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Exploring the Potential of Agricultural Waste Products as Innovative Building Materials

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ABSTRACT

The construction industry faces significant challenges, particularly due to the high levels of carbon dioxide and other greenhouse gas emissions it produces. The need for materials that reduce the carbon footprint while maintaining the quality and performance of final products has become a primary focus of research in the field. This study highlights the potential of transformed vegetal waste as a viable source for producing advanced building materials. These materials offer a tangible contribution to reducing the carbon footprint in construction. Large quantities of agricultural waste are generated globally, and their unmanaged decomposition—particularly through natural oxidation—significantly contributes to greenhouse gas emissions. This has prompted growing interest in utilizing such waste, through suitable processing, as a sustainable resource for advanced building applications. The study emphasizes the potential benefits of incorporating agricultural waste derivatives into construction to reduce carbon emissions and conserve natural resources. It examines the characteristics of vegetal waste derivatives, demonstrating their suitability for use as insulation and finishing components in buildings. The research methodology combines a review of previous studies to assess the proposed approach with experimental validation through laboratory testing. Key findings of the study are the development of versatile elements that can be applied across various parts of a construction project, highlighting the environmental benefits of using vegetal waste derivatives, including the reduction of greenhouse gas emissions, the promotion of circular economy principles, and the decreased reliance on traditional, resource-intensive building materials. The study underscores the importance of interdisciplinary collaboration to advance the use of vegetal waste derivatives as innovative building materials, ultimately contributing to a more sustainable built environment.

1. INTRODUCTION

The carbon footprint has become a major issue in the ongoing climate change crisis. Elements that increase the carbon footprint can be divided into two categories: natural processes, such as decomposition and the oxidation of organic and vegetal waste, and artificial processes, such as the industrial transformation of materials. The impacts of anthropogenic carbon emissions are well-documented. Although numerous regulations have been implemented to mitigate them, a universally effective strategy has yet to be established. Anthropogenic carbon emissions are generally attributed to industrial activity, transportation, and energy use associated with building operations.

The buildings and construction industry represented 36% of total energy consumption and 39% of energy-related carbon dioxide (CO_2) emissions in 2018, with 11% of these emissions originating from the production of building materials and products like steel, cement, and glass. The 2021 Global Status Report provides an update on the key factors influencing CO_2 emissions and global energy demand since 2017, along with examples of policies, technologies, and investments supporting low-carbon building practices.

Major trends in the global buildings sector—driven by rising emissions and rapid population growth—have necessitated additional efforts to address energy consumption and emissions, including embodied carbon. These efforts also emphasize the need to strengthen scientific research aimed at developing innovative strategies to improve efficiency and reduce the environmental impact of building stock [1].

In pursuit of reducing its environmental footprint, the construction sector has adopted various low-carbon technologies aimed at minimizing energy consumption and greenhouse gas emissions. These advancements prioritize minimizing reliance on high-emission materials such as cement and integrating environmentally friendly alternatives:

1. Green Concrete

The conventional production of concrete contributes to approximately 8% of worldwide CO_2 emissions, mainly stemming from the process of manufacturing cement. Green concrete utilizes industrial by-products like fly ash, blast furnace slag, and silica fume to substitute some of the cement, leading to a notable decrease in carbon emissions. Furthermore, carbon capture technologies are being incorporated into the concrete production process to trap CO_2 within the concrete itself [2].

2. Recycled Bricks and Aggregates

Demolition debris plays a major role in filling up landfills, but utilizing recycled bricks and aggregates presents a viable alternative by converting materials from dismantled structures. By grinding and reworking these materials, construction endeavors can decrease the need for new resources while minimizing embodied carbon emissions [3].

3. Bio-Based and Natural Materials

Bio-based substitutes such as hempcrete, straw bale, and mycelium-based composites are becoming more popular in addition to industrially recycled materials. These materials store atmospheric carbon and typically need less energy to generate. Straw and hemp, for example, are plentiful agricultural by-products that may be turned into insulation and structural components. The use of agricultural waste in building offers an additional opportunity to enhance sustainability, complementing the emission reductions achieved by the aforementioned technologies. The sector may further reduce its reliance on conventional, high-carbon materials by reusing items like rice straw, banana residue, and potato trash. The subsequent sections explore how these agricultural by-products can be utilized as practical filler and finishing materials in contemporary construction.

This article highlights the serious problem of emissions from agricultural processes, not only related to animal production but also to vegetal production. For example, in banana production, every ton of bananas produced generates three tons of vegetal waste [4]. The natural decomposition processes, such as photo degradation, oxidation, and bacterial degradation, are major contributors to the carbon footprint, leading to various environmental issues, including excessive greenhouse gas emissions, the proliferation of pathogenic organisms, and leachate production [5]. The concept of using agricultural waste as a building material has historical roots throughout human civilization. The approach proposed in this research introduces advanced building materials with modern performance by employing agricultural waste. This achieves two important goals: the permanent stabilization of agricultural waste, preventing degradation and oxidation (the main causes of spontaneous production of carbon dioxide and methane), and the reduction of traditional materials used in certain parts of buildings, which generally consume excessive energy with a negative environmental balance. Currently, the use of agricultural waste in buildings is based on engineering or design on a case-by-case basis, without a technology capable of producing a universal product suitable for modern uses. This research focuses on providing a universal application of agricultural waste as a "production unit," enabling controlled performance with clear sustainability in economic, technical, and carbon footprint terms.

Designers and engineers are increasingly employing these materials in their constructions, and there are well-established experiences in this field. Maraveas [6] demonstrated that agro-waste products have the potential to replace traditional building materials, resulting in long-term economic, environmental, and social sustainability. The compressive strength of building blocks with different marble dust and rice husk content, studied by Venkatesh et al. [7], highlights the possibility and potential of rice straw waste, when suitably transformed, as an advanced building material. The transformation of straw into solid blocks using mycelium, as proposed by the study [8], underscores the need to research and employ alternative building materials starting from vegetal waste to reduce the carbon footprint in futuristic architecture. The selected examples support the central hypothesis of this research: the substantial volume of vegetal waste represents a promising resource for developing a low-carbon building industry.

2. METHODOLOGY

The proposed methodology is built around three key axes. First, it provides a comprehensive review of case studies and the most relevant literature, offering a solid theoretical background. Second, it is based on both quantitative and qualitative data collections related to the use of agricultural wastes. Finally, it includes experiments on the proposed technology that converts agricultural waste into advanced building materials. Through these steps, the research paper aims to validate practical and effective methods for utilizing vegetal waste in sustainable construction practices, providing a framework for their future industrial applications. The comprehensive literature review provides essential data that highlights the potential of using agricultural waste as a building material. The evaluation demonstrates both the practicality and advantages of these materials while also acknowledging the high carbon footprint associated with them. By combining this data, we were able to hypothesize the potential for agricultural waste to drive transformation in sustainable construction.

The approach, which studies existing cases, allows us to explore alternative ways to employ agricultural wastes, with the ultimate goal of reducing environmental impacts while developing eco-friendly building materials. The study of existing cases in which agricultural wastes are used in building material production demonstrates the potential for exploring and developing such technologies. Case studies reveal opportunities for using agricultural waste in construction materials, exploring its potential to address challenges related to sustainability. The research introduces experiments to investigate and explore different mixtures and processes, aiming to develop suitable techniques based on the use of agricultural waste. This process creates alternative types of building materials characterized by new performance characteristics that enhance their applications. By considering different applications and uses, the study optimizes the obtained materials to meet a wide range of construction needs while enhancing overall sustainability.

3. LITERATURE REVIEW

The use of vegetal waste has been widespread in traditional construction methods across many regions globally. Adobe, a block made by mixing rough clay with broken straw, pressed, and sun-dried, is a major technology still used in desert regions [9]. In this process, straw is primarily used to reinforce the blocks, providing structural integrity and thermal comfort. Modern applications of compressed straw or other vegetal waste blocks, such as rice straw blocks with varying compositions to achieve specific performance characteristics, are becoming more common [10]. In some cases, straw from different agricultural processes is used to fill external wooden wall frameworks, which are then finished in a later phase. Other innovative approaches, such as the use of mycelium-stabilized straw blocks [8], have also shown promising results. However, the widespread adoption of these methods is hindered by high costs, complex production processes, and design rigidity. The examples mentioned are more design-oriented than they are advanced, innovative technologies.

Research examining the mechanical and physical properties of agricultural waste as a building material is quite scarce and often involves indirect methods, even though numerous studies have highlighted its environmental benefits. This study investigates the compressive strength, water absorption, thermal conductivity, and fire resistance of agricultural by-products to address this gap. Recent studies indicate that materials exhibiting favorable characteristics—such as moderate compressive strength, low thermal conductivity, and potential fire resistance when adequately treated—comprise rice straw, banana byproducts, and potato refuse. Further research is needed to optimize their performance and ensure compliance with building standards. By experimentally assessing these attributes and exploring their implications for sustainable construction, this study aims to contribute to this growing field [11].

Studies highlighting the serious impact of vegetal waste on the global carbon footprint have gained significant attention, with substantial literature and data supporting this concern. Particularly, the concentration of carbon dioxide near the land surface of banana fields and other crops, caused by the deterioration and oxidation of vegetal waste that typically covers these fields, is alarming. This carbon dioxide concentration leads to the death of small animals and insects that inhabit these environments. For instance, banana waste is widely available worldwide as agricultural waste from banana production. As this waste decomposes, it produces significant amounts of carbon dioxide and methane, contributing to global warming annually and negatively impacting the environment [12]. The global waste of banana fruits is estimated at fifty million tons, which includes fruits that are discarded or deemed unfit for consumption [13]. The actual quantity of waste, including the entire banana tree (which has a lifecycle of just one season), is abnormally high worldwide. It has been shown that every ton of bananas produces three tons of waste. Bananas are a vital agricultural crop, with around 114 million tons produced globally each year. They are highly valued for their nutritional content and digestibility and are typically consumed raw or used in various snacks and sweet food products [14]. Based on this information, the total quantity of banana production amounts to 342 million tons.

Over the past 20 years, straw and timber building techniques have advanced and matured to the point where they are now widely accepted for general use. Various establishments, such as schools, public buildings, business and office projects, community and recreational centers, and private and social housing, have incorporated straw bales. A strong desire for ecological, natural, and sustainable building solutions has driven the commissioning of numerous straw bale buildings in the UK [15].

The use of rice production waste as a building material also helps address the global problem of carbon emissions. Historically, farmers have burned straw in the fields to avoid the cost of handling such a large volume of material. This practice releases NOx, SOx, hydrocarbons, dioxins, and other particles, producing CO_2 emissions and posing a toxicological threat to the community (Figure 1) [16].

Rice straw, a byproduct of rice harvesting, is created when rice is harvested. The straw is removed along with the grains and is either stacked up or spread out in the field, depending on whether it was harvested by hand or by machine. The straw-to-paddy ratio varies from 0.7 to 1.4, depending on the type and development. The global production of rice straw is estimated to be between 800 and 1,000 million tons annually, with Asia producing 600 to 800 million tons each year [17].

Figure 1. Image of rice straw burning directly on the fields
Source: International Rice Research Institute [17]

As shown in Table 1, one kilogram of dry wood produces approximately 3.667 kilograms of CO_2, and dry vegetal agricultural waste exhibits a similar chemical composition. The CO_2 emissions from rice cultivation in Asia alone amount to 800 million tons, which, when multiplied by 3.667, results in a substantial carbon footprint over one year.

An alternative use for straw and other vegetal waste is mycelium cultivation, which produces solid blocks. Mycelium, the root structure of fungi, is a novel and increasingly popular option for making bricks and cladding. Mycelium-based materials have a minimal carbon footprint, require little energy, and are biodegradable. They offer excellent fire resistance, thermal and acoustic insulation, and are also cost-effective. Mycelium, a complex network of fungal threads, is a reliable industrial material with a wide range of applications. In this method, mycelium is cultivated from agricultural waste and mycelial cultures and then transformed into various shapes, including bricks, panels, and blocks. These solid forms are created by combining mycelium with organic materials, which serve as a nutrient-rich substrate. As the mycelium grows, it breaks down the organic components, forming an intricate web of connections that effectively binds the mixture into a solid mass. The resulting material is shaped into the desired forms and continues to grow, further increasing its strength [18].

An example of using agricultural waste in construction, as shown in Figure 2, is "the building made of 'grown' bio-bricks [19]." This structure was created by David Benjamin, principal of The Living, and is composed entirely of biodegradable materials. It was built using bricks that were grown, not manufactured, from a mixture of agricultural waste, natural digestion glue, and fungal mycelium. The bio-bricks were grown in custom-made molds and integrated into the architecture, particularly around the top, to help reflect light inward [20].

The research conducted by The Living focused on developing a new method for using agricultural waste as an advanced building material. The bricks used in the project exhibited significant advantages, such as reduced weight, flexibility, and complete recyclability. However, as we will discuss later, the process was highly complex and costly, limiting its broader potential.

Figure 2. Tower of "grown" bio-bricks by The Living opens at MoMA PS1
Source: Frearson [19]

3.1 Durability and long-term performance

Durability of building materials is the main performance factor for their adoption for construction applications. The long-term performance of the alternative materials under study, their resistance to environmental factors such as humidity, temperature fluctuations, and mechanical wear, must be tested, especially in those materials based on alternative resources. Building materials must have a measurable humidity and moisture resistance, thermal stability and structural integrity, and energy conservation and emission reduction. The results show that alternative construction materials derived from agricultural waste provide promising sustainability and environmental benefits. However, additional research and field testing are recommended to verify long-term performance in a variety of climatic conditions and optimize formulations for improved humidity and thermal resistance. Furthermore, further evaluation of economic efficiency and compliance with regulatory requirements is required to integrate these materials into the main building method [21].

This article explores the potential of existing methods for using agricultural waste as a building material to develop an innovative approach that meets various criteria, including durability, cost-effectiveness, real carbon footprint, and safety. The aim is to establish its viability as part of universal design, rather than merely a specialized engineering process.

4. DATA AND ESTIMATION OF AGRICULTURAL VEGETAL WASTE

Table 1 summarizes the major types of plant-based waste that are not suitable for animal feed, highlighting their substantial quantities and the associated catastrophic carbon footprint. This table also underscores a key finding of this research: utilizing these wastes as building materials has the potential to significantly reduce the global carbon footprint. The table illustrates the potential of waste derived from rice and bananas in terms of their large volumes. Additionally, potato waste is identified as a valuable source of natural adhesive [4, 22-28].

In this article, we focus on these three types of plant-based waste—rice straw, banana residue, and potato waste—due to their distinct physical and chemical properties (Table 2). By exploring their potential and addressing the associated challenges, we aim to demonstrate how these agricultural by-products can be effectively repurposed to contribute to sustainable construction practices and environmental conservation.

Table 2 presents the chemical composition of the selected plant-based wastes, offering detailed insights into their constituent elements [28]. This analysis facilitates the evaluation of how these wastes can be effectively combined or used individually in various applications. By understanding the chemical properties of each type of waste—rice straw, banana residue, and potato waste—we can better assess their compatibility and performance as building materials [29].

The data in Table 2 highlights key factors such as the concentration of cellulose, hemicellulose, lignin, and other relevant compounds, which influence the suitability of these materials for different uses. For instance, the high cellulose content in rice straw and banana residue enhances their potential as reinforcing agents in construction, while the natural adhesive properties of potato waste may offer unique benefits for binding and cohesion. This comprehensive chemical profile is crucial for optimizing the formulation of new building materials and ensuring their effective application in sustainable construction practices [30].

Table 1. Major types of vegetal waste that cannot be used to feed animals

Vegetation	Quantity for Year (2022) in the World (Millions of Tons)	Quantity of Vegetal Waste for Year (2022) in the World (Millions of Tons)	Quantity of CO_2 Produced if Burned by Natural Oxidation (Millions of Tons)
Tobacco	5.78 million metric tons	No data available	No data available
Rice	515	515*11= 5,665	5,665*3.6 = 20,394
Banana	135.11	3*135.11=405.33	405.33*3.6 = 1,459.188
Tomato	180	No data available	No data available
Potato's	376	No data available	No data available
Corn	1150	1150*1.43=1541	1541*3.6 = 5,547.6

Source: Studies [4, 22-28]

Table 2. Chemical performance of banana, rice, and potato

Vegetation	Banana	Rice Straw	Potato
Composition	60%–70% carbohydrates, 2%–3% protein, 4%–5% fiber, 4%–5% lipid, and 20% moisture	Moisture (25%): 38% cellulose, 25% hemicellulose, and 12% lignin	14.7% protein, 2.2% cellulose, 7.7% ash, 3.4% pectin, 66.8% starch, 0.9% reducing sugars, and 1.4% total soluble carbohydrates

Source: Study [28]

5. DISCUSSION

As demonstrated by the literature, there are several examples of rice straw being used as a construction material for closure blocks (Figure 3). The European Straw Bale Association (ESBA) was established in 2016 to promote straw construction as a building material and to provide a platform for sharing information and experiences among straw bale builders and designers across Europe. The five ESBA member nations—France, Belgium, the Netherlands, the United Kingdom, and Germany—successfully secured €6.4 million in funding for the UP STRAW: Urban and Public Buildings in Straw Project (2017-2020) under the INTERREG North West Europe Programme. UP STRAW aimed to significantly enhance public perception of straw building [31].

Figure 3. Blocks of rice straw pressed
Source: Study [31]

Figure 4. The use of rice straw pressed in enclosure walls
Source: Study [32]

The use of vegetal waste as building material is widespread, with numerous examples demonstrating its application (Figure 4). This article focuses on how to develop an advanced building material that meets various technical requirements. By definition, an advanced building material should be versatile enough to be used in different parts of a building and serve multiple functions. The final product from the proposed method is not intended to be a structural element; rather, its uses are defined as finishing, thermal, and acoustic insulation, and design material. However, the proposed material must fully meet the following requirements: fire resistance, low emissions of odors, low oxidation under natural elements like temperature variations, and reduced thermal and acoustic transmission capacity.

Another fundamental requirement is the low energy consumption in the production process. The reduced energy balance and carbon footprint are key findings presented in this article. The energy consumption in the proposed method is limited to grinding and pressing operations, with no thermal treatments involved. The reduced carbon footprint is ensured by using waste materials that, if left untreated, would undergo natural oxidation or fermentation, leading to carbon dioxide emissions. Additionally, substituting traditional materials with these alternatives drastically reduces the reliance on high-carbon footprint substances like cement and its derivatives.

Cement production is notorious for its significant environmental impact due to high energy consumption and CO_2 emissions. By replacing traditional materials with those derived from agricultural waste, the proposed method not only lessens the carbon footprint but also supports a more sustainable approach to construction, aligning with broader goals of reducing environmental impact and promoting eco-friendly practices.

The main core in this research is to produce a conceptual model of production verifying the possibility of shaping this product firstly, and satisfying the general requirements of a building material as solidity, bulk density, water and fire resistance. In the first exam, these requirements were satisfied; thus, these new materials can be admitted to the following phase in the future development of this research.

6. DESIGN AND CONCEPTUAL EXPERIMENTATIONS

This article aims to demonstrate that vegetal wastes, especially rice straw and banana waste, can be used either separately or in combination with other materials like sand, clay, or silica for various applications, both internal and external, or as filling materials. These agricultural wastes can be transformed into advanced and alternative building materials.

Table 3. Description of experiments on the wastes of banana, rice, and potato

Type of Experimentation	Description of Material Obtained	General Notes
Grinding the vegetal waste	Mix of dimensions (ranged from 2 mm to 15 mm). High level of water in the composite.	The composite material obtained is easy to handle and to mix with other components.
Mixing with other materials 50%	Silica, sand, and natural clay with a range of dimensions from 2 mm to 5 mm.	Different aspects and physical nature of the different mixes.
Pressing and drying the composite material blocks	Solid blocks with various thickness and elasticity.	All blocks obtained enjoy a high level of stability, with low thermal and sound transmittance coefficients.

Source: The authors

Experimentation involving the grinding, mixing, pressing, and drying of blocks made from agricultural wastes has produced compact and durable blocks of varying thicknesses (Table 3). Preliminary results indicate several valuable advantages: the obtained blocks exhibit high fire resistance, low levels of oxidation, and reduced odor emissions. These characteristics make the blocks suitable for many applications while maintaining both performance and low environmental impact.

This article highlights the opportunity to create advanced and high-performance building materials that not only address sustainability but also provide practical advantages in construction.

6.1 Application of the proposed blocks

Buildings are typically constructed from various materials, each serving specific purposes such as structural support, external and internal partitions, and finishing touches. The technology proposed in this article is intended for use in finishing materials, insulation elements, and decorative applications. The proposed materials utilize agricultural wastes, primarily rice straw and banana production residue, with the aim of producing modern building materials that meet contemporary design requirements. This technology offers various options to enhance both the visual appeal and performance of surfaces. For example, the proposed insulation components provide excellent thermal and acoustic performance, thereby improving building comfort and increasing energy efficiency. The use of these new materials promotes sustainability by repurposing agricultural waste and addressing the performance criteria needed in modern construction. This approach supports the development of eco-friendly building solutions that meet both functional and aesthetic needs, thereby advancing sustainable building practices.

7. SUMMARY OF KEY FINDINGS

The key findings of this research can be summarized as follows:

1. **Use of Recycled Materials:** Vegetal wastes, such as rice straw and banana processing by-products, can be transformed into valuable building materials. This approach can significantly reduce the carbon footprint associated with their disposal or improper treatment.
2. **Multiple Environmental Advantages:** The use of vegetal waste offers numerous environmental benefits by reducing carbon emissions at multiple levels. It not only mitigates emissions from the waste itself but also replaces traditional building materials.
3. **Increased Performance:** Tests on banana waste blocks have demonstrated their high suitability as thermal and acoustic insulation materials. These blocks also offer flexibility for use as finishing or decorative elements, with excellent fire resistance and reduced odor and oxidation emissions.
4. **High Energy Efficiency:** The production of these materials requires minimal energy consumption, thereby reducing the overall energy balance and carbon footprint.
5. **Future Research Perspectives:** Future research will explore new practical production techniques, enhancing the benefits of these materials and supporting their wider adoption in construction practices.

8. CONCLUSION

The research aims to highlight the potential of using agricultural waste as a valuable material in building construction. Employing agricultural waste can significantly reduce the carbon footprint associated with its natural degradation if left in fields. Additionally, using these materials diminishes the reliance on traditional building materials. Agricultural waste, often burned or left in fields, produces greenhouse gas emissions that exceed those from cars and residential buildings, as discussed in this article. By converting agricultural waste into building materials, we can achieve a substantial reduction in emissions, contributing to climate change mitigation. The research also emphasizes the advanced properties and flexible applications of agricultural waste in various building components, especially as insulation. Advanced materials are defined not only by their functional requirements but also by their capacity to improve energy management in construction practices.

Combining these materials addresses a range of building performance issues, from enhancing thermal insulation to reducing environmental impact. This innovative approach demonstrates how agricultural waste can be transformed into useful materials for the building sector, marking a significant step toward more environmentally friendly and sustainable construction practices. Future studies will focus on refining the methods developed from the conceptual experimentation results presented in this paper. Additionally, the research will aim to address technological challenges encountered during preliminary experiments, including processes and techniques to enhance efficiency, reduce costs, and improve material properties. The goal is to develop comprehensive standards and best practices for integrating agricultural waste into building procedures.

As a result, we advocate for innovative approaches to reduce the building sector's carbon footprint, confirming the potential benefits of these materials and promoting more environmentally friendly construction techniques.

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