ADVANCEMENTS IN SUSTAINABLE BUILDING MATERIALS: RECYCLING AND REUSE

Olugbenga Babajide SOYEMI and Victoria Abiola IMASUEN
Department of Civil Engineering, The Federal Polytechnic, Ilaro
jidesoyemi@federalpolyilaro.edu.ng and victoria.imasuen@federalpolyilaro.edu.ng

Abstract
The construction industry has a substantial negative impact on the environment due to its large resource consumption and waste creation. Sustainable building approaches are essential to reducing this impact. With a focus on the critical responsibilities of reuse and recycling, this study explores recent developments in ecologically friendly building materials. We show how sustainable substitutes like bio-based composites, salvaged wood, and recycled concrete aggregates can help a circular economy by examining cutting-edge materials and technologies in this area. Forests are preserved, and existing materials are repurposed when using salvaged wood, while bio-based composites made from renewable resources provide environmentally responsible alternatives with superior insulating qualities. Waste is kept to a minimum, and the need for natural aggregates is decreased by using recycled concrete aggregates made from damaged concrete buildings. The study emphasises how crucial it is to incorporate these environmentally friendly materials into building techniques in order to minimise resource usage, encourage long-term sustainability, and lessen ecological footprints. We highlight how the utilisation of recycled and repurposed materials can revolutionise construction methods by optimising resource utilisation and reducing ecological footprints. This study also examines the potential and obstacles related to the use of sustainable materials, such as legal restrictions, technological hurdles, and financial considerations. The construction sector may move towards more sustainable practices and help international efforts to achieve environmental sustainability and resource conservation by tackling these concerns through ongoing innovation and supportive regulations.
Keywords: Concrete, Construction Waste, Reuse, Green Environmental Protection, New Materials.

Introduction

As one of the biggest users of natural resources, the construction industry has a huge impact on environmental deterioration due to its high energy consumption, massive material extraction, and enormous waste production. Materials used in traditional construction, such as steel, glass, and concrete, go through energy-intensive and environmentally harmful procedures. The need for building materials is growing due to the quickening rate of urbanisation around the world, which makes sustainable options desperately needed. Examining how recycled and repurposed materials might help promote the circular economy and sustainable building practices is the focus of this research. Construction companies can lessen their environmental impact, save resources, and cut down on waste by using materials like recycled concrete aggregates, recovered timber, and bio-based composites. These environmentally friendly materials not only reduce negative effects on the environment but also increase the longevity and efficiency of building projects, encouraging a change to more conscientious and environmentally friendly building practices (Ashby, & Johnson, 2013; Kumar, *et. al.,* 2017; Sharghi, & Jeong, 2024).

The progress in sustainable building materials centres on the utilisation of recycling and reuse methods to diminish the environmental consequences, save natural resources, and establish more eco-friendly and effective construction techniques. Conventional building techniques often include the extraction and use of pristine materials, which contribute to the depletion of forests, loss of habitats, and significant release of carbon emissions (Calkins. 2008; Mateus, *et. al.,* 2010; Giesekam, *et. al.,* 2014). On the other hand, forward-thinking materials and methods prioritise sustainability via the process of recycling and reusing waste goods, with the aim of reducing the depletion of resources and minimising environmental damage. The growing focus on recycling and reuse in order to lessen the environmental impact of construction activities is a major factor driving the growth of sustainable building materials. Conventional building materials produce a significant amount of waste and pollution since they are frequently made from non-renewable resources. Modern sustainable materials, on the other hand, emphasise resource efficiency and a decrease in carbon footprints (Xiao, & Ding, 2014). Repurposed metals, reclaimed wood, and recycled concrete are examples of innovations that cut down on landfill trash while simultaneously lowering the demand for virgin materials. Buildings' lifespan sustainability is further supported by developments in material technology, such as bio-based composites and green insulation. Regulations and green certification programmes that encourage the use of environmentally friendly materials are supporting these efforts and causing a shift in construction practices towards more sustainable ones (Thomas, 2019).

Gao, (2023) had an extensive analysis on the current patterns in using waste resources for the purpose of producing concrete, emphasising their crucial contribution to the progress of sustainable building methods. A comprehensive comparative examination of several waste materials, including fly ash, slag, and recycled aggregates, to assess their influence on the characteristics and effectiveness of Concrete. He also introduced pioneering case studies, such as the use of repurposed glass and plastic waste in concrete, illustrating practical implementations of these environmentally-friendly methods. In addition, the assessment examines technical aspects, technological breakthroughs that enable the effective processing and incorporation of waste elements into concrete. The primary emphasis was on striking a balance between the environmental advantages and the technical, economic, and social difficulties that come with implementing these sustainable measures. The review highlights the need and possibility of using waste materials into the manufacturing of concrete, offering analysis of future trends in sustainable building.

Almusaed, *et. al.,* (2024) examines how recycled building materials might reduce construction sector greenhouse gas (GHG) emissions and energy usage. We evaluate the environmental effect of these materials throughout their lifespan using Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) in the circular economy paradigm. We found that using recycled materials in constructing may cut greenhouse gas emissions and save energy, therefore the future looks bright. They are crucial to promoting sustainable construction methods. Our study also emphasises the relevance of robust regulatory frameworks and technological advances in encouraging environmentally sound activities. Policymakers, industry stakeholders, and academics should collaborate to promote a circular economy in building. Our work contributes to sustainable building discourse by giving evidence-based insights that may inform construction industry environmental stewardship policies and operations. This study supports the European Union's 2030 aim of climate-neutral cities and the UN's 2030 Sustainable Development Goals. This research provides a factual basis for sustainable building rules and attempts to improve environmental stewardship.

The development of sustainable building materials that prioritise recycling and reuse provides substantial advantages in waste reduction, preservation of natural resources, and reduction of the carbon footprint associated with construction (Ngayakamo, & Onwualu, 2022). By incorporating these materials into construction procedures, the construction industry may aid in the advancement of sustainable urban development, advocate for circular economy concepts, and facilitate the worldwide shift towards greener and more resilient cities.

Methodology

The approach that was used for this study is intended to conduct an in-depth investigation and analysis of the practices of advancements in sustainable recycled and reused building materials within the built environment, with a particular emphasis on the potential of these activities to improve sustainability. The strategy that was used incorporates a comprehensive review of existing literature and construction reports in order to get a full grasp of the topic at hand.

Environmental Impact of Construction Materials

Steel, glass, and concrete are examples of traditional construction materials that have substantial detrimental consequences on the environment. These effects include the loss of habitats, pollution, and the depletion of sources of resources (Gibbs, & O'Neill 2015). Additionally, the mining, processing, and disposal of these minerals are all included in these operations. Approximately eight percent of the world's carbon dioxide emissions are caused by the manufacture of cement, which is an essential component of concrete. This is due to the fact that the production process for cement is very energy-intensive. On the other side, sustainable building materials aim to lessen the impact of these unfavourable outcomes by using renewable resources, implementing manufacturing techniques that are more energy-efficient, and enhancing the longevity of their performance. For instance, bio-based composites, which are created from plant fibres and agricultural waste, provide a sustainable alternative to traditional materials. Furthermore, advancements in recycling technology make it possible for commodities like as steel and concrete to be reused in an efficient manner, hence reducing the need for virgin resources (Chen, *et. al.,* 2024). In addition, sustainable materials are designed to have a longer lifespan, which lessens the impact on the environment caused by the need for replacement and the associated costs. In accordance with the overarching goals of environmental sustainability and climate change mitigation, these technologies not only contribute to the reduction of the carbon footprint of the construction sector, but they also support the conservation of resources and the reduction of waste.

Circular Economy in Construction.

The circular economy in construction is a strategy that aims to minimise waste and optimise resource efficiency by re-evaluating the whole life cycle of building materials and structures. The circular economy diverges from the conventional linear paradigm of "take, make, dispose" by prioritising the creation of structures that are durable, flexible, and can be dismantled in the future. This approach allows for the reuse, recycling, or repurposing of resources instead of just discarding them (Pomponi, & Moncaster, 2017). This method entails using sustainable resources, such as recycled aggregates or bio-based goods, together with novel building processes that provide effortless disassembly and material retrieval (Ngayakamo, & Onwualu, 2022). The circular economy in construction helps to decrease the environmental effect of building operations, save costs, and promote a more sustainable and resilient built environment by encouraging material loops, decreasing dependence on new resources, and minimising waste.

Advancement in Recycled Building Materials

The construction industry has been greatly influenced by the development of recycled building materials, leading to increased sustainability and less environmental impact. Advancements in recycling technology have expanded the capacity to efficiently repurpose and reuse a broader spectrum of materials, including concrete, steel, wood, plastics, and glass, in new building projects. Recycled concrete aggregate (RCA) is now being used as a replacement for virgin aggregate in concrete mixtures, although recycled steel retains its strength and durability for structural purposes. Currently, there are increasing techniques for transforming waste plastics into long-lasting building materials, such as composite timber and roofing tiles. In addition, designers are using materials such as shattered glass and repurposed wood into their designs due to their distinctive aesthetic properties and lower carbon emissions. These developments not only help to save natural resources and minimise waste, but also decrease the energy consumption and emissions related to the production of new building materials. As a result, they contribute to more environmentally friendly and economically efficient construction methods.

Recycled Concrete Aggregates (RCA)

Recycled concrete aggregates (RCA) are created by the processing of concrete obtained from destroyed structures and their integration into new concrete mixes, providing a sustainable substitute for natural aggregates. Recent technological improvements have greatly improved the quality and longevity of RCA, making it a feasible and competitive choice in the field of building. Advanced crushing and screening techniques are used to guarantee that the recycled aggregates satisfy the necessary criteria (Pacheco-Torgal, & Jalali, 2010; Lewis, & Preston, 2018). Additionally, chemical treatments may be used to enhance their performance by addressing concerns about strength and durability. These advancements enhance the material characteristics of RCA and also help to decrease the ecological footprint of concrete manufacturing by minimising waste and the need for new aggregates. This promotes a construction sector that is more sustainable and efficient in its use of resources.

Repurposed Wood

Utilising reclaimed wood from retired buildings and bridges not only provides a sustainable substitute for new wood, but it also makes a substantial contribution to the conservation of the human habitat (Cross & Warwick, 2008). Recent technological improvements have enabled the use of recovered wood in many applications such as cladding, flooring, and structural components. By using contemporary methods like kiln drying, cleaning, and milling, salvaged wood is guaranteed to surpass existing building standards. These procedures specifically target issues related to bugs, mildew, and the structural integrity of the object. Utilising recycled wood in modern construction not only decreases the need for new timber but also contributes to the conservation of forests. Furthermore, including used wood in current architectural projects imparts a distinctive character and emphasises their historical significance (Diarte, *et. al.,* 2019; De Vass, *et. al.,* 2023). Builders may use recycled wood to create structures that are visually appealing and have positive environmental impacts. This enables builders to show respect for the historical significance of the material while also promoting sustainable development practices.

Glass and Metal Recycled

Recycling building and demolition trash reduces the energy and raw material demands needed to make glass and metals. Recycling reduces the requirement for virgin materials. Recycled glass and metals have improved in quality and building usefulness due to advances in sorting, cleaning, and melting (Glass, & Dyer, 2020). New technology enabled these advantages. Cutting-edge sorting machinery removes pollutants entirely, resulting in purer recycled materials. Improved cleaning methods make it simpler to remove impurities that might affect material performance. Improvements in melting technologies have made it possible to efficiently reprocess recovered metals and glass, ensuring that these materials meet high industrial standards for strength, durability, and aesthetic appeal. Since recycled materials may be utilised for decorative treatments, facades, structural components, and insulation, they promote environmentally friendly building. This is because they have several uses. The construction industry helps create a circular economy by using recycled glass and metals, which conserves resources and reduces greenhouse gas emissions. Mostly because the circular economy relies on recycled resources.

Advances in Reusable Construction Materials

Advancements in reusable building materials are driving a shift towards more sustainable construction practices by focusing on materials that can be easily recovered and reused at the end of a building's life cycle. Modern design principles, such as modular construction and design for disassembly, are enabling components like steel beams, precast concrete panels, and structural timber to be reused in new projects with minimal processing. Innovative materials like cross-laminated timber (CLT) and engineered bamboo are designed for easy deconstruction and reuse, reducing waste and conserving resources. Additionally, systems such as prefabricated building modules and reversible connections allow entire sections of buildings to be relocated or repurposed without demolition. By integrating these reusable materials into construction, the industry reduces its dependence on virgin resources, minimizes waste, and lowers both the environmental footprint and costs, ultimately supporting a circular economy where materials are continuously cycled back into use (Generalova, *et. al.,* 2016; Novakova, & Sal, 2019; Charef, *et. al.,* 2021; Yakimchuk, *et. al.,* 2023).

Modular Building Elements

The benefits of modular building pieces, which are manufactured away from the construction site to facilitate assembly, disassembly, and reutilization, have been emphasised due to developments in reusable construction materials. This strategy significantly reduces construction waste by minimising on-site cutting and disposal. Additionally, it enhances efficiency by facilitating accurate production in regulated environments. Architects have more freedom to be creative when employing modular construction since its components may be quickly reconfigured, modified, or adjusted to fit evolving demands and design criteria (Generalova, *et. al.,* 2016). Contemporary modular systems are suitable for a range of applications, such as residential and commercial buildings, as well as educational and healthcare institutions. These advancements are achievable via the use of cutting-edge materials and technology that ensure the durability, heat efficiency, and visual appeal of the structures. Due to their robust construction and ability to endure diverse climatic conditions, these systems also promote sustainability. By using modular building components, the construction industry may achieve accelerated project timetables, reduced prices, and improved environmental performance, all while maintaining better quality standards and design flexibility (Liew, & Richard, 2018; Yakimchuk, *et. al.,* 2023).

Materials Based on Biotechnology

The term "biotechnology-based construction materials" refers to new materials that are produced from biological processes or derived from renewable resources like plants and agricultural waste. These materials are meant to improve the environmental performance and sustainability of building practices (Van Acker, *et. al.,* 2017). Among these materials are bio-based composites, which include mycelium (fungus-based) insulation and bricks. These materials are created with the help of fungal networks and organic waste, and they provide an alternative to traditional materials that is not only lightweight but also fire-resistant and biodegradable. Both algae-based bioplastics and bio-concrete, which integrates bacteria that create limestone to self-heal fractures, provide solutions that are long-lasting, renewable, and lower the carbon footprint of the building industry. Furthermore, bio-cements that are produced from microorganisms have the ability to bind soil particles or aggregate, so lowering the need for conventional cement, which requires a significant amount of energy to make. These biotechnology-based materials have the potential to cut greenhouse gas emissions, minimise resource consumption, and produce buildings that are more responsive to climate change. Additionally, they can promote a healthier and more sustainable built environment by using natural processes. Two examples of these cutting-edge materials are bio-composites, such as hempcrete and mycelium-based products (Malabadi, *et. al.,* 2023). Hempcrete is made from the woody core of the hemp plant mixed with lime and is praised for its excellent insulation properties, lightweight nature, and carbon sequestration capacity (Novakova, & Sal, 2019).

Adaptive Reuse of Buildings

Repurposing old buildings for new purposes while preserving its historic, cultural, or architectural importance is the approach that is referred to as adaptive reuse of buildings (Bullen, & Love, 2011). In adaptive reuse, rather than tearing down existing buildings, the emphasis is on refurbishing and changing them so that they may serve new roles. For example, factories can be converted into residential lofts, warehouses can be converted into offices, and churches can be transformed into community centres (De Silva, *et. al.,* 2019; Arfa, *et. al.,* 2022). By minimising the need for new building materials, this strategy helps to save resources. Additionally, it decreases the amount of garbage generated by demolition, and it often helps to retain the distinctive personality and legacy of the built environment. Through the revitalisation of underutilised areas, the reduction of urban sprawl, and the enhancement of the economic viability of neighbourhoods, adaptive reuse is another method that contributes to sustainable urban development. Owojori, *et. al.,* 2021 strike a balance between preserving cultural traditions and preserving the environment, which is an innovative answer to the issues that contemporary cities face.

Difficulties and Possibilities

To promote sustainability in the construction sector, it is crucial to prioritise the use of building materials that can be recycled and reused. However, despite the presence of positive advancements, the transition brings along its own distinct challenges and opportunities.

Difficulties

Performance and Technical Barriers: Recycled or reused materials often face challenges related to their performance, durability, and market acceptance, despite their considerable environmental advantages. Recycled materials may not always meet the rigorous performance requirements in some circumstances, which might potentially compromise the structural stability or longevity of a building (Charef, *et. al.,* 2021). Factors like as degradation and external factors might also hinder their widespread adoption due to durability concerns. Advancements in material science technology have the capacity to enhance the durability and reliability of recycled and reused materials. Market trust may be enhanced by conducting unique testing and certification methods to verify their effectiveness. Establishing standards, regulations, and optimal methodologies for the construction sector is vital to effectively incorporate these materials into building systems (Shooshtarian, *et. al.,* 2020). This ongoing effort will eventually expedite the transition to more ecologically sustainable construction methods by improving material properties and promoting broader acceptance and use.

Lack of Standardization: The lack of standardised protocols and rules for the utilisation of recycled and reused materials may lead to variations in quality, restrict the acceptance in the market, and impede broad utilisation. The presence of varying standards in different locations also presents a difficulty for the worldwide adoption. Recycled and reused materials often encounter doubt about their durability, strength, and long-term performance in comparison to virgin materials (Park, & Tucker, 2017). Ensuring the compliance of these materials with safety regulations, building rules, and performance requirements may be a difficult task, particularly in structural applications where dependability is of utmost importance.

Limited Availability and High Initial Costs: Without infrastructure, recycling collection, sorting, and processing may be expensive. Limited availability limits their usage in major projects. Sustainable building materials need regulations and financial incentives. Green solutions are cheaper for builders and developers with tax credits, grants, and subsidies. These incentives may be used to build energy-efficient systems or acquire environmental items. However, industrial recycling and reuse are required by law. Regulations that require recycled content in building materials, certify sustainable construction techniques, or penalise waste overproduction may encourage greener construction (Yakimchuk, *et. al.,* 2023). Market resistance/perception issues Due to misunderstandings about recycled and reused materials' durability, aesthetics, and appeal, the building industry avoids them. Consumers and builders pick conventional materials for safety and beauty. Builders, architects, and clients may avoid certain materials owing to their unreliability.

Possibilities

Technological Innovations: There have been advancements in technology that are improving the quality and performance of recycled and reused materials. Some examples of these advancements include enhanced sorting and processing processes, chemical recycling, and triple-digit printing. The development of innovations such as intelligent materials that are simple to deconstruct and reuse is also on the increase, which is offering new opportunities for environmentally responsible building practices.

Kibert (2016) explained that green building materials and methods can also be systematically incorporated into conventional construction through the application of building codes and regulations that encourage modular construction, adaptive reuse, and other sustainable practices. Governments and industry associations may establish a climate where sustainable materials are accepted as the standard, promoting a more resilient and sustainable built environment, by combining financial incentives with strong regulatory backing (Sharma, 2020).

Circular Economy Integration: Adopting circular economy concepts has the capacity to revolutionise the construction industry by creating structures that are constructed using materials that can be readily disassembled, reused, or recycled after they reach the end of their useful life. This methodology minimises waste, preserves resources, and yields economic advantages by promoting the ongoing use of materials (Geissdoerfer, *et. al.,* 2017; Pomponi, & Moncaster, 2017; Akanbi *et. al.,* 2018; EMF, 2019).

Environmental and Economic Benefits: The act of recycling and reusing materials has a significant role in reducing the amount of waste that is disposed of in landfills, decreasing carbon emissions, and preserving valuable natural resources. Furthermore, the adoption of these measures may lead to long-term cost savings due to reduced material expenses, waste disposal fees, and energy usage (Ngayakamo, & Onwualu, 2022). This, in turn, makes sustainable building methods more economically viable.

Growing Regulatory Support and Incentives: As governments and regulatory agencies become more aware of the need of ecologically responsible building processes, they are implementing regulations, subsidies, and incentives to promote the use of recyclable and reusable materials. Simultaneously, there is a growing trend towards environmentally conscious construction practices. These programs possess the capacity to enhance demand, as well as foster more progress in material innovation, which is a key objective of theirs (Park, & Tucker, 2017).

Increased Public Awareness and Demand: The building and construction industry is increasingly adopting sustainable materials due to the rising awareness of environmental issues and the need for environmentally friendly and sustainable constructions. With the growing focus on sustainability by consumers, organisations, and governments, it is likely that the market will become more receptive to recycled and reused materials (Huang, *et. al.,* 2018; Shooshtarian, *et. al.,* 2020).

New Business Models and Market Opportunities: The shift towards recyclable and reusable materials generates opportunities for new business models, such as material leasing, take-back programs, and recycling partnerships. These models have the capacity to enable firms to generate additional revenue streams while also promoting sustainability in the construction sector (Huang, *et. al.,* 2018; Kabirifar, *et. al.,* 2020).

Developing eco-friendly construction materials and technology requires extensive study. This requires the development of new materials with a low ecological footprint, the improvement of recycling technologies to improve material recovery processes, and a better understanding of recycled materials' longevity and performance in various construction applications. These topics need interdisciplinary research including academics, industry practitioners, and policymakers. Academic scholars create innovative scientific and technical answers. Industry experts provide insights and practical applications. Policymakers provide helpful incentives and regulations. Cooperation is necessary to ensure that breakthrough materials and methods are theoretically sound, practicable, and commercially feasible. The construction business may achieve sustainability by reducing its environmental effect and supporting global environmental conservation efforts. Combining the goals of several industry actors may accomplish this. This comprehensive approach will help build a stronger, greener construction sector by bridging the gap between innovation and sustainability.

Despite quality difficulties, lack of standardisation, and high starting costs, recyclable and reusable building materials have significant potential. Technological advances, supporting policies, and increased market demand may stimulate the use of sustainable materials, creating a more ecologically friendly and resilient built environment. To properly use these materials in construction, further research, investments, and government initiatives are needed to overcome the difficulties.

Conclusion

Reusing and recycling trash to make sustainable building materials is essential for reducing the construction industry's environmental impact. Traditional building methods squander a lot and use new resources, causing resource shortages and environmental damage. A circular economy framework and novel materials and methods may improve resource efficiency and waste reduction in the sector. Reusing wood, recycled glass, and recycled metals reduces the demand for new raw materials, reducing production energy and emissions. Improved sorting, cleaning, and treatment methods make these recycled materials high-performance. These techniques make the materials suitable for numerous construction applications. Modular construction and adaptive reuse lengthen resource life and reduce building environmental impact. This shift promotes long-term sustainability and economic resilience by opening new markets for recycled materials and lowering dependence on finite natural resources. The building sector may advance sustainable development and environmental protection by adopting these cutting-edge materials and methods.

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