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Reusable and Reconfigurable Material Concepts for Post-Disaster Temporary Modular Shelters: A Systematic Review From An Environmental Sustainability Perspective

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Abstract

Post-disaster temporary shelters in Indonesia often generate significant construction waste because of their single-use nature. This study aims to map reusable and reconfigurable concepts as the foundation of Temporary Modular Shelter (TMS) material design and to analyse their contributions to environmental sustainability. A Systematic Literature Review (SLR) following the PRISMA 2020 protocol was conducted on peer-reviewed articles and indexed proceedings published between 2015 and 2025, retrieved from Scopus, ScienceDirect, and Google Scholar. Of 412 records initially identified, 87 peer-reviewed studies met the inclusion criteria. Thematic analysis was performed using NVivo 12 with a hybrid deductive–inductive coding approach. The findings show that reusable–reconfigurable principles are operationalised through modular systems and reversible dry connections that allow shelter components to be potentially reused or adapted for permanent housing construction. Five main material components were identified: frames, wall panels, roofs, flexible elements, and flooring/base modules. The approach is reported in the reviewed literature to support construction waste reduction, circular economy practices, lower embodied carbon, and improved resource efficiency, although the magnitude of these benefits varies with material type, transport distance, and the number of reuse cycles. This study contributes an integrative sustainability-based framework linking reusable–reconfigurable principles with post-disaster TMS material systems. Remaining challenges include module standardisation, local human resource capacity, comprehensive Life Cycle Cost analysis, and socio-economic integration. The framework provides a reference for policymakers, researchers, and practitioners developing adaptive and sustainable temporary housing in disaster-prone regions.

Keywords: reusable materials, reconfigurable design, temporary modular shelter, post-disaster housing, environmental sustainability

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INTRODUCTION

Indonesia is recognized as one of the most disaster-prone countries in the world owing to its location along the Pacific Ring of Fire, which exposes the country to frequent earthquakes, volcanic eruptions, floods, and landslides. According to the National Disaster Management Agency (BNPB, 2023), thousands of disaster events are recorded annually, with earthquakes being one of the most significant hazards affecting human settlements and infrastructure. This condition places post-disaster housing provision as a critical issue in national disaster management, in which rapid response, technical feasibility, and environmental sustainability must be addressed simultaneously (Sari et al., 2025). Conventional temporary shelters in Indonesia commonly rely on single-use materials such as plywood, plastic tarpaulins, and low-cost wooden frames that ultimately become construction waste after the transition phase ends. This problem is exacerbated by the limited capacity of post-disaster waste management systems, which are often disrupted owing to infrastructure damage, thereby increasing environmental burdens in already vulnerable disaster-affected areas (Hosseini et al., 2022; Yosritzal et al., 2023).

Within post-disaster housing literature, several related terms are often used interchangeably and require careful distinction. Emergency shelters refer to immediate, very short-term shelters (hours to a few weeks) such as tents, tarpaulins, or communal facilities provided in the immediate aftermath of a disaster. Transitional shelters describe semi-permanent structures intended to bridge the period between emergency response and permanent reconstruction, typically lasting from several months to a few years. Temporary housing refers more broadly to dwellings used during the rebuilding phase without specifying the construction system. Permanent reconstruction housing denotes the final, durable replacement dwellings. In contrast, Temporary Modular Shelter (TMS) is defined in this study as a transitional shelter system constructed from prefabricated and standardized modular components designed with reversible connections, intended to be assembled rapidly after a disaster and capable of being dismantled, reconfigured, and reused, either for subsequent transitional applications or as components of permanent housing. This definition positions TMS as a subset of transitional shelters that is explicitly engineered for material reuse and reconfiguration across the post-disaster recovery cycle.

The TMS approach has emerged as an alternative paradigm emphasizing modularity, prefabrication, rapid assembly, and adaptability. TMS systems are designed to enable efficient construction while allowing dismantling and reassembly through reusable and reconfigurable principles (Jafari Sharami & Teimouri, 2023; Nekooie & Tofighi, 2020). The reusable concept refers to the ability of building components or materials to be used across multiple construction cycles without substantial functional degradation, whereas reconfigurable refers to the flexibility of components to be rearranged into different spatial or structural configurations. These concepts are conceptually rooted in the cradle-to-cradle and design-for-disassembly approaches, which position construction materials as long-term assets within circular material flows rather than disposable products (Crowther, 2018; McDonough & Braungart, 2010).

The Indonesian context strengthens the relevance of reusable–reconfigurable TMS systems. First, the country experiences recurring disasters, particularly in earthquake-prone provinces such as West Sumatra, the Special Region of Yogyakarta (DIY), West Java, and East Java, where the same locations may require shelter intervention multiple times within a decade. Second, post-disaster waste management capacity is structurally limited, with disposal infrastructure frequently overwhelmed after major events. Third, Indonesia has long-established construction traditions based on renewable local materials, including bamboo and timber, and these materials are widely available across the archipelago. Bamboo species such as Guadua and laminated Moso, in particular, have been shown to offer high tensile and flexural performance suitable for modular framing (Yadav et al., 2021). Fourth, community-based reconstruction (rebuild-yourself or gotong royong approaches) is culturally embedded and has been successfully applied in cases such as the 2006 Yogyakarta earthquake recovery, where families assembled their own shelters with technical guidance. These conditions make reusable–reconfigurable TMS systems particularly suitable for the Indonesian setting because they align with locally available materials, community-based assembly practices, and the practical need for repeated deployment.

Despite the growing literature on modular and sustainable construction, previous studies remain fragmented in analytical focus and implementation scope. Several studies have emphasized the use of local and renewable materials in post-disaster shelters (Christian & Feriadi, 2022; Nicolalde et al., 2022), while others have focused on modular connection systems and digital fabrication (Roxas et al., 2023). In a broader sustainability context, (Hosseini et al., 2021) examined construction waste reduction and circular economy practices. Although these studies contribute valuable insights, they generally examine reusable, reconfigurable, technical, and environmental aspects separately rather than as an integrated design framework. Comprehensive synthesis comparing operational definitions, measurement indicators, material characteristics, environmental contributions, and implementation challenges of reusable–reconfigurable TMS systems is still absent. Studies addressing the Indonesian context remain limited, despite Indonesia's distinctive socio-cultural conditions, disaster characteristics, and local material traditions.

Accordingly, this study aims to (1) map the concepts of reusable and reconfigurable as the foundation of post-disaster TMS material design based on scientific literature; (2) identify material components possessing reusable and reconfigurable characteristics; (3) analyze the contributions of these concepts to environmental sustainability; and (4) identify implementation challenges and future development directions. To address these objectives, four research questions were formulated as follows. (RQ1) How are reusable and reconfigurable concepts defined and operationalized within the TMS material design literature? (RQ2) What material components exhibit reusable and reconfigurable characteristics? (RQ3) How do these concepts contribute to environmental sustainability? (RQ4) What implementation challenges and research gaps remain in the existing literature? By answering these questions, the study contributes an integrative sustainability-oriented framework that connects reusable–reconfigurable principles with environmental sustainability dimensions in post-disaster TMS material systems, providing an applicable reference for governments, academics, and construction practitioners in Indonesia.

METHOD

This study employed a Systematic Literature Review (SLR) using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 protocol (Page et al., 2021). The SLR approach was selected because it enables a systematic, transparent, and replicable synthesis of scientific literature relevant to the research topic. The PRISMA protocol was adopted to ensure traceability throughout the literature selection process, from identification to inclusion.

Data Sources and Search Strategies

Literature searches were conducted in three scientific databases: Scopus, ScienceDirect, and Google Scholar. These databases were chosen for their broad coverage of peer-reviewed publications relevant to modular construction, post-disaster housing, and sustainability studies. The publication period was restricted to 2015–2025 to ensure inclusion of contemporary studies on reusable and reconfigurable modular systems. The literature search was conducted between January and March 2026.

A primary search string was constructed using Boolean operators around four conceptual clusters: shelter type, design principle, material focus, and sustainability orientation. The primary search string was:

("temporary shelter" OR "modular shelter" OR "post-disaster housing") AND ("reusable" OR "reconfigurable" OR "circular") AND ("material" OR "component") AND ("sustainability" OR "environmental")

To address potential narrowness of the primary string, a complementary screening of related terms was performed. Specifically, the keywords "emergency shelter", "transitional shelter", "temporary housing", "prefabricated shelter", "deployable shelter", "design for disassembly", and "circular construction" were used in supplementary searches and cross-checked against the primary results. Records identified through these supplementary searches were screened against the inclusion criteria using the same protocol; only studies addressing both modular post-disaster housing and reusable–reconfigurable concepts were retained, in keeping with the focused scope of this review.

The search string was adapted to the syntax of each database. In Scopus, the search was applied to the TITLE-ABS-KEY field with Boolean operators preserved. In ScienceDirect, the string was simplified into AND/OR combinations supported by the advanced search interface, with the publication-year filter applied. For Google Scholar, which does not fully support Boolean syntax and is not strictly reproducible because of algorithmic ranking, the following procedure was applied: the advanced search interface was used; results were sorted by relevance; the search date and result counts were recorded; and the first 200 results (the first 20 pages, at 10 results per page) were screened. This procedural transparency is acknowledged as a limitation of Google Scholar use in SLR work.

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria are presented in **Table 1**. The criteria were defined a priori to ensure that all retrieved articles addressed the research questions and met basic methodological quality. Screening reliability and inter-rater procedures are described separately under Quality Appraisal and Coding, as they are review procedures rather than article-level inclusion criteria.

Table 1. Inclusion and Exclusion Criteria

Aspects	Inclusion Criteria	Exclusion Criteria
Type of publication	Peer-reviewed journal articles; indexed conference proceedings with full methodology reported	Unindexed books, theses, blog posts, opinion pieces, technical or institutional reports without peer review
Year of publication	2015–2025	Before 2015
Language	English and Indonesian	Other languages
Topic	Materials or components of TMS / post-disaster temporary housing; reusable or reconfigurable principles; environmental sustainability of shelter systems	Permanent housing without any transitional context; purely socio-psychological aspects without material/technical content; topics unrelated to disaster shelter
Accessibility	Full text available	Abstract only
Quality appraisal	Clear research objectives, transparent methodology, traceable data sources, and adequate analytical evidence (appraisal score ≥ 3 of 5)	Unclear methodology, unsupported conclusions, duplicated findings, retracted publications, or appraisal score < 3 of 5

Quality Appraisal Procedure

Methodological quality of articles passing the topical screening was appraised using a five-item rubric adapted from PRISMA-related quality appraisal practices, as the present review does not include experimental intervention studies for which formal risk-of-bias instruments (e.g., RoB 2 or ROBINS-I) are designed. Each article was scored from 0 to 1 on five items are (1) clarity of research objectives and questions; (2) transparency of methodology and reproducibility; (3) appropriateness of analytical approach for the stated aim; (4) traceability of data sources and citations; and (5) clarity of conclusions in relation to the evidence presented. Item scores were summed to yield a quality score between 0 and 5. Articles scoring ≥ 3 were retained for inclusion; articles scoring < 3 were excluded as part of the eligibility phase. Two reviewers independently appraised all articles; disagreements were resolved by discussion until consensus was reached

PRISMA Stages

The article selection process followed the four PRISMA stages are identification, screening, eligibility, and inclusion. Identification yielded 412 records in total, comprising 187 from Scopus, 134 from ScienceDirect, and 91 from Google Scholar (first 200 sorted by relevance). At the pre-screening stage, 96 duplicate records were removed through DOI matching and manual verification, and 8 additional records were removed for other reasons (non-retrievable full text, non-research items such as editorials, and clearly mis-indexed records), leaving 308 records for screening. Title and abstract screening excluded 165 records as topically irrelevant, producing 143 reports sought for full-text retrieval. Of these, 12 reports could not be retrieved as full text. The remaining 131 reports underwent full-text eligibility assessment, in which 44 reports were excluded for the following reasons: 18 were irrelevant to TMS material design, 14 did not substantively discuss reusable or reconfigurable concepts, 7 lacked sufficient sustainability analysis, and 5 were non-scientific in nature or had incomplete data. After the eligibility phase, 87 peer-reviewed studies were included in the final synthesis. The PRISMA flow diagram is presented in **Figure 1**.

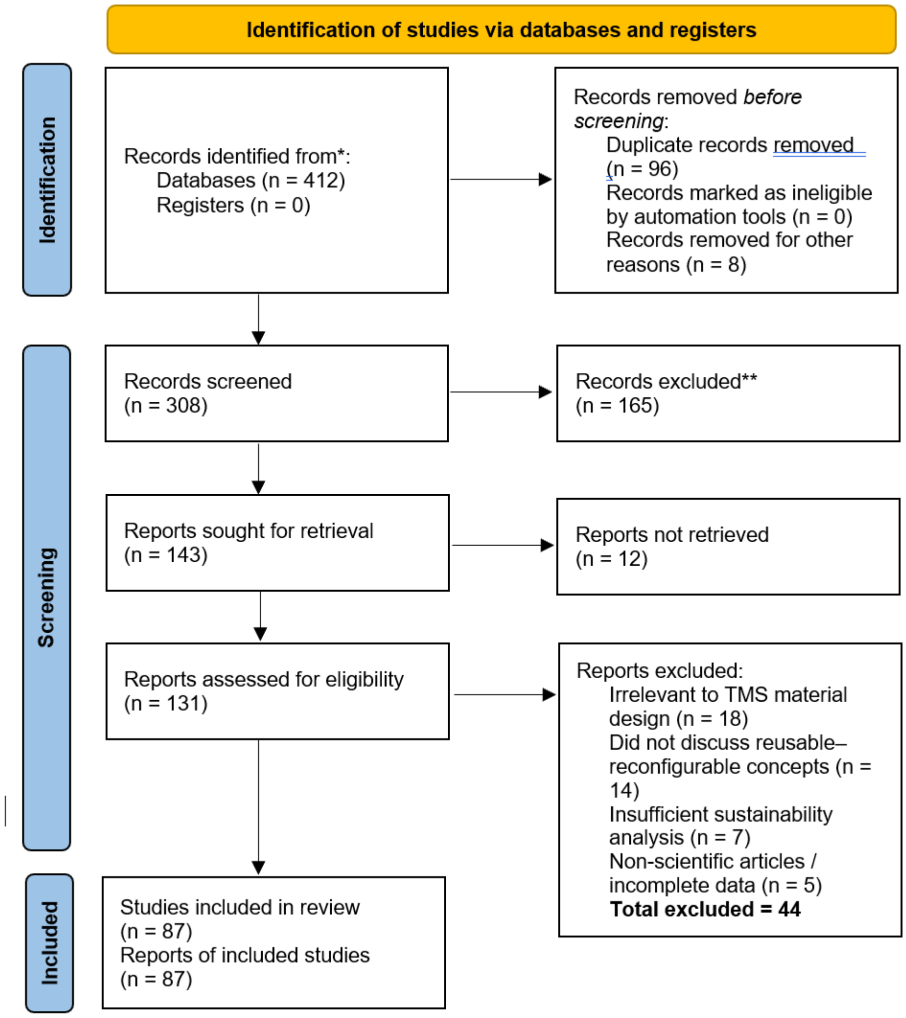

Figure 1. PRISMA Flow Chart Article Selection Process

Data Analysis and Coding

Data analysis used thematic analysis supported by NVivo 12 software. A hybrid deductive–inductive coding strategy was adopted. The deductive part of the framework was developed before coding from the four research questions, yielding five top-level themes are (1) definitions and operationalization of reusable concepts; (2) definitions and operationalization of reconfigurable concepts; (3) identified material components; (4) contributions to environmental sustainability; and (5) implementation challenges. The inductive part allowed sub-themes to emerge directly from the data during open coding of each article. Each article was coded twice: an initial open-coding pass produced descriptive labels close to the source text, and a second pass grouped these initial codes into sub-themes nested under the five top-level deductive themes. Sub-themes were refined iteratively until thematic saturation was reached. Coding was conducted independently by two reviewers; coding disagreements were discussed and resolved by consensus, with a third senior researcher consulted where consensus could not be reached.

Inter-rater reliability was calculated separately for two distinct review stages. For the title and abstract screening stage, Cohen's Kappa was 0.82, indicating excellent agreement. For thematic coding of the included articles, Cohen's Kappa was 0.79, also indicating substantial-to-excellent agreement (Vanbelle et al., 2024). Both values are reported to provide a transparent record of reviewer agreement at the distinct procedural points where it is methodologically meaningful.

RESULTS AND DISCUSSION

Descriptive Characteristics of the Reviewed Articles

Among the 87 included studies, the publication-year distribution shows a marked upward trend during 2020–2025, which accounts for 68% of the dataset. This indicates that sustainability-oriented TMS design has emerged as a rapidly growing research focus in the past five years. **Table 2** summarizes the descriptive characteristics of the reviewed articles across four dimensions: publication year, geographical context, disaster type, and research method.

Table 2. Descriptive characteristics of the 87 reviewed articles

Dimension	Category	Number	%
Publication year	2015–2019	28	32%
	2020–2025	59	68%
Geographical region	Asia (incl. Indonesia, India, Iran, Philippines, China)	37	42%
	Europe	24	28%
	Americas (North and South combined)	14	16%
	Africa	7	8%
	Australia/Oceania	5	6%
Disaster type	Earthquake	44	51%
	Flood	16	18%
	Conflict / displacement	12	14%
	Tsunami	7	8%
	Volcanic eruption	4	5%
	Other	4	4%
Research method	Case study	33	38%
	Experimental analysis	21	24%
	Numerical simulation	16	18%
	Literature review / conceptual	10	12%
	Mixed methods	7	8%

Indonesia was the explicit study location in 12 articles (13.8%), making it one of the most frequently studied countries within the Asian subset. The geographical category Americas combines studies from both North America (predominantly the United States) and South America (predominantly Ecuador, Chile, and Peru), reflecting the relatively small individual counts that do not justify separate reporting for this review

Mapping Reusable and Reconfigurable Concepts in TMS Literature

The concepts of reusable and reconfigurable are closely interconnected in the TMS literature and collectively form the foundation of circular post-disaster housing systems. Reusable refers primarily to the ability of components or materials to be used across multiple construction cycles without significant functional degradation, whereas reconfigurable emphasizes the adaptability of components to be rearranged into different spatial or functional configurations. Together, these principles support modular construction systems that extend material lifespan, reduce construction waste, and improve reconstruction flexibility. **Table 3** summarizes the operational definitions, strategies, indicators, and examples of these two concepts as derived from the reviewed literature.

In the reviewed literature, the reusable concept is operationalized through three main approaches: component-level reuse, material-level reuse, and functional reuse (Crowther, 2018; Gorgolewski, 2008; Iacovidou et al., 2018). Component-level reuse refers to the direct reuse of intact components without structural modification, such as transferring wall panels from temporary shelters to permanent housing structures. Material-level reuse involves reprocessing materials into new construction elements, while functional reuse refers to repurposing components for different applications. The most commonly identified indicators are the number of reuse cycles, material recovery rate, structural integrity after dismantling, and deconstruction–reassembly cost. Al-Najjar & Dodoo, (2023) reported that cross-laminated timber modular systems could achieve up to approximately 85% recovery of structural components during the first reuse cycle and retained approximately 60% structural integrity after three cycles in their laboratory-based mechanical evaluation; these values are therefore experimental laboratory estimates rather than field measurements, and their generalizability to other materials and field conditions should be interpreted with caution.

Table 3. Operational definitions of reusable and reconfigurable concepts in TMS design

Concept	Definition	Operational Strategy	Indicators	Example from Literature
Reusable	Ability of components or materials to be used across multiple construction cycles without substantial functional degradation	Component-level reuse; material-level reuse; functional reuse (repurposing for different applications)	Number of reuse cycles; material recovery rate; structural integrity after dismantling; deconstruction–reassembly cost	Cross-laminated timber modules reported in Al-Najjar and Dodoo (2023)
Reconfigurable	Capacity of components to be rearranged into different spatial or structural configurations	Dimensional modularity; reversible dry connections; standardized interfaces; design for disassembly	Number of possible configurations; reassembly time; tool requirements; interface compatibility	Industrialized Building System (IBS) modules described by Nekooie and Tofighi (2020); DfMA–BIM integration by Roxas et al. (2023)

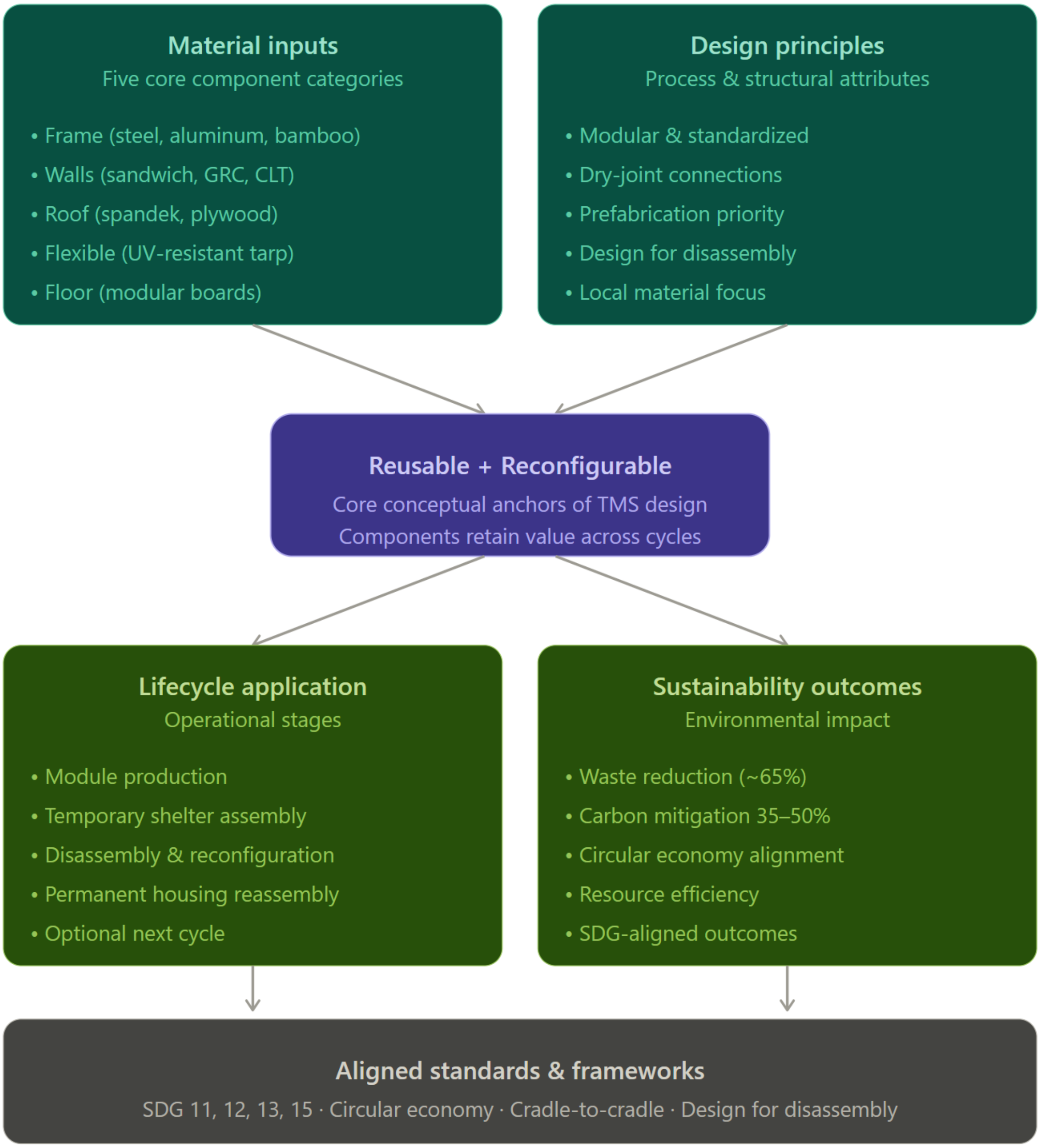

Figure 2. Conceptual Mapping Framework of Reusable–Reconfigurable TMS Systems

Reconfigurable principles are generally implemented through dimensional modularity, reversible dry-connection systems, and spatial adaptability. These characteristics enable modular components to be rearranged into multiple layouts that respond to changing user needs (Kai, 2022; Nekooie & Tofighi, 2020; Roxas et al., 2023). Nekooie and Tofighi (2020) showed that orthogonal symmetrical modular systems with Industrialized Building System (IBS) connections could generate at least five distinct spatial configurations for households of one to six occupants. Similarly, Roxas et al. (2023) integrated Design for Manufacturing and Assembly (DfMA) with Building Information Modeling (BIM) to improve modular precision and reduce construction costs by approximately 30% in their Philippines case study. Based on the synthesis of these findings, a conceptual mapping framework was developed, presented in **Figure 2**.

Description of the Conceptual Mapping Framework

The framework presented in Figure 2 was derived inductively from the thematic coding of the 87 included articles, organized under the four research questions and synthesized into a five-element structure. Its main elements are (1) material inputs, listing the five component categories identified in the literature (frame, wall panels, roof, flexible elements, and flooring/base modules); (2) design principles, summarizing recurring process and structural attributes such as modularity, standardization, dry-joint connections, prefabrication, and design for disassembly; (3) the core conceptual anchors (reusable + reconfigurable) that connect the input and design layers to the output layers; (4) lifecycle application, capturing the operational stages from module production through temporary deployment, dismantling, reconfiguration, and reassembly into permanent housing; and (5) sustainability outcomes, summarizing the environmental impacts reported in the literature. A horizontal band at the bottom places the framework within established external references (SDG 11, 12, 13, and 15; circular economy; cradle-to-cradle; design for disassembly).

The direction of relationships in the framework reflects a hypothesized causal structure derived from the coded literature: material inputs and design principles converge on the reusable–reconfigurable anchors, which in turn manifest in operational lifecycle stages and produce measurable sustainability outcomes. The framework directly addresses the four research questions: RQ1 is answered by the core anchors and their connection to material inputs and design principles; RQ2 is answered by the material inputs layer; RQ3 is answered by the sustainability outcomes layer; and RQ4 is reflected in the implementation challenges discussed in Section 3.6. While the framework was generated inductively from the coded data, it is conceptually consistent with the cradle-to-cradle and design-for-disassembly traditions, and aligns with circular economy principles.

Identified Material Components

Based on the thematic analysis of the 87 articles, five main material components were identified as having significant reusable and reconfigurable characteristics in TMS design. **Table 4** presents these components together with their dominant materials, reusable–reconfigurable features, reuse potential rating, and key references. The reuse potential rating (High / Medium / Low) was derived from the synthesis of evidence across studies: High indicates broad evidence of component-level reuse with limited functional degradation; Medium indicates partial or material-level reuse with potential rework; Low indicates limited reuse evidence, typically because of material wear or low recoverable value.

Material terminology has been standardized across this article and **Table 2** the spelling "aluminum" is used throughout for consistency; "Wall panels" replaces the previously inconsistent "Wall/Panel" label; and "Flooring / base modules" replaces "Floor/Base". These choices follow the more common usage in international post-disaster shelter literature and avoid confusion between distinct component categories.

Contribution to a Sustainable Environment

The reviewed literature suggests that reusable–reconfigurable TMS systems contribute to environmental sustainability through three principal pathways: construction waste reduction, implementation of circular economy practices, and carbon-footprint mitigation with improved resource efficiency. Each pathway is discussed in turn, with explicit attention to the type of evidence (simulation, prototype, case study, or estimation) underlying the most-cited quantitative claims.

Table 4. TMS Material Components with Reusable–Reconfigurable Characteristics

Component	Dominant Material	Reusable–Reconfigurable Features	Reuse Potential	Main References
Main structure (frame)	Cold-formed steel; aluminum; bamboo (Guadua / laminated Moso)	Reversible bolted connections; bamboo as renewable material; high corrosion resistance	High	(Nicolalde et al., 2022; Roxas et al., 2023; Yadav et al., 2021)
Wall panels	Sandwich panels; GRC; local wood boards; cross-laminated timber	Light weight; good thermal insulation; demountable without destruction	High	(Al-Najjar & Dodoo, 2023; Christian & Feriadi, 2022)
Roof	Corrugated metal roofing; corrugated metal roofing with plywood substrate	Dry, weatherproof joints; can be reinstalled with minor modifications	Medium	(Christian & Feriadi, 2022; Yosritzal et al., 2023)
Flexible elements	UV-resistant tarpaulin; textile membranes	Can be rolled, folded, and reinstalled across multiple deployments	Medium	(Albadra et al., 2021; Ammoun & Uzunoğlu, 2020)
Flooring / base modules	Wooden panels; composite panels; recycled-plastic modules	Detachable modules that can be rearranged for new spatial layouts	Medium	(Gharib et al., 2022; Iacovidou et al., 2018)

Construction Waste Reduction

Several reviewed studies report that reusable modular systems can reduce post-disaster construction waste by up to approximately 65% compared with conventional single-use shelters. This figure is reported by Hosseini et al. (2022) on the basis of a MIVES–Knapsack multi-criteria sustainability model applied to temporary housing unit configurations, and should therefore be interpreted as a model-based estimate rather than a field measurement. The estimate assumes full component recoverability after the transition phase and excludes losses caused by damage during deployment. Generalizability to other disaster contexts, material types, and operational conditions is therefore limited.

Circular Economy Implementation

Reusable–reconfigurable approaches operationalize the circular economy by replacing the linear take–make–dispose pattern with closed-loop material flows that retain value through reuse, repair, refurbishment, and remanufacture (Khalifa et al., 2022). **Table 5** summarizes a conceptual comparison between the two approaches as represented in the reviewed literature. The values reported in **Table 5** are aggregated estimates from multiple studies and should be read as indicative ranges rather than universal benchmarks; actual outcomes depend on material type, transport distance, the number of reuse cycles, and the efficiency of dismantling and storage

Table 5. Comparison of Linear vs. Linear Approaches Circular on TMS Design

Aspects	Linear Approach (Conventional)	Circular Approach (Reusable–Reconfigurable)
Material cycle	Extraction → production → use → disposal	Extraction → production → temporary housing use → dismantling → reuse in permanent housing
Component life	3–12 months (single use)	Multi-cycle use; components potentially reusable for years to decades
Post-disaster waste	High; most components become waste	Minimal; only consumables become waste (estimated reduction up to ~65% ; Hosseini et al., 2022)
New material at permanent housing stage	Almost entirely new materials	Reduced by ~60–70% through component reuse (literature-based estimate)
Transport load	Procurement and distribution carried out twice	More efficient; main procurement carried out once
Construction carbon emissions	High; accumulation across two production and construction cycles	Lower; potential reduction of ~35–50% in reviewed studies (range depends on material and transport)

Carbon Footprint Mitigation and Resource Efficiency

Dong et al., (2018) demonstrated through a life-cycle assessment of prefabricated temporary housing with renewable energy systems that the production of construction materials such as steel, cement, and aluminum generates significant carbon emissions, from raw-material extraction to manufacturing. Reusing temporary housing components for permanent housing construction can substantially lower the demand for new material production during the reconstruction phase, thereby reducing carbon emissions across the construction supply chain. Al-Najjar and Dodoo (2023) reported that modular construction based on cross-laminated timber and design-for-disassembly principles can reduce construction-related carbon emissions by up to approximately 38% compared with conventional methods, based on cradle-to-gate life-cycle inventory modelling. As with Section 3.5.1, these figures should be read as study-specific estimates contingent on system boundaries, material assumptions, and reuse-cycle assumptions.

The use of renewable local materials, particularly bamboo, further strengthens the environmental profile of TMS. Bamboo has a rapid growth cycle of approximately 3–5 years and absorbs substantial atmospheric carbon dioxide during growth. Yadav et al. (2021) demonstrated that Moso bamboo laminated with recycled rubber tubes possesses high tensile and flexural strength, enabling it to substitute for structural steel in certain applications. Such combinations provide dual environmental benefits by promoting low-carbon materials while simultaneously valorizing materials (used rubber) that would otherwise become waste.

Implementation Challenges

Four principal challenges to the implementation of reusable–reconfigurable TMS systems in Indonesia were identified across the reviewed literature. These are summarized in Table 6 with their explanation, impact on TMS implementation, and suggested future direction. The Indonesian context is given particular attention, with reference to local construction skills, procurement systems, land tenure, community acceptance, maintenance capacity, local material availability, and disaster logistics.

Table 6. Implementation challenges and recommended future directions

Challenge	Explanation	Impact on TMS Implementation	Suggested Future Direction
Lack of national module and connection standardization	Absence of agreed-upon module dimensions, joint types, and precision tolerances at the national level	Limited interoperability of components across projects, regions, and procurement cycles; difficulty consolidating reusable inventories	Develop a national TMS standard covering module dimensions, joints, and quality grades through BNPB and PUPR-coordinated technical guidance
Limited local technical capacity	Reversible dismantling and reassembly require higher technical skills than conventional construction; skilled workers are often scarce in affected areas	Slower deployment, increased rework, lower quality of reassembled components, and reduced trust in modular approaches at the community level	Develop standardized training and certification for modular assembly and disassembly through BPBD, vocational schools, and community-based programmers
Insufficient Life Cycle Cost analysis	Most reviewed studies remain conceptual or experimental, with limited longitudinal LCC evidence on economic efficiency of reuse	Difficult to justify higher up-front costs of modular systems to procurement bodies; persistent perception that reusable systems are not cost-effective	Conduct integrated LCA–LCC studies covering multiple reuse cycles, transport, storage, and maintenance, anchored in Indonesian price databases
Limited socio-economic integration	Land tenure, community preferences, local construction practices, and maintenance capacity are not yet integrated systematically into TMS planning	Modular systems may be technically successful yet socially or institutionally unsustainable, with low community acceptance or maintenance failure	Develop socio-technical assessment protocols and integrate community participation, land-tenure mapping, and procurement reform into TMS planning

The findings of this systematic review indicate a paradigm shift in post-disaster temporary housing design from the conventional linear take–make–dispose approach toward circular construction based on reusable and reconfigurable principles. Contemporary studies increasingly position TMS as a sustainable transitional housing system in which components can be reused and reconfigured through modular systems and reversible dry connections (Crowther, 2018; Khalifa et al., 2022). This shift is conceptually aligned with cradle-to-cradle and design-for-disassembly approaches that emphasize closed-loop material cycles and long-term material value (Kai, 2022; McDonough & Braungart, 2010). The review also reveals important regional differences: studies from Southeast Asia generally emphasize affordability, local resource utilization, and community participation, whereas studies from Europe and developed regions priorities industrial precision, prefabrication, and BIM integration. These differences indicate that reusable–reconfigurable TMS systems are highly context-dependent and cannot be universally standardized without considering socio-economic conditions and local construction culture (Ahmed & O'Brien, 2009; Christian & Feriadi, 2022).

Direct Answers to The Research Questions

RQ1 (definition and operationalization). Reusable and reconfigurable concepts are operationalized in the reviewed literature through component-level, material-level, and functional reuse, combined with modularity, reversible dry connections, and design for disassembly. The two concepts are complementary: reusable principles ensure component value retention across cycles, while reconfigurable principles ensure spatial and functional adaptability.

RQ2 (material components). Five core material components consistently emerge in the literature as reusable–reconfigurable: frames (cold-formed steel, aluminum, bamboo), wall panels (sandwich, GRC, cross-laminated timber), roofs (corrugated metal with optional substrate), flexible elements (UV-resistant tarpaulin and textile membranes), and flooring/base modules (wood, composite, or recycled-plastic panels). Frames and wall panels show the highest reuse potential, while roofs, flexible elements, and flooring exhibit medium reuse potential.

RQ3 (environmental sustainability contribution). The reviewed literature reports three principal sustainability pathways: construction waste reduction (estimated up to ~65% in model-based studies), circular economy implementation through reuse–repair–refurbish–remanufacture mechanisms, and carbon footprint mitigation (with reduction estimates ranging ~35–50% in reviewed cases, contingent on material and transport assumptions).

RQ4 (challenges and gaps). Four main implementation challenges remain: lack of national standardization, limited local technical capacity, insufficient Life Cycle Cost evidence, and weak socio-economic integration. Research gaps include the predominance of conceptual and experimental studies over longitudinal field validation, limited integrated LCA–LCC work, and limited Indonesia-specific empirical evidence.

Critical Reflection on Trade-offs

A balanced reading of the evidence requires acknowledging that reusable–reconfigurable systems may not always be environmentally superior to conventional approaches. First, the embodied environmental burden of repeated transport, storage, and maintenance of modular components may, under certain conditions, offset the savings from reduced material production. This is particularly relevant in archipelagic settings such as Indonesia, where transport over long distances may be unavoidable. Second, there is an inherent tension between rapid emergency response and reconfigurable design complexity: highly modular systems with reversible connections often require longer initial assembly and more skilled labor than simple single-use shelters, which can be problematic in the first weeks after a disaster. Third, the economic case for reusable TMS depends strongly on procurement structures and the availability of public budgets that span multiple disaster cycles; without institutional commitment to maintain reusable inventories, higher up-front costs cannot be amortized.

Fourth, the cultural acceptability of modular shelter components in Indonesian post-disaster communities is not uniform. Affected communities often have strong preferences for spatial layouts, materials, and finishes that reflect local building traditions. Modular systems that look or feel "industrial" may face lower acceptance, even when technically sound. These trade-offs collectively suggest that reusable–reconfigurable TMS systems should be implemented as part of a wider socio-technical package that includes standardization, training, procurement reform, and community engagement, rather than as a purely technical solution.

CONCLUSION

This systematic review identifies reusable and reconfigurable principles as the strategic foundation of post-disaster Temporary Modular Shelter material design, operationalized through modular systems and reversible dry connections. Across the 87 reviewed studies, five material components consistently emerge as candidates for reuse and reconfiguration: frames, wall panels, roofs, flexible elements, and flooring/base modules. Frames and wall panels show the highest reuse potential. The reviewed evidence supports three environmental sustainability pathways: construction waste reduction, circular economy implementation, and carbon footprint mitigation with improved resource efficiency, while four implementation challenges persist, namely module standardization, local technical capacity, Life Cycle Cost evidence, and socio-economic integration. The main contribution of this study is an integrative sustainability-based framework that directly links reusable–reconfigurable principles with TMS material systems, lifecycle stages, and environmental outcomes **(Figure 2)**. The framework provides a single reference model that addresses the previous fragmentation of the literature. From a policy perspective, the findings translate into five practical recommendations for Indonesia. (1) Develop national TMS module standards covering dimensions, joints, and quality grades through coordination between BNPB and the Ministry of Public Works and Housing. (2) Establish reusable shelter component inventories at the provincial or regional level so that components from one event can be redeployed in another. (3) Incorporate design-for-disassembly clauses into disaster shelter procurement specifications. (4) Provide standardized training and certification for local workers in modular assembly and disassembly, building on existing BPBD and vocational-school networks. (5) Require integrated LCA and LCC assessment for large-scale post-disaster shelter programmers before procurement decisions are made. Future research should focus on quantitative validation through comprehensive Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) studies spanning multiple reuse cycles, empirical testing in real post-disaster environments in Indonesia, and the integration of Building Information Modeling (BIM) with design-for-disassembly principles. Multidisciplinary research that integrates technical, social, economic, and institutional dimensions is necessary to strengthen the implementation framework of reusable–reconfigurable TMS systems in disaster-prone regions.

AUTHOR CONTRIBUTIONS

Conceptualization, SNS and S; methodology, SNS, S, and FN; software, SNS and AM; validation, S, FN, and AM; formal analysis, SNS, FN, and AM; investigation, SNS and AM; resources, SNS and S; data curation, SNS and FN; writing—original draft preparation, SNS; writing—review and editing, S, FN, and AM; visualization, SNS and AM; supervision, S and FN; project administration, SNS; funding acquisition, SNS and S.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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