perencanaan bangunan gedung. Jurnal Penelitian

Jalan dan Jembatan, 3(2). https://doi.org/10.59900/ptrkjj.v3i2.171
Laia, B., Zebua, D., Daeli, I. A., Harita, H., Zalukhu, M. H., Daeli, S. D., & Giawa, J. F. K. (2025). Mengenal dunia teknik sipil: Pondasi untuk masa depan. SIHOWUBOOKS, 2(1).
Laia, B., Zebua, D., Daeli, S. D., Harita, H., Zalukhu, M. H., & Giawa, J. F. K. (2024). Rahasia menulis buku sampai selesai. SIHOWUBOOKS, 1(1).
Laia, B., Zebua, D., Ndraha, A. B., Lase, D., Laoli, D., & Waruwu, F. K. F. (2024). Panduan lengkap menggunakan SPSS untuk pemula: SPSS dari nol, panduan praktis & sistematis untuk pemula. SIHOWUBOOKS, 1(1).
Laia, B., Zebua, D., Zalukhu, M. H., Harita, H., Daeli, I. A., & Daeli, S. D. (2025). Jenis-jenis tanah dan klasifikasinya dalam teknik sipil. SIHOWUBOOKS, 2(1).
Papamichael, I., Voukkali, I., Loizia, P., & Zorpas, A. A. (2023). Construction and demolition waste framework of circular economy: A mini review. Waste Management & Research, 41(12), 1728–1740. https://doi.org/10.1177/0734242X231190804
Paroipo, W. T., Cahyono, M. S. D., & Zebua, D. (2022). Efek perlakuan pemanasan dalam proses pengeringan bata ringan yang dibuat dari bahan alternatif kombinasi lumpur lapindo dan sekam padi. Jurnal Penelitian Jalan dan Jembatan, 2(2), 9–13. https://doi.org/10.59900/ptrkjj.v2i2.82
Ridwan, D., Zebua, D., & Solihin. (2023). Analisis pengukuran longitudinal section pada jalan Mulyosari menggunakan waterpass. Jurnal Penelitian Jalan dan Jembatan, 3(2). https://doi.org/10.59900/ptrkjj.v3i2.169
Satoinong, L., Desnalia, D., Mintura, S., Paroipo, W. T., Gulthom, A., Simamora, J., & Zebua, D. (2024). The impact of communication on project performance in construction projects. Innovative Research in Civil and Environmental Engineering (IRCEE), 1(1). https://doi.org/10.70134/ircee.v1i1.45
Soto-Paz, J., Arroyo, O., Torres-Guevara, L. E., Parra-Orobio, B. A., & Casallas-Ojeda, M. (2023). The circular economy in the construction and demolition waste management: A comparative analysis in emerging and developed countries. Journal of Building Engineering, 78, 107724. https://doi.org/10.1016/j.jobe.2023.107724
Swarnakar, V., & Khalfan, M. (2024). Circular economy in construction and demolition waste management: An in-depth review and future perspectives in the construction sector. Smart and Sustainable Built Environment. https://doi.org/10.1108/SASBE-02-2024-0056
Syifa, F., Bayu, M. D., & Saputra, P. D. (2026). Strategi pengelolaan limbah konstruksi berbasis konstruksi berkelanjutan: Systematic literature review. Construction and Material Journal, 8(1). https://doi.org/10.32722/cmj.v8i1.8274
Teras, D., Tjahjono, B., Ridwan, R., Saepudin, A., Arniansyah, A., Leihitu, D. D. J., & Zebua, D. (2024). Planning road construction based on smart city: Challenges and solutions. Innovative Research in Civil and Environmental Engineering, 1(1). https://doi.org/10.70134/ircee.v1i1.44
Teras, D., Zebua, D., & Fiya. (2023). Proses penapisan terkait amdal pada pembangunan jalan di Desa Bangun Harja. Jurnal Penelitian Jalan dan Jembatan, 3(2). https://doi.org/10.59900/ptrkjj.v3i2.170
Tjahjono, B., Zebua, D., & Mita, V. (2023). Analisis kajian literatur risiko keselamatan dan kesehatan kerja (K3) dalam pembangunan gedung bertingkat di Indonesia. Jurnal Penelitian Jalan dan Jembatan, 3(2). https://doi.org/10.59900/ptrkjj.v3i2.168
Tjahjono, B., Zebua, D., & Rusnani. (2023). Perbandingan nilai momen pada SPColumn dengan hasil eksperimen. Jurnal Penelitian Jalan dan Jembatan, 3(1), 1–7. https://doi.org/10.59900/ptrkjj.v3i1.130
United Nations Environment Programme. (2025). Global status report for buildings and construction 2024/2025: Not just another brick in the wall—The solutions exist. Scaling them will build on progress and cut emissions fast. https://doi.org/10.59117/20.500.11822/47214
Victar, H. C., & Waidyasekara, K. G. A. S. (2024). Circular economy strategies for waste management in Sri Lanka: A focus on demolitions and repurpose and material recovery and production stages. Waste Management & Research, 42(11), 953–976. https://doi.org/10.1177/0734242X231206988
Wibowo, L. S. B., & Zebua, D. (2021). Analisis pengaruh lokasi dinding geser terhadap pergeseran lateral bangunan bertingkat beton bertulang 5 lantai. Ge-STRAM: Jurnal Perencanaan dan Rekayasa Sipil, 4(1), 16–20. https://doi.org/10.25139/jprs.v4i1.3490
Zalukhu, M. H., Zebua, D., Laia, B., Harita, H., Laia, O., & Zai, F. S. (2024). IBM SPSS secara detail: Panduan komprehensif setiap fitur. SIHOWUBOOKS, 1(1).
Zebua, D. (2020). Pushover analysis pada bangunan beton bertingkat tinggi terhadap beban gempa berdasarkan SNI-1726:2012 [Tugas akhir, Universitas Widya Kartika]. Repository Universitas Widya Kartika. http://repository.widyakartika.ac.id/id/eprint/1058
Zebua, D. (2022). Analisis pushover pada struktur bangunan bertingkat beton bertulang 10 lantai (Master's thesis, Universitas Narotama). Universitas Narotama Repository. http://repository.narotama.ac.id/id/eprint/1962
Zebua, D. (2023). Analisis displacement struktur beton bertulang pada gedung rumah sakit. Jurnal Penelitian Jalan dan Jembatan, 3(1), 20–25. https://doi.org/10.59900/ptrkjj.v3i1.133
Zebua, D. (2024). Membangun Nias: Teknik dan tradisi konstruksi. SIHOWUBOOKS, 1(1).
Zebua, D., & Giawa, J. F. K. (2025). Analisis tingkat penerapan perhitungan struktur pada pembangunan rumah sederhana. Jurnal Ilmu Ekonomi, Pendidikan dan Teknik, 2(2), 79–84. https://doi.org/10.70134/identik.v2i2.722
Zebua, D., & Giawa, J. F. K. (2025). Qualitative study of maintenance of wooden structures of traditional houses in damp

environments. Innovative Research in Civil and Environmental Engineering, 2(1), 54–60. https://doi.org/10.70134/ircee.v2i1.723

Zebua, D., & Koespiadi, K. (2022). Pushover analysis of the structure a 10-floor building with ATC-40. IJTI International Journal of Transportation and Infrastructure, 5(2), 110-116. https://doi.org/10.59900/ijti.v5i2.110

Zebua, D., & Koespiadi. (2022). Performance evaluation of high-rise building structure based on pushover analysis with ATC-40 method. Applied Research on Civil Engineering and Environment (ARCEE), 3(02), 54-63. https://doi.org/10.32722/arcee.v3i02.4334

Zebua, D., & Laia, B. (2025). Insinyur dalam teknik sipil. SIHOWUBOOKS, 2(1).

Zebua, D., & Siswanto, I. (2023). Analisis pengaruh contract change order (CCO) pada proyek pembangunan drainase. Jurnal Penelitian Jalan dan Jembatan, 3(2). https://doi.org/10.59900/ptrkjj.v3i2.167

Zebua, D., & Wibowo, L. S. B. (2022). Effect of soil type on lateral displacement of reinforced concrete building. Applied Research on Civil Engineering and Environment, 3(3), 127–134. https://doi.org/10.32722/arcee.v3i03.4965

Zebua, D., & Wibowo, L. S. B. (2022). Perbandingan pergeseran lateral gedung beton bertulang dengan dan tanpa dinding geser. RACIC: Rab Construction Research, 7(1), 11–19.

Zebua, D., & Wibowo, L. S. B. (2023). Pengaruh jenis tanah terhadap simpangan lateral gedung beton bertulang. Jurnal Riset dan Pengembangan Sumber Daya, 6(1), 1–10. https://doi.org/10.25139/jprs.v6i1.4901

Zebua, D., Daeli, S. D., Harita, H., Daeli, I. A., Laia, B., Zalukhu, M. H., Giawa, J. F. K., Zebua, F. D., & Mendrofa, K. B. (2025). Teknologi dan peralatan konstruksi untuk insinyur sipil. SIHOWUBOOKS, 2(1).

Zebua, D., Daeli, S. D., Harita, H., Zalukhu, M. H., Laia, B., & Giawa, J. F. K. (2024). Cepat dan praktis belajar jurnal ilmiah. SIHOWUBOOKS, 1(1).

Zebua, D., Giawa, J. F. K., & Waruwu, J. P. (2025). Integration of smart infrastructure systems and innovative materials to enhance sustainability, performance, and resilience in modern civil engineering. Innovative Research in Civil and Environmental Engineering, 2(2). https://doi.org/10.70134/ircee.v2i2.838

Zebua, D., Giawa, J. F. K., Loi, A., & Zebua, C. (2025). Performance assessment of high-rise building foundations subjected to variable soil and load conditions in coastal environments. Journal of Development Technology and Sustainability, 1(1). https://doi.org/10.70134/jodetos.v1i1.892

Zebua, D., Harita, H., Daeli, S. D., Zalukhu, M. H., & Laia, B. (2024). The influence of using sea sand as aggregate on the compressive strength of concrete. Innovative Research in Civil and Environmental Engineering, 1(1), 1–6. https://doi.org/10.70134/ircee.v1i1.41

Zebua, D., Harita, H., Zalukhu, M. H., Laia, B., Daeli, S. D., & Zalukhu, B. S. (2024). IBM SPSS: Panduan praktis analisis data untuk penelitian dan statistik. SIHOWUBOOKS, 1(1).

Zebua, D., Laia, B., Giawa, J. F. K., & Mendrofa, K. B. (2026). Analysis of the effect of soil classification on displacement and inter-story drift of reinforced concrete buildings. RESWARA: Jurnal Riset Ilmu Teknik, 4(3). https://doi.org/10.70716/reswara.v4i3.665

Zebua, D., Laia, B., Harita, H., Zalukhu, M. H., Daeli, S. D., & Gowasa, E. F. (2024). Mengenal aplikasi IBM SPSS statistic serta fungsi fitur-fiturnya. SIHOWUBOOKS, 1(1).

Zebua, D., Laia, B., Zalukhu, M. H., Daeli, S. D., Harita, H., & Giawa, J. F. K. (2024). Strategi sukses tata kelola jurnal dan pencapaian akreditasi nasional. SIHOWUBOOKS, 1(1).

Zebua, D., Laia, B., Zalukhu, M. H., Daeli, S., Harita, H., & Giawa, J. F. K. (2024). Praktis belajar struktur beton prategang. SIHOWUBOOKS, 1(1)

Zebua, D., Mendrofa, P. S. S., Telaumbanua, F. T., Mendrofa, R. W., & Laoli, P. J. (2024). Analisis statistika keandalan struktural dalam teknik sipil. IDENTIK, 1(1). https://doi.org/10.70134/identik.v1i1.241

Zebua, D., Prayoga, P., & Waruwu, P. C. E. (2023). Evaluasi dan desain pengembangan infrastruktur pengaliran drainase di wilayah Ngagel Tirto Kota Surabaya. Jurnal Penelitian Jalan dan Jembatan, 3(1), 26–32. https://doi.org/10.59900/ptrkjj.v3i1.134

Zebua, D., Putra, A. A. S., Wibowo, L. S. B., & Alfiani, S. (2023). Evaluation of seismic performance of hospital building using pushover analysis based on ATC-40. Journal of Civil Engineering, Science and Technology, 14(2). https://doi.org/10.33736/jcest.5326.2023

Zebua, D., Shofiyah, A., & Purnomo, H. D. (2023). Analisis desain kinerja model halte berdasarkan lingkungan di tempat terpilih. Jurnal Penelitian Jalan dan Jembatan, 3(1), 8–19. https://doi.org/10.59900/ptrkjj.v3i1.132

Zebua, D., Waruwu, E., Lase, D., Yanita, R., & Giawa, J. F. K. (2025). Analisis kinerja struktur gedung beton bertulang sesuai ATC-40. Inovasi Pembangunan: Jurnal Kelitbangan, 13(1). https://doi.org/10.35450/jip.v12i03.816

Zebua, D., Wibowo, L. S. B., Cahyono, M. S. D., & Ray, N. (2020). Evaluasi simpangan pada bangunan bertingkat beton bertulang berdasarkan analisis pushover dengan metode ATC-40. Ge-STRAM: Jurnal Perencanaan dan Rekayasa Sipil, 3(2). https://doi.org/10.25139/jprs.v3i2.2475

Zebua, D., Wibowo, L. S. B., Cahyono, M. S. D., & Ray, N. (2020). Analysis pushover pada bangunan bertingkat beton bertulang 7 lantai menggunakan metode FEMA-356. Seminar Nasional Ilmu Terapan (SNITER), 4(1).

Zebua, D., Wibowo, L. S. B., Rahman, H., & Rifani, R. (2022). Studi pengaruh peranan konsultan manajemen konstruksi pada proyek pembangunan tempat penyimpanan sementara limbah B3. Jurnal Penelitian Jalan dan Jembatan, 2(2), 1–8. https://doi.org/10.59900/ptrkjj.v2i2.81

Zebua, D., Zalukhu, M. H., Daeli, S. D., Harita, H., Laia, B., & Zebua, F. D. (2024). Indeks jurnal ilmiah: Memahami Google Scholar, SINTA, GARUDA, Scopus, Copernicus, dan Crossref. SIHOWUBOOKS, 1(1).

Zebua, D., Zalukhu, M. H., Laia, B., Daeli, S. D., Harita, H., & Zebua, D. Y. (2024). Pedoman aplikatif mengolah data penelitian dengan SPSS: Menguasai statistik dengan SPSS. SIHOWUBOOKS, 1(1).

Zebua, W., Lase, C. A., Mendrofa, E. F., & Zebua, D. (2026). Analisis jenis struktur rumah tinggal di Nias. IDENTIK, 3(2). https://doi.org/10.70134/identik.v3i2.1367

Zhao, J., Abdul Aziz, F., Deng, Y., Ujang, N., & Xiao, Y. (2024). A review of comprehensive post-occupancy evaluation feedback on occupant-centric thermal comfort and building energy efficiency. Buildings, 14(9), Article 2892. https://doi.org/10.3390/buildings14092892

Ziliwu, P. I. A. P., Daeli, J. R., Mendrofa, K. B., Ziliwu, I. S., Harefa, A. C., Laoli, P. J., & Zebua, D. (2025). Perbandingan data dukungan tanah hasil analisis sondir dengan metode empiris Meyerhof dan Schmertmann. Seminar Nasional Ilmu Terapan (SNITER), 9(1).