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DEVELOPING A CONCEPTUAL FRAMEWORK FOR PRELIMINARY SUSTAINABILITY ASSESSMENT OF EMERGING CONSTRUCTION MATERIALS

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Abstract

The construction industry is undergoing a profound transformation driven by concerns about sustainability, particularly the environmental impact of the materials used. Researchers are seeking to address such adverse impacts by introducing new sustainable construction materials; however, such emerging materials often lack clear criteria by which to verify claims about their sustainability. Traditional methods, including life cycle assessment (LCA), are comprehensive but present challenges, particularly in the early stages of development, in terms of information availability, complexity, and high resource requirements. In an attempt to mitigate these gaps, this paper proposes a simple framework for preliminary sustainability assessment of emerging construction materials, providing an accessible and easy-to-use tool for assessing sustainability claims. The three dimensions of this framework, environmental responsibility, economic viability, and social equity, provide a balanced view and identify key areas for assessment, including carbon footprint, embodied energy, resource efficiency, pollution management, life cycle cost, recyclability, market competitiveness, health and safety concerns, jobs, and societal benefits. By proposing a simplified and comprehensive framework that can be applied during the early stage of materials development where the limited data obstructs the assessment process, the proposed framework assists researchers in evaluating the sustainability of their newly developed materials and help in reducing uncertainties.

Keywords: *sustainable construction materials, sustainable construction, sustainability assessment*

1. Introduction

The construction industry is going through a period of transformation, driven by the need to address environmental, resource and technological issues. Central to this transformation is the principle of sustainability, a guiding principle for balancing environmental conservation, social equity and economic growth. Sustainable development means the ability to meet the needs of the present, but not at the expense of the ability of future generations to meet their own needs [1]. According to this general definition, and in the terms of the United Nations report Our Common Future, society, economy and environment need to be combined in three dimensions. While such general definition offer potential for application in many areas, it also creates ambiguity in that the criteria and indicators for achieving sustainability vary according to context.

In the context of the construction industry, sustainability involves processes and technologies that minimize environmental degradation, maximize resources, and improve social welfare. Sustainable construction aims to use environmentally friendly materials, use energy efficiently in buildings, and minimize waste over the life of the building. The purpose of these technologies is to avoid critical environmental issues such as greenhouse gas emissions, conserve natural resources, and mitigate the effects of climate change. Despite these goals, construction continues to degrade the environment. Globally, it uses 40% of natural resources, 40% of total primary energy consumption, consumes 15% of the planet's freshwater resources, produces 25% of the planet's waste, and produces 40–50% of greenhouse gases [2,3]. Such statistics demonstrate the need to move towards sustainable construction.

In response to this challenge, engineers and researchers are constantly exploring the possibility of producing "sustainable construction materials" as part of efforts to achieve sustainability in the construction sector. The construction materials play a critical role in achieving the overall sustainability of any construction project because they have a deep impact on the factors such as energy consumption and waste generation [4]. Generally, "emerging construction materials" can be classified into two broad categories in terms of their primary driving factors: "engineering-based materials" and "environmentally based materials" [5]. Engineering-based materials target specific technical challenges or performance improvements. For example, prestressed concrete has enhanced the efficiency of building structures, and fiber-reinforced polymers, initially developed for application in aerospace and marine engineering, are now being adopted worldwide in civil engineering to strengthen decks and bridges. On the other hand, environmentally based materials are emerging in response to growing environmental concerns. While the properties of emerging engineering materials can be relatively easily verified, assessing the sustainability of environmentally based materials is more challenging in the absence of globally agreed methodologies.

A well-established tool for assessing the environmental impact of construction materials is "life cycle assessment". LCA involves a thorough analysis of a material's footprint over its whole life, including extraction of raw materials, production, use, and eventual disposal [6]. "Cradle-to-grave" analysis is a basis for LCA and forms a key part of defining a whole range of material's environmental expenses. LCA takes into consideration factors such as energy consumption, greenhouse gas emissions, use of water, and creation of waste at each stage of its life cycle. LCA, in its utility, holds significant obstacles, most notably with new materials in early phases of development. First, LCA involves critical and reliable information, and such information is often not present and, in many cases, incomplete at development and experimental phases [7]. For example, a researcher developing new recycled concrete will not have information about its long-term durability, consumption of energy, and emissions generated during its processing. Therefore, LCA is a complex and time-intensive tool, and it takes sophisticated software, expertise, and complex analysis and calculation capabilities; therefore, it can discourage less experienced and less well-funded researchers. Lastly, diversity in terms of production processes and characteristics introduces an added level of complexity in its analysis. Variability in raw materials, processing, and geographical locations can cause discrepancies in LCA, and comparisons between different materials can become challenging [8].

Within the bounds of such restrictions, many developers involved in developing environmentally friendly materials face a significant lack of resources supporting their claims towards being sustainable, and therefore, may face a challenge in gaining acceptance for their innovations in the industry even when environmental improvements are significant [7]. As a result, there is a clear need for simplified and effective assessment methods that encourage innovation in sustainable construction materials development [9]. In the absence of available and reliable assessment tools, the need for a simplified conceptual framework for early-stage sustainability is evident. A more efficient and less resource-intensive alternative to full life cycle analysis would allow for an early initial assessment of sustainability at the early stages of materials development. In such way, a conceptual understanding of sustainability would be prioritized, with a focus on core concepts that represent its multidimensional aspects; environmental, economic, and societal; at the conceptual level.

2. Literature review:

Many researchers have studied sustainability in construction materials, and this section will review the most prominent studies that have contributed to developing the conceptual understanding of sustainability in building materials. The review will be in chronological order.

Trusty and Horst [10] pioneered the adaptation of sustainability assessment principles to local context by focusing on local factors such as local resource availability and local carbon emissions. In drawing out the importance of creating evaluation tools that captured effectively localized settings' specific traits, their work became a key starting point for such development.

Dasgupta and Tam [11] developed a multi-criteria decision analysis framework for the evaluation of sustainable building materials. Their model included environmental, economic and social dimensions including energy efficiency, cost and societal benefits. What was novel about their model was its participatory stakeholder nature, where architects and engineers not only defined the criteria but also weighed them, making the evaluation context-sensitive and flexible for use in a variety of settings, setting a precedent for a participatory stakeholder approach to materials evaluation.

Bakhom and Brown [12] proposed a sustainability scoring system (SSS) for evaluation of materials during their life cycle, with consideration of ten key factors such as embodied energy, durability, and social impact. In the study, it was emphasized that planning for sustainability at early stages is critical, for it is during such stages that long-term performance of a project is determined in a considerable manner through such choices. By connecting selection of a material with performance at a structural level, the authors emphasized an important role played by decision-support tools in supporting environmentally friendly practice in construction.

Akadire and Olumolaye [13] expanded the scope of sustainable materials assessment with 24 Sustainability Assessment Criteria (SAC) derived through literature review and expert surveys. The 24 factors were categorized under six factors; resource efficiency, life cycle cost, social benefit, performance capacity, waste reduction, and environmental impacts; and proposed a comprehensive system for materials selection.

Ding [14] examined the environmental consequences involved in the construction industry, with life cycle analysis (LCA) being an efficient tool for analysis of a material's life cycle. In spite of its acknowledged value, several application deficiencies, specifically in developing countries, have been discovered, such as persistent informational gaps. To counteract such weaknesses, he proposed starting localized LCA studies in a bid to bridge such gaps and promote worldwide environmental accountability in terms of choosing materials.

Some studies have been conducted with regards to worldwide tools for assessing the sustainability of buildings. Park et al. [15] examined the weaknesses of worldwide tools, such as LEED, BREEAM, and CASBEE. According to them, most such tools over-emphasize environmentally focused factors, sometimes at the expense of social and financial factors at times. In addition, they emphasized defects in application protocols in terms of suitability in a variety of worldwide regions. That criticism was re-emphasized in a study conducted by Kamali and Hewage [16], in which worldwide frameworks such as LEED and Living Building Challenge (LBC) have been criticized for not being adaptable enough for geographical diversity worldwide. Thus, such a study emphasized the role for combining several factors in a universally applicable model.

Obon and Henry [17] developed a model that integrates an analysis of a building's material sustainability with the United Nations Sustainable Development Goals (UN SDGs). According to them, such a model promotes factors such as embodied energy and reusability in addition to social factors such as creating jobs and workplace security.

Sahlola et al. [18] constructed a system dynamics model with an Analytic Hierarchy Process (AHP) for environmentally friendly selection of materials in construction. The model included factors such as life-cycle cost and waste generation, and its effectiveness was proven with case studies for concrete and wood materials. The study emphasized balancing social, environmental, and economic factors at early stages of selection of materials.

Wilson and Green [19] focused their studies on simplifying evaluation of new and emerging materials, with a high level of consideration for important environment-related factors such as embodied energy and pollution potential. Their model emphasized region suitability and integration, and reconciling complex assessments with real-time operational capacities.

3. Framework Development:

The conceptual framework developed in this study aims to provide a foundation for early-stage sustainability assessment of emerging construction. It is expected to support the challenges that researchers face when assessing new materials for which detailed data is missing. It offers a structured means of understanding and defining key concepts of sustainability, allowing common understanding by practitioners and researchers. In this regard, it is not intended for use as a definitive assessment tool but rather as a conceptual understanding and preliminary evaluation tool. Since its orientation is toward usability and adaptability, this framework will close the gap in theory and practice regarding the responsible development of sustainable construction materials.

As highlighted by Jabareen [20], a conceptual framework gives a logical shape to abstract ideas by relating the core concepts; the same notion is echoed by Ravitch and Riggan [21] who argue that conceptual frameworks are helpful in yielding some common research vocabulary, give a premise for collaboration, and eventually help make decisions. In this paper, the framework fills the gap that exists between theoretical concepts of sustainability and actual practices in the construction industry; hence, allowing the researchers to make a preliminary evaluation.

This framework was developed in a structured approach, combining the evidence from existing literature and aligning these onto the needs of early-stage assessments. The development process included the following steps:

- **Literature Review**: An extensive review of foundational studies was conducted aiming at identifying recurring themes and concepts relevant to construction material sustainability. This step ensured that the framework is underpinned by robust academic knowledge that reflects the changing agenda of sustainability research.

- **Identification of Core Concepts:** Key concepts of sustainability were looked for, emphasizing their broad relevance and applicability. These factors; environmental responsibility, economic viability, and social equity;

constitute the foundations of the framework. They are meant to be informative and flexible so that the framework is applicable in a broad array of contexts and projects.

- **Organization and Structuring:** The identified concepts were organized in a systematic way into a coherent, logical framework. Each of these concepts was contextualized to indicate their place in sustainability assessment, ensuring clarity and usability for researchers conducting preliminary evaluations by simplifying the core concepts into a set of guiding questions.

3.1. Identification of Core concepts:

The development of the conceptual framework for early-stage sustainability assessment of emerging construction materials starts with the identification of the pillars of sustainability. These are generally set, based on the literature on sustainability, as the necessary dimensions for the achievement of balanced and sustainable outcomes in various areas, including the construction sector. Their integration into the framework indeed guarantees a holistic approach to assess the sustainability of materials at their initial stages of development.

The selection of these three pillars is grounded in extensive academic research and reflects their centrality in sustainability discourse. First identified within the Bruntland Report [1], the pillars have gained quite widespread usage in models such as the Triple Bottom Line [22] that refers to the need for congruence within environmental, economic, and social dimensions.

- **Environmental Responsibility:** The environmental responsibility of construction materials emphasizes their minimization of ecological impact along the complete life cycle, starting from the extraction of raw materials through the degradation and disposals. Minimizing greenhouse gas emissions, conserving natural resources, and proper waste management are imperative in this pillar. This befits the principles set forth by the Brundtland Report of 1987, which has been a leading advocate for development that meets present needs without compromising the ability of future generations. The construction sector's contribution to global carbon emissions and resource depletion is highlighted in studies such as [2,6]; thus, the dire need for the adoption of environmentally responsible practices. Some of the metrics include carbon footprint, embodied energy, and resource efficiency, critical in ensuring that the materials contribute positively toward the attainment of global sustainability goals.
- **Economic Viability :**Economic viability focuses its attention to financial sustainability in construction materials such that they remain economically viable and competitive in terms of life-cycle costing. It integrates initial cost, operational and life-cycle costing, and life-cycle expenses, in a drive towards long-term cost-effectiveness. Economic viability is supported in approaches such as Elkington’s Triple Bottom Line, whose objective is a balance in terms of economic, environment, and social performance.
- **Social Equity** :Social equity covers the societal impact related to construction material impacts in terms of health, safety, and welfare. It assures equity in the distribution of resources and benefits so as to positively affect communities and workers. This pillar therefore aligns with the SDGs where there is a call for inclusion and fairness. For instance, in two independent studies, Kamali and Hewage [16] and Opon and Henry [17] social consideration is very vital in creating jobs, integrating cultures, and assuring the safety of workers. Deliberations on social equity ensure that beyond the meeting of material technical and environmental requirements, the material contributes to societal development.

3.2. Core Concepts of the Sustainability Assessment Framework

The three dimensions of sustainability were captured by a set of carefully chosen core concepts for the development of the sustainability assessment framework for emerging construction materials. Concepts are underpinned by an extensive review of relevant academic literature, with a focus on early-stage material evaluation applications. Three criteria have been kept in mind while selecting the concepts for the framework.

First, wide applicableness: Chosen concepts have a breadth such that they can apply to a variety of material types, and in most geographical locations. For instance, emphasis placed on resource efficiency and waste reduction ensures that even under resource-constrained situations, the concept can be utilized, such as with observations by Akadiri and Olomolaiye [13] and Franzoni [23]. Secondly, usability in practice: The framework was designed to be utilized both for researchers and for practitioners with no need for massive or complex sets of information, enhancing its utility in early stages of material development. In its approach, this is in line with that proposed by Ravitch and Riggan [21] and Wilson and Green [19] that conceptual tools must be simple to use, for only then can they be of greatest utility in practice. Thirdly, compatibility with worldwide move towards sustainability: Concepts utilized have a bearing with worldwide programs towards sustainability such as the United Nations Sustainable Development Goals to curtail carbon dioxide emissions, increase economic viability, and achieve social gain universally [17].

These criteria will, in return, enable the incorporation of clearly defined concepts of environmental, economic and social factors into a single framework that ensures an effective and integrated assessment of new construction materials. The core concepts of the proposed framework are explained below according to the three pillars of sustainability: Environmental Responsibility, Economic Viability, and Social Equity.

Environmental Responsibility

- **Carbon Footprint**: It assesses the overall greenhouse gas emissions for a material during its lifecycle. It considers emissions at raw material extraction, production, transportation, use, and disposal phases. Materials with less carbon footprint, including recycled aggregates or bio-based composite, closely comply with worldwide climatic objectives [8]. An effectively documented case is fly ash in concrete production, which lessens carbon emissions in comparison to conventional Portland cement [3].
- **Embodied Energy:** Embodied energy is defined as the overall energy utilized in producing and transporting materials. It involves direct and indirect use of energy such as using electricity and fuel in material extraction, processing, and delivery processes. Sustaining embodied energy can significantly minimize a project's environmental impact [12]. For instance, taking a local material and using renewable sources during fabrication accomplishes this purpose, as argued in work conducted by Finnveden et al. [7].
- **Resource Efficiency**: Resource efficiency addresses ideal use of raw materials and reduces wastage. Sustainable construction materials utilize renewable materials or off-cuts generated in industries such as slag and recycled glass [23]. Practices such as disassembly design and modular construction maximize resource efficiency through efficient reuse and recycling towards the end of a material life [5].
- **Pollution Management:** Pollution management addresses the reduction of pollutants produced during a material's production, use, and disposal phases. Examples include minimizing air emissions, controlling water pollution, and regulating hazardous wastes [8]. For instance, low-VOC (volatile organic compound) paint reduces poor indoor air and harmful emissions during use [16].

Economic Viability

- **Life-Cycle Costing (LCC):** Life-cycle costing assesses the full financial impact of a material, from production through disposal. In a systemic view, life-cycle costing identifies materials with higher initial expense but long-term savings in durability, less maintenance, or efficiency in terms of energy [13]. For example, high-performance insulation materials could have a higher price tag at first but yield significant savings in terms of energy over a period [14].
- **Recyclability and Reusability**: Recyclability and reusability prioritize financial gain through recovered and reused materials. For instance, steel is an efficient recipient of recycling, maintaining its integrity even through many cycles of reuse, and reduces cost in terms of managing waste and supporting circular economy [16].
- **Market Competitiveness:** Market competitiveness assesses whether or not sustainable material can compete with traditional alternatives in terms of price, performance, and availability. Incentives granted by governments, green labels, and innovation in terms of materials science often drive improvements in terms of acceptance in the marketplace, such as for cross-laminated timber (CLT) for use in structures [15].

Social Equity

Social equity focuses on the societal effects of construction materials to offer inclusion, health, and quality to workers, communities, and occupants. It incorporates ethical concerns in the selecting and use of materials.

- **Health and Safety:** This concept incorporates safety for workers and occupants by reducing risks in material handling, installation, and usage. For example, using non-toxic and low-emission materials, such as natural insulation products, enhances indoor air quality and reduces health hazards [16].
- **Job Creation**: Sustainable materials can generate employment in a local economy in the production, installation, and maintenance processes. Development of community and improvement of skill acquisition among local workers are also possible by encouraging the utilization of regionally sourced materials [17].
- **Community Benefits:** Community benefits represent harmony between materials and regional culture and climate. Locally adopted raw materials not only enhance regional customs but also ensure a superior contribution in terms of adorning and working construction works [24].

Figure (1) illustrates the proposed conceptual framework, which consists of three dimensions of sustainability: environmental responsibility, economic viability, and social justice. These three dimensions are then divided into core concepts that are most important in conducting a preliminary sustainability assessment of emerging construction materials. Each concept is then simplified by a guiding question that can be used to make initial assessments of materials, accompanied by conceptual links that describe why these questions are successful in understanding sustainability.

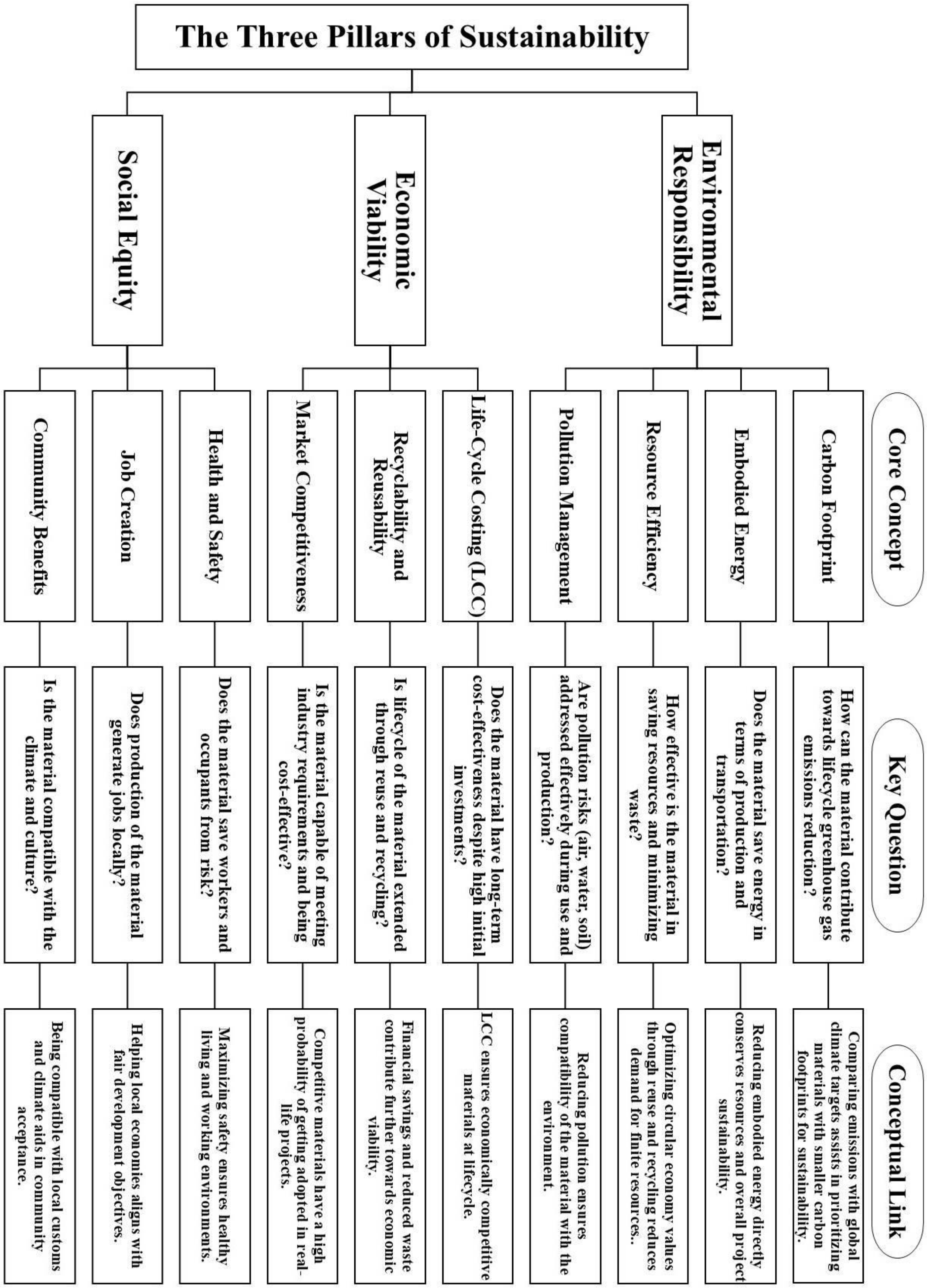

Fig. 1: The proposed conceptual framework for preliminary sustainability assessment of emerging construction materials.

4. Conclusions

The construction industry is under tremendous pressure to reduce its environmental impact and contribute to sustainable development. One of the most prominent ways to achieve this goal is to develop sustainable construction materials, but emerging building materials often face difficulties in verifying whether they are truly sustainable. The prevailing methodologies for assessing the sustainability of building materials, such as life cycle assessment (LCA), have their own set of limitations and sometimes become impractical and ineffective during the early stages of research when information is not readily available and complex. Instead, in this study, a conceptual framework for assessing the initial sustainability of emerging building materials is presented, which essentially includes three interrelated dimensions: environmental responsibility, economic feasibility, and social equity. This framework represents a simple tool for assessing materials at the early development stage, with balanced and integrated consideration of key indicators such as carbon footprint, life cycle cost, efficiency, and societal impact. In the future, case studies will need to validate the proposed framework and extend its adaptability for use with a range of materials. By contributing to the sustainable development of materials, it helps support the key role of construction in reducing its environmental footprint, improving efficiency in the economy, and enhancing social equity in construction processes.

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