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Derleme

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Sürdürülebilir Yapı Malzemelerinin Seçiminde Çevresel Etki Değerlendirmesi

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Öne Çıkanlar:

- Sürdürülebilir yapı malzemelerinin çevresel, ekonomik ve sosyal etkileri çok boyutlu olarak incelendi.
- Geri dönüştürülmüş, doğal ve yerel malzemelerin kullanımına yönelik değerlendirmeler sunuldu.
- Malzeme seçiminde yaşam döngüsü ve gömülü enerji kriterlerinin önemi vurgulandı.
- Uygulamadaki engeller ve çözüm önerileri (teknoloji, teşvik, farkındalık) tartışıldı.

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Amaç:
Bu çalışma, sürdürülebilir yapı malzemelerinin seçiminde çevresel etkilerin nasıl değerlendirileceğini analiz ederek, yapı sektöründe çevre dostu uygulamaların yaygınlaştırılmasına katkı sağlamayı amaçlamaktadır.

Yöntem:
Çalışmada ilk adım olarak, sürdürülebilirlik kavramının tarihsel gelişimini ve yapı sektörüyle ilişkisini daha iyi kavrayabilmek amacıyla, küresel ölçekte bugüne kadar atılmış tüm önemli adımlar ve temel kilometre taşları kapsamlı şekilde analiz edilmiştir. Bu çerçevede, sürdürülebilirliğin çevresel, ekonomik ve sosyal boyutlarıyla nasıl evrildiği ortaya konmuştur. Devamında, ScienceDirect, Google Scholar ve Web of Science gibi saygın veri tabanlarında “sürdürülebilir yapı malzemeleri”, “yeşil malzemeler”, “gömülü enerji”, “LCA” ve “çevresel etki değerlendirmesi” gibi anahtar kelimeler kullanılarak sistematik bir literatür taraması gerçekleştirilmiştir. Toplamda 81 akademik yayın değerlendirmeye alınmıştır. Bu yayınlar, sürdürülebilir malzeme kullanımı, yerel ve doğal kaynakların etkisi, yaşam döngüsü analizleri ve sürdürülebilirlik kriterleri başlıkları altında bütüncül bir yaklaşımla analiz edilmiştir.

Sonuç:
Sürdürülebilir malzemeler, yaşam döngüsü boyunca düşük enerji tüketimi ve karbon salımı ile çevreye duyarlı çözümler sunar. Geri dönüştürülmüş çelik, hempcrete, doğal lif takviyeli beton gibi malzemeler öne çıkmaktadır. Ancak yüksek maliyet, sınırlı erişim ve sektörel alışkanlıklar önemli engellerdir. Bu zorluklar, teknolojik gelişmeler, teşvik mekanizmaları ve farkındalık artırıcı politikalarla aşılabilir. Malzeme seçiminde sürdürülebilirlik artık isteğe bağlı değil, zorunlu bir kriterdir.

Anahtar Kelimeler: Sürdürülebilir Yapı Malzemeleri, Enerji Verimliliği, Yeşil Tasarım, Sürdürülebilir Yeniden Yapılanma, Çevre Dostu

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Review

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Environmental Impact Assessment in The Selection of Sustainable Building Materials

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Highlights

- The multidimensional environmental, economic, and social impacts of sustainable building materials were examined.
- Assessments regarding the use of recycled, natural, and local materials were presented.
- The importance of life cycle and embodied energy criteria in material selection was emphasized.
- Barriers to implementation and proposed solutions (technology, incentives, awareness) were discussed.

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Abstract: This study examines the use of sustainable building materials within the construction sector from a multidimensional perspective. As environmental threats intensify and natural resources become scarcer, sustainable materials are no longer a choice but a necessity. The study evaluates the environmental impacts of these materials throughout their life cycle and assesses their economic viability and social contributions. It also identifies key challenges to their adoption and proposes actionable solutions. The findings demonstrate that sustainable materials are not only environmentally friendly but also economically viable and socially beneficial. These materials serve as a fundamental element in shaping a future-oriented building paradigm and play a crucial role in achieving global sustainability goals.

Keywords: Sustainable Building Materials, Energy Efficiency, Green Design, Sustainable Reconstruction, Environmentally Friendly

1. Introduction

The primary objective of this study is to examine the role of sustainable building material selection in reducing environmental impacts and to evaluate how the use of sustainable materials can be more effectively promoted in the construction sector. The study begins by addressing the historical development of sustainability and its relevance to the building industry, followed by a discussion on how material selection should be guided by sustainability criteria. It then analyzes the environmental, economic, and social benefits of using materials derived from recycled and renewable sources.

Finally, green building certification systems and the multidimensional considerations in sustainable building design are discussed.

Before the Industrial Revolution, limited use of steam-powered machinery and population constraints due to wars and diseases kept environmental impacts relatively low.

However, the industrialization process that began in the early 1900s gained momentum especially after the **1970s**, leading to significant environmental degradation through increased fossil fuel consumption and uncontrolled urbanization [1]. Today, the growing impact of climate change and environmental degradation has made sustainable approaches essential, particularly in the building sector [2]. In this context, adopting sustainable methods in building design and construction is critical for reducing environmental concerns and developing structures that are compatible with ecosystems.

Sustainable construction requires the integration of eco-friendly components. This approach not only mitigates environmental impacts but also brings long-term economic and social benefits [3]. Given the carbon emissions and resource consumption caused by traditional construction materials, the use of sustainable materials has become a necessity rather than a choice [4]. Material selection is one of the most tangible indicators of a sustainable mindset. Engineers and construction professionals are expected to make decisions based on environmental impact, renewability, recyclability, and life cycle analysis [5]. Conscious use of natural resources, waste minimization during production, and ensuring energy efficiency are the core objectives of sustainable material management [6].

Materials derived from recycled and renewable sources support both environmental and economic sustainability [7]. These materials aid in waste management, reduce carbon footprints, lower greenhouse gas emissions, and minimize energy consumption [8]. Sustainable materials offer advantages not only during the production and construction stages but also by lowering maintenance costs during a building's service life. For this reason, construction professionals assess materials based on multiple criteria such as energy efficiency, life cycle costs, and occupant health. At this point, green building certification systems such as LEED provide valuable guidance [9].

Sustainable building design should also address multiple aspects such as climate resilience, water conservation, greenhouse gas reduction, wetland restoration, and public engagement [10]. These elements ensure not only environmental harmony but also long-term societal acceptance of buildings. Due to increasing environmental concerns, the use of sustainable materials is no longer optional but essential [11]. This necessity is not only about protecting nature but also about reducing costs and contributing to global sustainability goals [12].

Sustainability is not only an environmental concept but also encompasses economic development, social equity, and responsible resource management [13]. The most widely accepted definition was provided by the Brundtland Commission: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Definitions of sustainability emphasize its multidimensional nature and call for integrated approaches that include resource management, social well-being, and environmental protection [14-17]. This integrated perspective has influenced many disciplines, including architecture, urban planning, manufacturing, and energy systems.

The contributions of this study to the scientific literature can be evaluated from several perspectives. First, it provides a systematic review of existing knowledge on the selection of sustainable building materials and addresses parameters directly linked to the environmental impacts of the construction sector from a holistic standpoint.

Table 1. Key Milestones in Global Sustainability Efforts [24]

Year	Event / Document / Organization	Contribution / Description
1972	Club of Rome – The Limits to Growth Report	Warned about the unsustainable nature of economic and population growth on finite planet resources.
1972	UN Conference on the Human Environment (Stockholm)	First global environmental summit; introduced the idea of sustainable development.
1980	World Conservation Strategy	Integrated conservation and development; precursor to sustainability principles.
1987	Brundtland Report – Our Common Future	Defined sustainable development and addressed global environmental and economic challenges.
1992	UN Earth Summit (Rio de Janeiro)	Adopted Agenda 21, Rio Declaration, and principles of sustainability in global policy.
1997	Kyoto Protocol	First legally binding climate treaty to reduce greenhouse gas emissions.
2000	UN Millennium Development Goals (MDGs)	Set 8 global goals including environmental sustainability.
2002	World Summit on Sustainable Development (Johannesburg)	Reviewed Rio commitments; emphasized implementation and partnerships.
2012	Rio+20 Conference	Introduced the concept of the 'green economy'; led to the formation of SDGs.
2015	UN Sustainable Development Goals (SDGs)	Adopted 17 goals to achieve a better and more sustainable future by 2030.
2015	Paris Agreement (COP21)	Legally binding international treaty on climate change to limit global warming below 2°C.
2021	COP26 (Glasgow)	Emphasized net-zero targets, coal phase-down, and climate finance.
2022	Stockholm+50	Focused on environmental protection, climate change, and sustainability on the 50th anniversary of the 1972 Stockholm Conference.
2023	COP28 (Dubai)	Included the first official mention of fossil fuel phase-out; global stocktake initiated.
2024	COP29 (Baku, Azerbaijan)	Focused on carbon markets, climate finance, adaptation, and loss and damage frameworks.
2025	UN Sustainable Development Summit (New Delhi, India, March 5–7)	Assesses global SDG progress, proposes acceleration strategies, and reinforces 2030 Agenda commitments.

Second, it offers a practical evaluation framework for construction professionals by combining current trends in sustainable material management with the criteria of green building certification systems. The originality of this study lies in its comprehensive approach to sustainable material selection—not only from an environmental standpoint, but also by considering economic, social, and ethical dimensions.

The integration of these elements, which are often addressed separately in the literature, into a unified model distinguishes this work from previous studies and enhances its scientific contribution.

2. Historical Development of the Concept of Sustainability

Many of the environmental and social problems faced today stem from the long-term consequences of the industrialization process that accelerated in the 1970s, which were not sufficiently anticipated at the time [18]. Before the Industrial Revolution, factors such as the absence of steam-powered machines, population limitations due to wars, and relatively low levels of consumption helped keep environmental problems at a minimum [19].

However, over time, the diversification and expansion of industrial sectors, combined with rapid and unplanned urbanization, led to an irregular pattern of global growth [20]. This was accompanied by a rising population growth rate and increasing pressure on natural resources, resulting in serious disruptions to ecological balance [21].

In particular, the intensive use of non-renewable energy sources and natural raw materials has triggered a range of complex issues that threaten both nature and human life, including global warming, environmental pollution, and the loss of biodiversity [22]. These developments have made sustainability-oriented solutions unavoidable and have necessitated global cooperation [23].

In this context, under the leadership of the United Nations (UN), sustainability-focused research has been conducted at local, national, and international levels. Various conferences addressing environmental, economic, and social challenges have been organized. These meetings have played a crucial role in defining sustainable development goals and shaping environmental policies (see Table 1).

3. Components of Sustainability

Sustainability consists of three interrelated dimensions: environmental, economic, and social sustainability. These components ensure that sustainable development is addressed through a holistic approach [25].

- **Environmental Dimension:** Environmental sustainability is based on the conservation and renewal of natural resources. It aims to protect environmental heritage for future generations while also focusing on improving environmental values and maintaining the balance of natural ecosystems. Practices such as protecting biodiversity, reducing waste, and using renewable energy sources fall within this dimension [26].
- **Economic Dimension:** Economic sustainability focuses on creating income and employment opportunities to ensure the long-term economic well-being of societies. It involves planning economic activities in ways that do not harm natural resources, supporting local development, and using resources efficiently [27].
- **Social Dimension:** Social sustainability seeks to promote equality, justice, and

quality of life among individuals and communities. It includes ensuring access to essential services such as health care, education, security, and housing for all, as well as protecting gender equality and cultural diversity. This dimension aims to strengthen the social fabric of communities and enhance social cohesion [28].

When these three dimensions are considered together, sustainability emerges as a holistic approach that encompasses not only environmental protection but also economic development and social justice.

Figure 1 visually presents the key factors that make up each component, while Table 2 summarizes the main benefits of sustainability for society, the environment, and the economy.

While the concept of sustainability generally represents a holistic approach encompassing environmental, economic, and social dimensions, its tangible impacts are most

Table 2. Key Benefits of Sustainability

ENVIRONMENTAL BENEFITS	ECONOMIC BENEFITS	SOCIAL BENEFITS
Protection of ecosystems and enhancement of biodiversity	Reduction of operating costs	Improvement of air, thermal, and acoustic environments
Improvement of air and water quality	Increase in property value and income	Enhanced user comfort and health
Reduction of solid waste	Improved employee productivity and satisfaction	Reduced pressure on social infrastructure
Conservation of natural resources	Improved economic performance	Contribution to overall quality of life

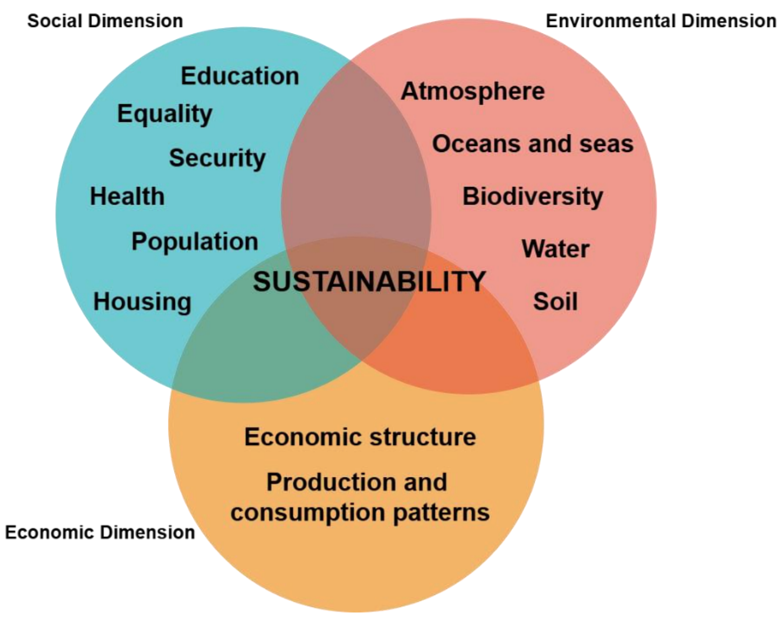

Figure 1. Key Factors of Sustainability Components (Haştemoğlu, 2006)

evident at the sectoral level [29]. In particular, the construction sector plays a critical role in sustainability due to its intensive use of natural resources, energy, and land [30]. Therefore, integrating sustainability principles into the construction industry is of great importance. One of the most effective ways to achieve this integration is by considering sustainability criteria in the selection of building materials [31]. The following section examines how building materials can help reduce environmental impacts while also contributing to long-term economic efficiency and social well-being.

4. Evaluation of Building Materials from a Sustainability Perspective

The concept of sustainable built environment refers to systems that can maintain their existence indefinitely without causing depletion of the resources that sustain them, and without any deterioration in their fundamental properties [32]. This approach aims for buildings to possess not only physical durability but also long-term environmental, economic, and social balance.

Sustainable building materials, on the other hand, are materials that consume minimal energy throughout their lifespan and do not harm the environment or human health at any stage—from raw material extraction, processing, use, maintenance, and repair to final disposal [33]. These materials are often referred to as "green building materials" and hold a significant place in today’s world, where natural resources are increasingly limited.

Green building materials contribute to sustainable development goals by minimizing environmental impacts [34]. Therefore, in the selection of building materials, it is essential to consider not only traditional criteria such as performance, quality, aesthetics, and cost, but also sustainability indicators [35]. In this context, the fundamental characteristics of sustainable building materials include the following:

- They do not contain toxic components and therefore pose no harm to human health [36].
- Their recyclable or reusable nature helps minimize waste generation [37].
- At the end of their useful life, they do not damage the natural environment [38].
- When sourced from local materials and producers, they reduce the carbon footprint and support the regional economy [39].

In assessing the environmental impacts of buildings, it is important to consider not only the properties of the materials used but also the entire life cycle of the building. The life cycle encompasses all stages from the extraction of raw materials, through the construction and usage phases, to the final demolition and disposal [40-42].

This life cycle can be examined in three main phases:

i. **Pre-construction Phase** – Involves raw material acquisition, production, and transportation processes [43].
ii. **Construction Phase** – Includes the construction process and the maintenance and repair activities carried out throughout the building’s lifespan [44].
iii. **Post-construction Phase** – Covers demolition, waste management, and recycling activities following the end of the building’s service life [45].

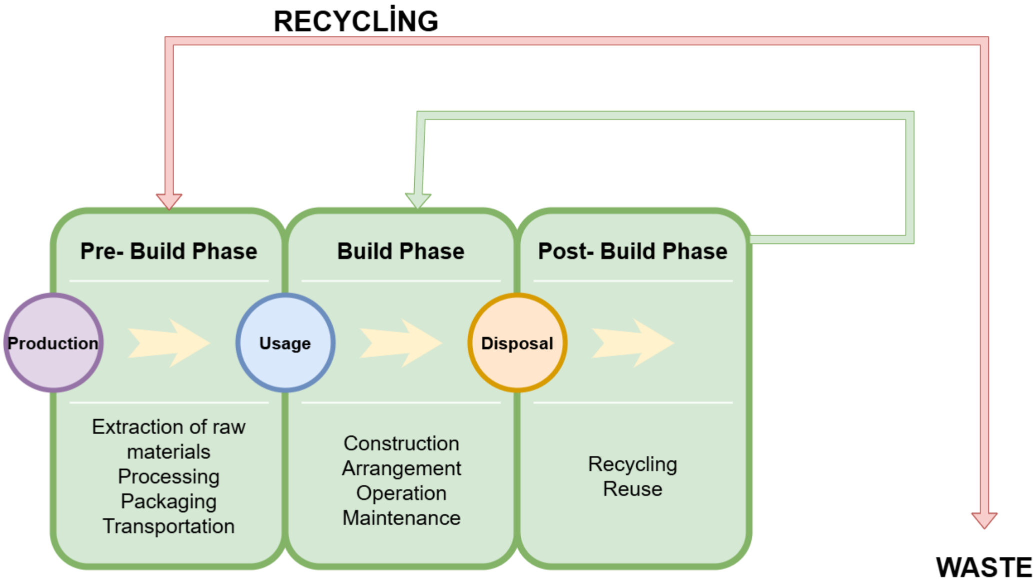

Figure 2.Life cycle of building materials [19]

The details of these three phases and the associated criteria for sustainable building materials are presented in Figure 2.

Adopting this cyclical approach in building design and material selection is of critical importance for reducing environmental impacts and ensuring the efficient use of resources. Sustainable built environment refers to the integration of sustainable development principles into the entire construction cycle of a building and its infrastructure—from the planning, design, and construction phases to the extraction and processing of raw materials, usage, demolition, and subsequent waste management. The initial step in this process involves improving the quality of building materials and enhancing the reliability and efficiency of construction practices. At the same time, environmental impacts, technological advancements, resource consumption, and socio-economic conditions must also be taken into account [46].

One of the primary goals in the construction sector should be to reduce resource consumption. In this context, applicable strategies may be implemented either directly or indirectly [47]. These strategies can be summarized as follows:

- **Reducing material waste:** Preventing material waste during construction offers both economic and environmental benefits. It contributes to the global reduction of construction waste, lowers overall costs, and helps make housing more affordable [48].

- **Use of recycled materials:** Effectively utilizing recycled materials in the construction sector is a powerful strategy for reducing environmental impacts. This approach offers numerous advantages, including the conservation of natural resources, reduced need for landfill disposal, lower energy consumption, and the prevention of pollution resulting from manufacturing processes. It also supports the development of more durable building materials [49].

Improving energy efficiency: Reducing energy consumption in buildings and minimizing the embodied energy of construction materials are key objectives.

Table 3. Sustainability Criteria [51, 52]

DIMENSION	CRITERIA
ENVIRONMENTAL	Is there a reduction in waste?
	Can air pollution be prevented?
	Is the produced material toxic to the environment?
	Does it reduce CO_2 emissions?
	Does it help preserve existing biodiversity in nature?
	Does the material have harmful effects on soil quality?
	Does the material absorb environmental odors?
	Is the produced material recyclable?
	Does it have high reusability?
	Can visual pollution be prevented?
	Does it prevent noise pollution?
	Is the amount of energy consumed low?
	Can it be obtained from natural and local resources?
	Can water pollution be prevented?
ECONOMIC	Can the energy consumed during transport and storage of raw materials be minimized?
	Can transportation costs be reduced?
	Is maintenance and repair easy?
	Is it durable and long-lasting?
	Does it enable the use of fewer materials in goods and service delivery?
SOCIAL	Is the material suitable for the social fabric of the region?
	Can it provide a healthy environment?
	Does the material ensure safety for humans?
	Does it meet housing needs?
	Can it support social balance such as education, cultural activities, suitable jobs, and homes?
	Does it support the local workforce?

Measures to achieve these goals include the adoption of alternative energy sources, enhancement of insulation systems, and increased efficiency in lighting and water heating systems [50].

- **Water conservation:** Efficient water use can be achieved through technologies such as rainwater harvesting systems, greywater reuse, water-saving fixtures, and automatic shut-off taps [51].

- **Durability and maintenance:** Ensuring that buildings are durable and long-lasting is critical to a sustainable construction industry. A structure's ability to maintain its performance throughout its service life should be considered from the design stage. Additionally, buildings should be adaptable and convertible to meet changing needs, maintenance costs should be optimized, and technologies that offer cost-effective solutions throughout the life cycle should be prioritized [52].

In the selection of construction materials, in addition to conventional parameters such as performance and cost, sustainability criteria must also be taken into account. These criteria are detailed in Table 3.

In line with this approach, the concept of embodied energy has emerged as a critical metric for evaluating the environmental impacts of building materials. Embodied energy refers to the total amount of energy consumed throughout all stages of a material's life—from raw material extraction to manufacturing and transportation. This concept enables a more holistic assessment of the overall environmental impact of materials [53].

Table 4 presents the embodied energy values (in MJ/kg) for various commonly used building materials. These values vary significantly depending on the type of material. For instance, a natural and minimally processed material such as adobe block contains only 0.47 MJ/kg, whereas structural steel, which requires high temperatures and energy-intensive processes, reaches up to 35.00 MJ/kg.This stark contrast clearly illustrates the influence of material selection on sustainability. For example, in the production of a structural element weighing 10 tons, using adobe blocks would require approximately 4,700 MJ of energy, whereas the same weight in steel would demand as much as 350,000 MJ—a more than 70-fold increase. Therefore, embodied energy values go beyond being mere numerical indicators and become strategic decision-making tools in the design phase, directly impacting the environmental footprint of a building [54]. The Victoria University of Wellington in New Zealand has provided the following embodied energy coefficients for selected building materials:

As illustrated in Figure 3, environmental considerations in sustainable material selection encompass a wide range of factors including health (e.g., air quality and reduction of VOCs), community impact (e.g., local sourcing and inclusivity), carbon footprint, energy efficiency, and life cycle aspects such as production, usage, and disposal.

Table 4. Embodied Energy Coefficients of Selected Building Materials (MJ/kg)

Material	Embodied Energy (MJ/kg)
Adobe block	0.47
Concrete block/brick	0.94
Ceramic brick	2.50
Glazed brick	7.20
Cement	7.80
Glass	15.90
Steel (structural)	35.00

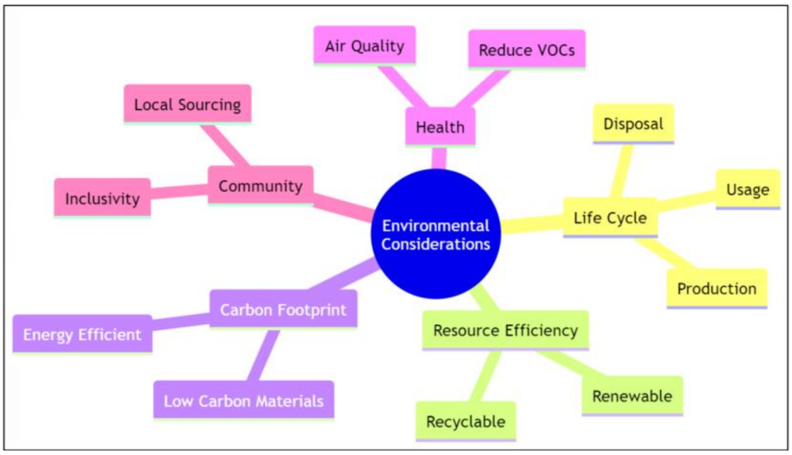

Figure 3. Environmental Assessments of Sustainable Materials

Figure 4. Economic Benefits of Sustainable Materials

The figure highlights how these interconnected elements contribute to resource efficiency and environmental Sustainability [55].

As illustrated in Figure 4, the economic benefits of sustainable materials are multifaceted. In addition to technical advantages such as energy efficiency, low maintenance costs, long-term savings, and durability, external factors like government support, increasing market demand, and regulatory policies also contribute to the financial attractiveness of sustainable materials. Although they may have a high initial cost, the decreasing cost of materials over time and the competitive edge they offer support the widespread adoption of sustainable built environment practices [56].

5. Challenges and Proposed Solutions

The adoption of sustainable materials in building design and construction brings with it a number of significant challenges. One of the most prominent obstacles is the limited availability of such materials—an issue that is particularly evident in regions where sustainable practices have not yet been fully integrated into supply chains [57]. Although these materials are highly favored for their renewable and recyclable nature, the lack of widespread accessibility leads to increased costs, rendering them unaffordable for many construction projects [58].

The potential of sustainable materials to reduce greenhouse gas emissions and other environmental harms has been scientifically demonstrated. However, their high costs and limited supply often deter construction companies and developers from using them on a large scale [67]. Furthermore, the construction industry has traditionally relied on conventional methods and materials. Industry leaders and practitioners often show reluctance to move away from these traditional approaches, making the integration of sustainable materials into mainstream construction practices more difficult [58].

One of the key solutions to these challenges lies in the continuous advancement of technology. Technological innovation plays a crucial role in lowering the cost and improving the availability of sustainable materials [59]. For instance, developments in materials science and manufacturing processes can reduce the carbon content of construction materials, allowing for the creation of more environmentally friendly products while also enabling more cost-effective production [60]. Additionally, improvements in supply chain logistics could facilitate the distribution of these materials to regions where they are currently scarce. This would help reduce overall costs and make sustainable materials a more competitive alternative to traditional ones [59]. Moreover, advances in technology are expected to enhance the quality and durability of sustainable materials, making them more suitable for long-term building projects.

Another effective approach to overcoming resistance in the construction industry is raising awareness about the long-term benefits of sustainable materials. Industry leaders and practitioners need to be informed about the financial, environmental, and social advantages of these materials, as many still lack sufficient knowledge regarding the potential cost savings and increased property value associated with sustainable building practices [61]. This awareness can be enhanced through industry conferences, educational programs, and collaborations with environmental organizations that advocate for sustainable built environment practices.

Moreover, public policies and government incentives can play a crucial role in accelerating the widespread adoption of sustainable materials. Regulations that mandate the use of such materials in certain types of construction projects, as well as financial incentives for developers who meet sustainability criteria, can encourage the industry to embrace these materials more broadly [62]. Such policies help alleviate cost-related concerns and foster broader acceptance of sustainable materials across the construction sector.

6. Investigation of Building Materials According to Sustainability Criteria

Within the scope of sustainable building design, various applications have been developed to reduce environmental impacts, increase energy efficiency, and minimize the use of natural resources. In this context, the use of local, natural, and recycled materials provides significant environmental and socioeconomic benefits. Utilizing locally sourced materials helps reduce energy consumption associated with transportation and production, while also supporting local employment and contributing to regional development [63].

6.1 Recycled-Based Building Materials

Recycling is one of the fundamental components of the green building approach. Reusing waste construction materials allows for the conservation of natural resources, and the reduction of mining activities and environmental pollution. In particular, reprocessing demolition debris into recycled concrete bricks is an effective method for decreasing both energy consumption and waste generation [64].

6.2 Fiber-Reinforced Concrete Applications

Fiber-reinforced concrete, obtained by adding natural or synthetic fibers to the concrete matrix, exhibits superior properties in terms of tensile strength, crack resistance, and overall durability. These concretes are especially preferred in structures exposed to harsh environmental conditions, such as marine structures, bridges, and industrial floors. Concrete reinforced with natural fibers derived from coconut, bamboo, or even human hair presents compelling alternatives from an environmental sustainability perspective [65].

6.3 Alternative Brick and Block Systems

Numerous natural and low-energy materials have been developed as alternatives to conventional bricks and blocks used in the construction sector:

- **Sandbag construction systems** involve stacking polypropylene or geotextile bags filled with locally available sand, offering an economical and eco-friendly building method [66].
- **Adobe bricks** are traditional building materials produced by mixing earth and water and drying them in the sun, based on local production and low energy consumption [67].
- **Compressed Stabilized Earth Blocks (CSEB)** are structural elements produced using modern stabilization techniques and are advantageous due to minimized transportation costs via on-site production [68].
- **Compressed sand bricks**, produced from a mixture of river sand and cement, are suitable in regions where proper soil is not available [69].
- **Hydraform bricks**, made by hydraulically compressing soil mixtures with a small amount of cement, are notable for their low embodied Energy [70].
- **Fly ash bricks**, manufactured by converting industrial waste from thermal power plants into cement-based bricks, offer a low-cost alternative, albeit with limited areas of application [71].

6.4 Natural and Renewable Resource-Based Building Materials

- **Hempcrete** is a lightweight, breathable, and highly thermally insulating natural building material made from a mixture of hemp hurds and a lime-based binder [72].
- **Bamboo**, due to its high tensile strength and rapid growth rate, can be used as a structural component in sustainable built environment [73].

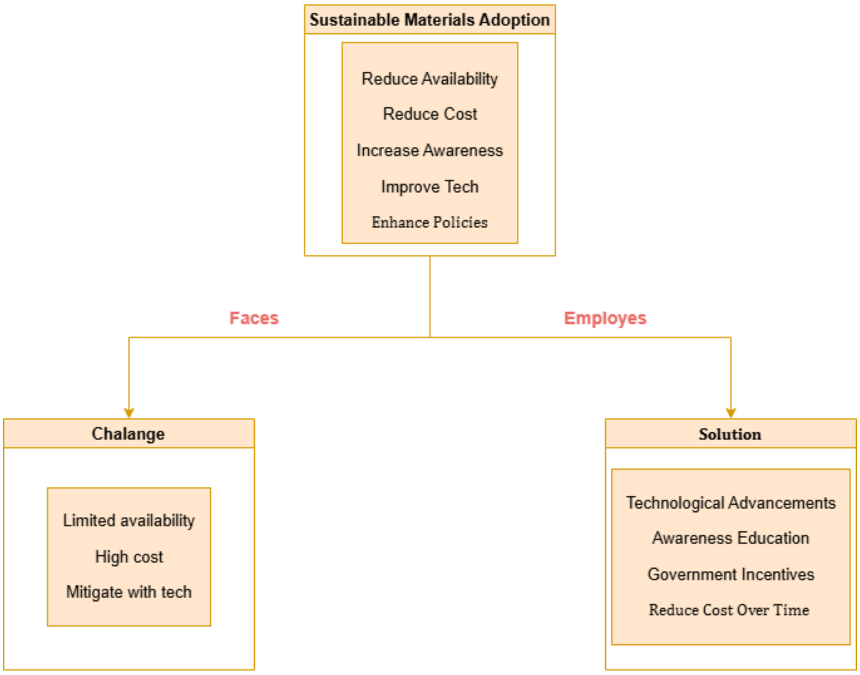

Figure 5. Challenges and Solutions in the Adoption of Sustainable Materials

- **Straw bales** are a low-cost solution commonly used for insulation, particularly in rural areas, and enable the reuse of agricultural waste [74].

6.5 Other Sustainable Material Approaches

- **Recycled aggregates**, obtained by reprocessing construction and demolition waste, are commonly used in infrastructure applications such as backfilling and concrete production [75].
- **Recycled plastics** provide durable and long-lasting solutions in areas such as flooring systems and piping [76].
- **Low-VOC paints**, which emit minimal volatile organic compounds, contribute to indoor air quality and are considered user-health-friendly sustainable materials [77].
- **Natural and recycled insulation materials**, including cellulose, sheep wool, cork, and cotton, offer environmentally friendly options that improve energy Efficiency [78].

These examples demonstrate that sustainability in the construction sector involves more than just energy-efficient design strategies—it is also directly influenced by material selection. Utilizing local resources, reusing waste materials, and opting for natural-based products not only help reduce environmental impacts but also contribute to long-term economic and social sustainability. For instance, natural-based materials like hempcrete are notable for their low energy requirements during production and their capacity to sequester carbon. Likewise, industrial by-products such as fly ash can be repurposed into building materials, reducing waste and preserving natural resources. Additionally, natural fiber-reinforced concretes offer eco-friendly alternatives to traditional reinforced concrete. In this context, material choices clearly play a critical role in achieving holistic sustainability in building design and construction.

7. Discussion

The environmental benefits of sustainable materials in the construction sector are substantial. Numerous studies have employed the Life Cycle Assessment (LCA) methodology to evaluate the environmental impacts of various materials. These assessments typically consider parameters such as carbon footprint, resource depletion, and energy consumption. The findings indicate that sustainable materials such as recycled steel, low-carbon concrete, and bamboo can reduce greenhouse gas emissions by up to 50% compared to conventional materials like traditional concrete and steel [79]. One notable study revealed that buildings constructed using recycled steel generated 30% less waste and emitted 35% less CO_2 over their life cycle. Furthermore, renewable materials such as wood and cork have been shown to make significant contributions to resource conservation, as these materials can regenerate faster than their rate of consumption [80].

As illustrated in Figure 6, environmental benefits account for the largest share (45%) among the key aspects considered in the evaluation of sustainable building materials. This indicates that reducing environmental impacts—such as greenhouse gas emissions and resource depletion—remains the most critical driver for the adoption of these materials. In comparison, economic advantages represent 25% of the total, highlighting the growing recognition of cost savings, energy efficiency, and long-term value in sustainable construction practices.

Another key environmental advantage of sustainable materials is their energy efficiency, particularly during the production and end-of-life phases. Materials that require less energy for manufacturing, transportation, and recycling such as locally sourced timber contribute to a substantial reduction in the overall carbon footprint of buildings [79].

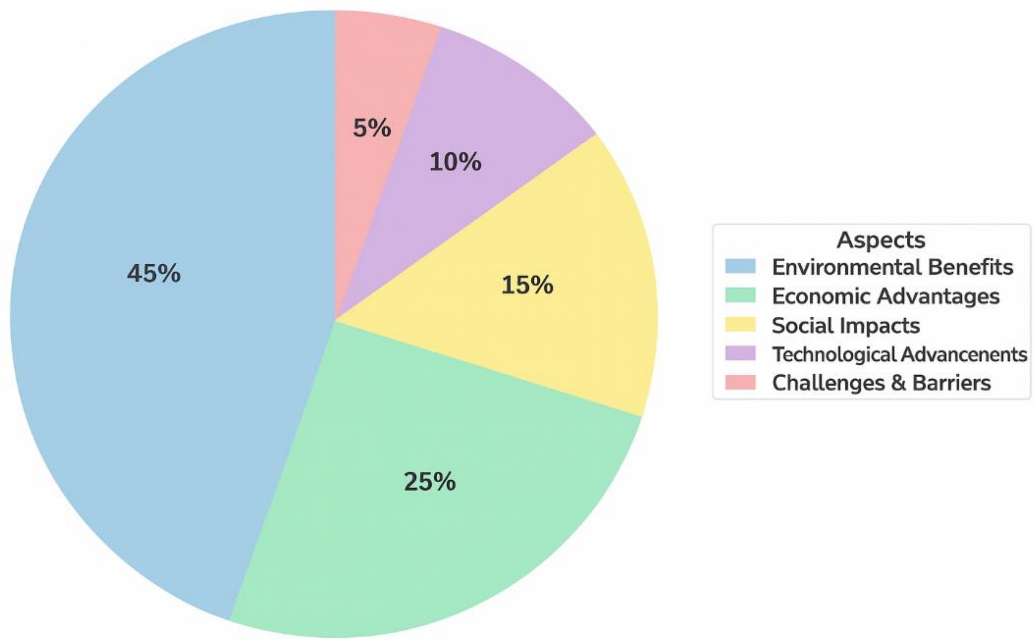

Figure 6. Key Impacts of Sustainable Materials on Building Design [80]

Social impacts constitute 15% of the considerations, emphasizing how sustainable materials contribute to occupant well-being and public health. Technological advancements (10%) and challenges & barriers (5%) are also acknowledged, reflecting the necessity for innovation and policy support to address limitations in adoption.

There is substantial evidence supporting the environmental, economic, and social benefits of using sustainable materials in building design and construction. These materials play a critical role in reducing greenhouse gas emissions, conserving natural resources, and enhancing the health and well-being of building occupants [81].

However, factors such as cost, accessibility, and structural performance pose significant barriers to their widespread adoption.

The data suggest that while environmental and economic gains are well recognized, overcoming the remaining challenges represented by the smallest portion in Figure 6 requires coordinated efforts through technological innovation, regulatory frameworks, and increased stakeholder awareness.

8. Conclusion

The use of sustainable materials in building design and construction provides significant environmental, economic, and social benefits. The findings confirm that materials such as recycled steel, bamboo, and low-carbon concrete can substantially reduce greenhouse gas emissions and contribute to the conservation of natural resources. Life Cycle Assessment (LCA) emerges as a critical tool for analyzing environmental impacts.

From an economic perspective, although the initial costs of sustainable materials may be higher, their long-term advantages include reduced operational expenses, energy savings, and lower maintenance requirements—making them cost-effective over time. Socially, the use of sustainable materials enhances indoor air quality, reduces health risks associated with toxic emissions, and improves the well-being of building occupants. Furthermore, the use of locally sourced materials supports community engagement and promotes local economic development.

However, challenges still remain—particularly in developing regions where issues such as cost and limited accessibility are more pronounced. To overcome these barriers, technological innovations, government incentives, and stronger legal and regulatory frameworks are of critical importance.

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