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A review of sustainable construction and waste management: Brick manufacturing using agro-industrial wastes

ABSTRACT

The construction industry is a large consumer of natural resources and a significant contributor to environmental deterioration. Sustainable construction practices, particularly in brick manufacture, have become important for mitigating these consequences. The use of agro-industrial waste as an alternative raw material in brick manufacture is an innovative approach to waste management and resource conservation. This research investigates the viability of using agro-industrial wastes such as rice husk ash, fly ash, bagasse, and other byproducts to make bricks. It assesses their environmental, economic, and technological advantages while confronting problems such as material variability, processing methods, and regulatory adherence. This thorough research seeks to establish a framework for using agro-industrial waste into conventional construction methods to attain sustainability objectives.

Keywords: Natural resources, sustainable construction, agro-industrial waste, waste management

1. INTRODUCTION

The construction business is critical to building contemporary civilisation by providing the infrastructure needed for housing, transportation, and industry. However, its fast expansion, fuelled by urbanisation, population growth, and industrial development, has caused considerable environmental issues [1]. Among construction materials, bricks are fundamental, widely used for their durability, availability, and versatility. Unfortunately, traditional brick manufacturing is resource-intensive, relying heavily on the extraction of natural clay and the firing process, which contributes significantly to greenhouse gas emissions. The extensive use of clay leads to the depletion of fertile topsoil, a critical resource for agriculture, and disrupts local ecosystems. Additionally, the high energy consumption of kiln operations, often powered by fossil fuels, exacerbates air pollution and global warming [2]. Growing interest in sustainable building methods that strive to lessen the ecological impact of the sector is a reaction to these environmental worries. Sustainable building focusses on decreasing resource usage, waste, and environmental impact [3].

Within this framework, the use of agro-industrial wastes in brick manufacturing has emerged as a promising solution. Agro-industrial wastes, such as rice husk ash, fly ash, sugarcane bagasse ash, coconut shell ash, and other by-products, offer a dual benefit. On one hand, they address the issue of waste disposal, preventing these materials from accumulating in landfills or being openly burned. On the other hand, they reduce the reliance on traditional clay and energy-intensive production methods, thereby conserving natural resources and reducing emissions [4]. The incorporation of agro-industrial byproducts in brick manufacturing aligns with global sustainability aims, notably the United Nations' Sustainable Development Goals (SDGs). It specifically contributes to objectives including responsible consumption and production, climate action, and sustainable urban development [5]. Through the integration of recycled resources, the building sector may advance towards a circular economy, wherein waste is transformed into useful raw materials. The figure 1 shows the some of the industrial agro wastes.

The use of agro-industrial wastes in bricks is not only an environmental imperative but also an economically viable option. These materials are often readily available and low-cost, particularly in agricultural and industrial regions [6]. For instance, rice husk ash is abundantly generated in rice-producing countries, while fly ash is a common by-

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product of coal-fired power plants. Utilizing these wastes in brick production can lower raw material costs, create opportunities for local businesses, and generate employment in waste collection and processing sectors. Moreover, waste-based bricks often exhibit enhanced properties, such as improved thermal insulation, reduced weight, and superior durability, making them competitive with conventional bricks [7].



Figure 1. Agro industrial wastes. A) Coconut Coir Dust B) Rice husk C) sugar cane bagasse D) Wheat Straw

Despite the potential benefits, the adoption of agro-industrial wastes in brick manufacturing faces several challenges. The variability in the chemical composition and physical properties of these wastes can affect the quality and performance of the bricks. Standardizing the processing and proportioning of waste materials is essential to ensure consistent product quality [8]. Additionally, the lack of awareness among manufacturers, builders, and consumers about the benefits of waste-based bricks can hinder market acceptance. Regulatory frameworks and policies that incentivize sustainable construction practices are crucial for encouraging the adoption of these materials on a larger scale [9]. Technological advancements in material processing and brick production techniques have facilitated the incorporation of agro-industrial wastes. Innovations such as mechanical blending, chemical treatments, and advanced firing methods have improved the compatibility and performance of waste-based bricks [10]. Furthermore, research and development efforts continue to explore new waste materials, optimize production processes, and enhance the properties of sustainable bricks.

Collaborative efforts among academia, industry, and governments are critical to overcoming technical and economic barriers and promoting the widespread adoption of these practices [11]. The figure 2 shows agro waste bricks.

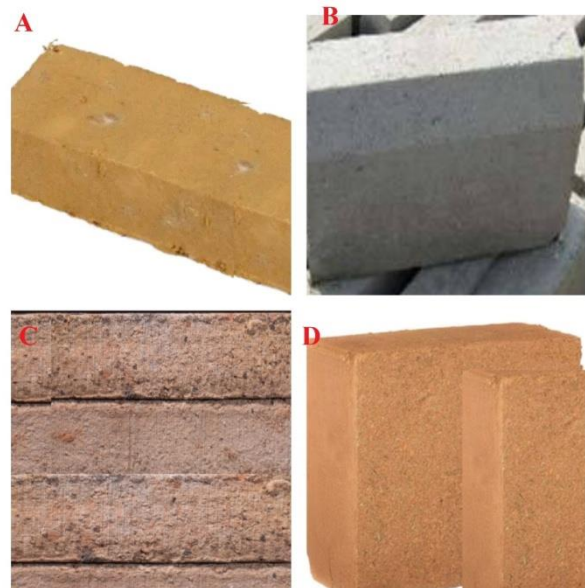


Figure 2. Agro industrial waste Bricks. A) Rice husk bricks B) Fly Ash Bricks C) Wooden dust bricks D) Coir dust bricks

This review aims to provide a comprehensive overview of the potential of agro-industrial wastes in brick manufacturing, highlighting their environmental, economic, and technical advantages. It also examines the challenges associated with their use and offers insights into strategies for scaling up production and adoption. By exploring the current state of knowledge and practice, this review seeks to contribute to the global transition towards a more sustainable construction industry [12]. Through innovative approaches and collective action, the integration of agro-industrial wastes in brick manufacturing can pave the way for a greener, more resilient future. The worldwide construction business is expanding rapidly, fuelled by urbanisation, population expansion, and infrastructural development [13]. Conventional construction materials, including bricks, heavily rely on non-renewable resources like clay and contribute significantly to greenhouse gas emissions during production. Traditional clay brick production involves the excavation of topsoil, leading to soil degradation and loss of agricultural land. Furthermore, the firing process in kilns consumes substantial amounts of fossil fuels, exacerbating air pollution and contributing to global warming [14]. The urgent need for sustainable alternatives has led to increased interest in utilizing waste

materials. By integrating agro-industrial wastes into brick production, the construction industry can reduce its environmental footprint while addressing the challenge of managing increasing amounts of industrial and agricultural by-products [15].

1.2. Importance of Sustainable Construction

Sustainable construction is an essential paradigm in modern building practices, aiming to minimize environmental impacts while enhancing resource efficiency and socio-economic benefits. The traditional construction industry has historically relied heavily on non-renewable resources and energy-intensive processes, leading to significant environmental degradation and carbon emissions [16]. In contrast, sustainable construction prioritizes strategies that conserve resources, reduce waste, and promote the reuse and recycling of materials, aligning with global sustainability goals [17].

Sustainable methods may transform the brick production industry by tackling environmental and economic issues. Conventional brick manufacture requires the mining of vast amounts of clay, a limited resource, as well as the usage of significant energy, which is frequently supplied from fossil fuels [18]. This process not only depletes natural resources but also contributes to air pollution and greenhouse gas emissions. By adopting sustainable methods, such as incorporating recycled or waste materials into brick production, manufacturers can significantly reduce the demand for virgin raw materials and lower energy usage. For instance, typical clay in bricks may be replaced with industrial wastes like fly ash, slag, and quarry dust, minimising resource extraction and keeping trash out of landfills [19]. The adoption of sustainable materials also aligns with the principles of a circular economy, where waste is viewed as a resource to be reintegrated into production cycles. Using waste-based materials in brick manufacturing has dual benefits: it addresses waste management challenges and reduces the carbon footprint of construction materials. For example, utilizing agricultural residues, such as rice husk ash or coconut coir, in brick production not only enhances the thermal and acoustic properties of the final product but also provides an environmentally friendly solution to agricultural waste disposal [20].

Sustainable building methods in brick production provide significant financial benefits in addition to environmental ones. The integration of recycled or locally available waste materials can lead to substantial cost savings by reducing the dependence on expensive raw materials [21]. Moreover, the development of eco-friendly bricks

can open up new markets, catering to the growing demand for green building materials. Such innovation can create opportunities for small-scale entrepreneurs and startups to enter the construction industry with sustainable solutions [22]. Socially, sustainable construction contributes to community development by fostering job creation in waste management, material processing, and eco-friendly product manufacturing. The establishment of recycling facilities and the processing of alternative materials generate employment opportunities, particularly in rural and underdeveloped areas. These activities also promote environmental awareness and education, encouraging communities to adopt sustainable practices in their daily lives [23].

Furthermore, the use of sustainable construction materials enhances the overall durability and efficiency of buildings [24]. For instance, bricks made from recycled or alternative materials often exhibit improved thermal insulation properties, reducing energy consumption for heating and cooling in buildings. This contributes to long-term savings for occupants and reduces the environmental impact of energy usage in the built environment [25].

In conclusion, the importance of sustainable construction, particularly in brick manufacturing, cannot be overstated. By minimizing environmental impacts, conserving natural resources, and promoting economic and social benefits, sustainable practices support global efforts to combat climate change and transition to a circular economy [26]. The integration of waste-based materials not only addresses pressing environmental challenges but also offers a pathway for innovation and economic growth. As the construction industry evolves, embracing sustainable methods will be critical to building a resilient and equitable future [27].

1.3. Scope of Review

This review focuses on agro-industrial wastes used in brick manufacturing, evaluating their mechanical properties, environmental benefits, and economic feasibility. It also examines challenges in scaling up production and adopting these practices globally. The potential of agro-industrial by-products, such as fly ash, rice husk ash, sugarcane bagasse ash, and other local waste materials, as partial or total replacements for traditional brick-making components is specifically highlighted. Case studies, technical developments, and legislative frameworks that promote sustainable building methods are highlighted in the review. In order to hasten the building industry's adoption of waste-based bricks, it also points out research gaps and offers suggestions for additional study.

2. AGRO-INDUSTRIAL WASTES IN BRICK MANUFACTURING

The integration of agro-industrial wastes into brick manufacturing presents an innovative and sustainable approach to reducing environmental impacts, conserving natural resources, and enhancing the performance of bricks [28]. These

materials, often regarded as waste, are rich in beneficial properties that can improve the mechanical, thermal, and environmental characteristics of bricks. Below is a detailed discussion of key agro-industrial wastes used in brick manufacturing. Figure 3 shows the Agro industrial waste used in Brick Manufacturing

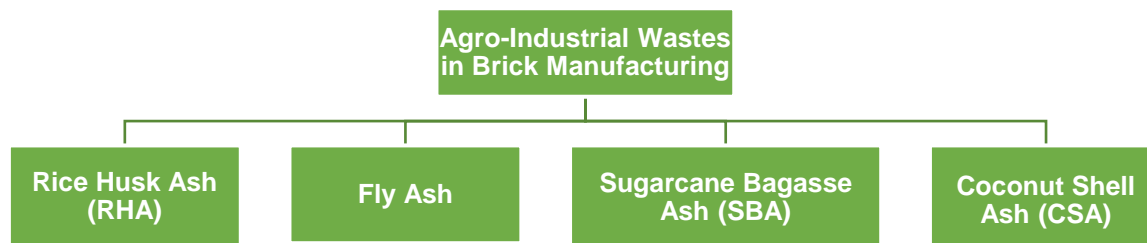


Figure 3. Agro industrial waste used in Brick Manufacturing

2.1. Rice Husk Ash (RHA)

An important source of silica, rice husk ash is a by-product of milling rice and usually makes about 85–90% of its composition. This high silica content makes RHA an excellent candidate for partial substitution of clay in brick production. Incorporating RHA into bricks has multiple benefits. Firstly, it enhances the thermal insulation properties of bricks, making them energy-efficient for use in construction [29]. The improved insulation can reduce heating and cooling energy requirements in buildings, thereby lowering their overall environmental footprint. Additionally, RHA reduces the overall weight of bricks without compromising their structural integrity, facilitating easier handling and transportation. Its incorporation also diverts large quantities of rice husk from being burned or disposed of in landfills, thereby mitigating air pollution and waste management issues. Research indicates that bricks containing RHA exhibit improved durability and resistance to shrinkage, further enhancing their appeal as a sustainable construction material [30].

2.2. Fly Ash

Fly ash is a fine, powdery waste produced after the burning of pulverised coal in thermal power plants. It is one of the most commonly utilised industrial byproducts in brick manufacture due to its quantity and great qualities [31]. Fly ash bricks are noted for their higher strength and durability than traditional clay bricks. Their low water absorption rate lowers the possibility of moisture penetration and subsequent structural damage over time. Fly ash's pozzolanic characteristic improves compressive strength when utilised as a primary or auxiliary ingredient in brick manufacture. Furthermore, fly ash bricks are environmentally benign since they greatly reduce the need on

natural clay and the carbon emissions associated with typical brick fire techniques [32]. By using fly ash, the sector handles the environmental problem of controlling coal combustion byproducts while simultaneously supporting waste valorisation and circular economy principles.

2.3. Sugarcane Bagasse Ash (SBA)

Burning sugarcane bagasse yields sugarcane bagasse ash, a byproduct of the production of sugar. Because it contains a lot of silica and other pozzolanic compounds, SBA is a great element for producing bricks [33]. When added into bricks, SBA increases compressive strength by reacting with calcium hydroxide to generate calcium silicate hydrates, which improves the material's binding qualities. In addition to mechanical benefits, SBA helps to reduce the environmental impact of brick manufacture by providing an efficient way to recycle sugar mill waste. It also reduces the amount of clay required, which conserves natural resources and saves energy during the burning process [34]. The adoption of SBA in brick production supports sustainable waste management and promotes a circular approach to resource utilization in the agro-industrial sector.

2.4. Coconut Shell Ash (CSA)

Coconut shell ash is an emerging material in sustainable brick manufacturing, derived from the combustion of coconut shells, a common agricultural waste in tropical regions. CSA is characterized by its high carbon content and lightweight properties, which make it an attractive additive for producing lightweight and energy-efficient bricks [36]. The inclusion of CSA enhances the thermal insulation capabilities of bricks, making them ideal for energy-conscious building applications. Its use also contributes to waste

reduction and provides a sustainable alternative to traditional materials. Furthermore, CSA's availability in regions with abundant coconut cultivation offers a localized and cost-effective solution for eco-friendly brick production. [37]

2.5. Other Wastes

Several other agro-industrial wastes have been explored for their potential in brick manufacturing, each offering unique advantages based on their chemical composition and regional availability. The figure 4 shows the various other wastes used in brick manufacturing [38].

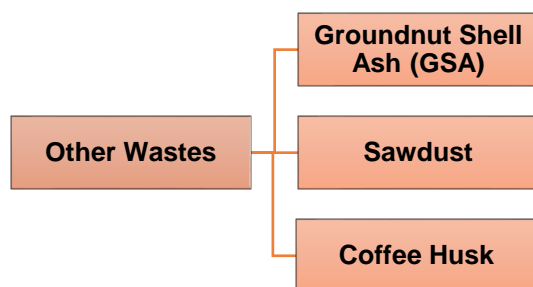


Figure 4. Other waste used in brick manufacturing

2.5.1. Groundnut Shell Ash (GSA)

Groundnut shell ash is an innovative material derived from the combustion of groundnut shells, which are abundant agricultural residues in many regions. Its high silica content, typically exceeding 50%, makes it an excellent additive in brick manufacturing. When used as a partial substitute for clay, GSA enhances the mechanical properties of bricks, particularly strength and durability[39].

- **Strength and Durability:** The silica in GSA reacts with other compounds during the firing process, forming silicate structures that improve the compressive strength and weather resistance of bricks. This ensures a longer lifespan and reduces maintenance costs for structures made with GSA-enhanced bricks.
- **Lightweight Properties:** The reduced density of bricks made with GSA enhances their transportability, lowering logistical costs and energy consumption associated with distribution. This makes GSA bricks particularly advantageous in construction projects in remote areas.
- **Environmental Impact:** Utilizing GSA mitigates waste disposal issues associated with groundnut shells, which are often burned in open fields, contributing to air pollution. By recycling these shells into bricks, the agricultural and construction sectors work together to reduce carbon emissions and promote sustainability.

2.5.2. Sawdust

Sawdust, a by-product of the woodworking and furniture industries, is widely available in regions

with active timber processing operations. Its integration into brick manufacturing offers several benefits, particularly in enhancing thermal insulation and promoting lightweight construction materials [40].

- Sawdust provides thermal insulation by burning off organic material during fire, leaving tiny spaces in bricks. These holes increase the thermal insulation qualities of bricks, minimising heat transmission and increasing construction energy efficiency.
- Sawdust decreases brick density, making them simpler to handle, transport, and install. Lightweight bricks are especially useful in situations where decreasing structural load is critical, such as earthquake-prone areas.
- Sawdust is a frequent industrial waste that requires proper waste treatment. By recycling it in the production of bricks, manufacturers lessen the environmental effect of the wood-processing sector and support a circular economy.
- Sawdust is a sustainable and locally supplied alternative to traditional materials, making it particularly useful in locations with a strong woodworking industry.

2.5.3. Coffee Husk

Coffee husk is a renewable by-product generated during coffee bean processing. It is rich in organic compounds, including cellulose and lignin, making it a viable raw material for eco-friendly brick manufacturing [41].

- **Eco-Friendly Bricks:** Coffee husk bricks have lower embodied energy compared to traditional clay bricks due to their organic composition. During the firing process, the organic matter burns off, creating a porous structure that improves insulation and reduces the density of the bricks.
- **Thermal Insulation:** The porosity resulting from burned-off organic content enhances the bricks' thermal insulation properties, which is ideal for maintaining comfortable indoor temperatures in both hot and cold climates.
- **Waste Management Solution:** Coffee production generates large quantities of husk, which can pose environmental challenges if not properly managed. Using coffee husk in brick production provides an effective way to recycle this waste, reducing landfill accumulation and associated methane emissions.
- **Economic Potential:** In coffee-producing regions, integrating coffee husk into brick manufacturing offers opportunities for value addition, creating new revenue streams for coffee growers and processors while fostering sustainable practices.

Table 1. Agro-Industrial Wastes in Brick Manufacturing

Material	Source	Key Properties	Benefits in Brick Manufacturing	Environmental Impact
Groundnut Shell Ash	Agricultural residue from groundnuts	High silica content; lightweight	- Enhances strength and durability- Reduces brick weight for easy transport- Provides longer-lasting bricks	- Mitigates air pollution from open burning of shells- Promotes waste recycling
Sawdust	By-product of woodworking industry	Organic content; reduces density	- Improves thermal insulation- Creates lightweight bricks- Provides sustainable use for wood industry waste	- Reduces landfill waste- Minimizes deforestation by replacing clay with recycled sawdust
Coffee Husk	Residue from coffee processing	Rich in organic compounds (cellulose, lignin)	- Enhances thermal insulation- Produces eco-friendly, energy-efficient bricks- Reduces overall brick density	- Addresses waste management issues in coffee-producing regions- Lowers methane emissions from husk decomposition

Table 1 shoes the comparison of Agro-Industrial Wastes in Brick Manufacturing [42].

This table concisely summarizes the key characteristics, benefits, and environmental impacts of using groundnut shell ash, sawdust, and coffee husk in sustainable brick production. It highlights the role of these agro-industrial wastes in promoting eco-friendly practices while enhancing brick quality and performance [43]. The use of groundnut shell ash, sawdust, and coffee husk in brick manufacturing exemplifies innovative approaches to sustainable construction. These materials not only improve the performance characteristics of bricks but also address critical environmental challenges by reducing waste and conserving natural resources. By tailoring brick compositions to local waste availability, industries can create cost-effective and eco-friendly building materials, supporting global efforts toward a sustainable future [44].

3. ENVIRONMENTAL BENEFITS

The integration of agro-industrial wastes in brick manufacturing not only provides a sustainable solution to waste management but also brings several environmental and economic benefits. These benefits span waste management, carbon emissions reduction, and conservation of natural resources [45].

3.1. Waste Management

Incorporating agro-industrial wastes such as groundnut shell ash, sawdust, and coffee husk in brick manufacturing addresses the pressing issues of waste disposal and resource conservation [46].

- **Waste Diversion:** By using these materials, large amounts of agro-industrial waste are kept out of open dumping sites and landfills. For

instance, bricks may be successfully made from rice husk ash and sugarcane bagasse ash, which are by-products of agricultural operations. This lessens the negative effects of waste on the environment, stops contamination of the land and water, and lessens the discharge of toxic gases from burning agricultural leftovers without proper

- **Resource Conservation:** By replacing conventional materials like clay with these agro-industrial by-products, the need for new raw materials is minimized. This reduces the pressure on natural resources, thereby conserving them for future use. The shift also helps in reducing the demand for energy-intensive manufacturing processes, contributing to sustainable development goals.

3.2. Reduction in Carbon Emissions

Traditional brick making uses high-temperature kilns that produce significant volumes of carbon dioxide (CO₂). The process of burning clay bricks is energy-intensive, sometimes reliant on fossil fuels, and contributes significantly to carbon emissions in building. However, the use of agro-industrial waste provides a potential alternative to this high-energy method [47].

- Utilising elements such as fly ash and rice husk ash in brick manufacture can minimise energy consumption during burning. These materials already include silica and other chemicals that react with lime, thus clay bricks do not require high-temperature sintering. This reduction in energy usage results in reduced greenhouse gas emissions linked with the manufacturing process.
- The building sector may lower its carbon footprint by using waste materials instead of burning them. The use of agro-industrial

wastes as partial replacements for clay saves energy and reduces emissions from typical brick kilns.

3.3. Conservation of Natural Resources

Replacing clay with agro-industrial wastes in brick manufacturing is crucial for the conservation of natural resources, particularly fertile topsoil, which is essential for agriculture. The global demand for construction materials has led to extensive extraction of clay, contributing to soil degradation and loss of arable land. Using alternative materials helps to mitigate these effects [48].

- **Fertile Topsoil Preservation:** Clay is a vital resource for agriculture, providing nutrients and support for plant growth. The extraction of large quantities of clay for brick production can lead to soil erosion and desertification. By substituting clay with agro-industrial wastes, such as groundnut shell ash and sawdust, manufacturers can help preserve fertile topsoil and maintain agricultural productivity.
- **Sustainable Construction:** The use of these materials in construction not only conserves natural resources but also supports sustainable building practices. Agro-industrial by-products are often abundant, locally available, and can be sourced at a lower cost, making them economically viable alternatives to clay. This approach ensures that construction materials are aligned with the principles of a circular economy, where waste is repurposed and reused.

Finally, using agro-industrial wastes in brick production offers a multifaceted way to address urgent environmental issues [49]. It tackles waste management, lowers carbon emissions, and preserves natural resources, all of which support sustainable growth in the building industry. A more robust and sustainable future may be achieved by the industry by incorporating these materials into industrial processes [50].

4. BENEFITS AND CHALLENGES OF AGRO-INDUSTRIAL WASTE-BASED BRICKS

In terms of durability, cost savings, and mechanical qualities, using agro-industrial wastes in brick production has several advantages. However, there are other difficulties, especially with regard to quality control, processing, and long-term performance in various environmental settings [51].

4.1. Mechanical Properties

Agro-industrial waste-based bricks exhibit varying mechanical properties depending on the type and proportion of waste materials used. Key mechanical parameters include [52]:

- **Compressive Strength:** One important measure of a brick's capacity to support weight is its compressive strength. Bricks' compressive strength may be considerably increased by adding agro-industrial wastes like fly ash, rice husk ash, and groundnut shell ash. By reacting with lime during the fire process, these materials' pozzolanic qualities create calcium silicate hydrates, which increase the brick's overall strength.
- **Water Absorption:** Compared to conventional clay bricks, bricks made from agro-industrial waste often absorb water at a slower rate. This is beneficial because it lessens moisture intrusion, which can cause damage like cracking or efflorescence. For example, because fly ash is inert and reduces porosity, bricks made with fly ash exhibit less water absorption.
- **Thermal Conductivity:** Bricks can become better insulators by reducing their heat conductivity by the addition of materials like sawdust or coconut shell ash. Because it may assist maintain consistent inside temperatures and lessen the need for artificial heating and cooling, this characteristic is advantageous for building energy efficiency.
- **Flexural Strength:** The addition of waste materials can improve the flexural strength of bricks, which is their ability to withstand bending forces without breaking. This is especially true for bricks containing sawdust, which provides a lightweight yet strong structure.

Key mechanical parameters of bricks incorporating agro-industrial wastes include compressive strength, water absorption, thermal conductivity, and flexural strength. Because of their pozzolanic qualities, which react with lime during burning to generate calcium silicate hydrates, agro-industrial wastes such as fly ash, rice husk ash, and groundnut shell ash greatly increase compressive strength, hence enhancing the overall strength of the brick. These bricks generally exhibit lower water absorption rates compared to traditional clay bricks, reducing moisture infiltration and preventing issues like efflorescence and cracking. The inclusion of materials like sawdust or coconut shell ash also lowers the thermal conductivity, making the bricks better insulators and more energy-efficient for buildings. Additionally, the addition of these wastes can improve flexural strength, allowing the bricks to withstand bending forces without breaking, especially in bricks containing sawdust, which contributes to their lightweight yet strong structure [54].

4.2. Cost Analysis

The incorporation of agro-industrial wastes into brick manufacturing generally results in cost savings. Using agro-industrial wastes in brick manufacturing offers significant economic benefits, including reduced raw material costs. These waste materials, such as rice husk ash, fly ash, and sugarcane bagasse ash, are often abundant and locally available, making them economically viable substitutes for clay or other traditional binding agents [55]. Incorporating these materials also results in energy savings by reducing the temperature required during the firing process, which lowers fuel consumption. However, processing costs must be considered, as they include expenses for milling, drying, and homogenizing the waste to meet necessary specifications. Quality control is critical to ensure

consistency in the mechanical properties of the final product. Additionally, transportation costs can add to overall expenses if the waste materials are not sourced locally. Therefore, while the use of agro-industrial wastes reduces the overall cost of production, efficient logistics and local sourcing strategies are essential to manage transportation costs effectively [56].

4.3. Durability and Long-Term Performance

The durability of bricks incorporating agro-industrial wastes is generally adequate, but the long-term performance under varying environmental conditions needs further investigation. Bricks made with agro-industrial wastes demonstrate significant durability, withstanding exposure to environmental stresses such as moisture, temperature variations, and freeze-thaw cycles [57].

Table 2. Benefits and Challenges of Agro-Industrial Waste-Based Bricks

Aspect	Benefits	Challenges
Mechanical Properties		
Compressive Strength	- Enhanced strength due to pozzolanic reactions from agro-industrial wastes like fly ash and rice husk ash.- Improved durability from reduced water absorption.	- Variability in strength depending on waste type and proportion.- Consistency in quality needs rigorous processing and quality control.
Water Absorption	- Lower water absorption rates compared to traditional clay bricks.- Reduced risk of moisture infiltration.	- Need for precise mix designs to avoid excessive porosity.
Thermal Conductivity	- Lower thermal conductivity, improving insulation properties of bricks.- Energy-efficient buildings.	- Dependence on the specific agro-waste material used.- Consistency in insulating properties.
Flexural Strength	- Improved flexural strength from lightweight, strong materials like sawdust.	- Variation in flexural strength with different waste types.- Quality control to maintain uniform properties.
Cost Analysis		
Reduced Raw Material Costs	- Lower costs due to use of abundant agro-industrial wastes.- Economically viable alternatives to traditional materials.	- Processing costs for milling and homogenizing the wastes.- Increased transportation costs if not sourced locally.
Energy Savings	- Reduced energy intensity during firing due to waste incorporation.- Lower fuel costs.	- Costs associated with managing waste materials before they can be used in production.
Durability and Long-Term Performance		
Durability	- Good resistance to environmental stresses like moisture and temperature variations.- Adequate weathering resistance.	- Potential durability issues under specific conditions (e.g., high humidity).- Long-term performance needs further research.
Long-Term Performance	- Stable performance in varying environmental conditions.- Reduced risk of degradation over time.	- Need for extended field testing to validate performance.- Long-term effects of agro-waste inclusion not fully understood.

Their resistance to degradation and weathering highlights their potential for long-term use in construction. However, the long-term performance

of these bricks is influenced by factors such as the type and proportion of waste used, the firing process, and the specific environmental conditions

in which they are deployed. For instance, bricks containing rice husk ash may exhibit reduced durability under high humidity conditions due to increased porosity. Therefore, more research is required to fully understand their long-term performance in various climates. Long-term field tests are crucial for monitoring the durability and performance of these bricks over extended periods, especially in diverse environmental settings [58]. These tests will aid in refining mix designs and processing methods to enhance the bricks' durability and overall performance. In the end, although there are many advantages to using agro-industrial wastes in brick production, including lower expenses and better mechanical qualities, there are drawbacks as well, including issues with processing, shipping, and guaranteeing long-term durability. Addressing these issues and maximising the use of waste materials in sustainable building will need ongoing research and development in this area [59]. Table 2 shows the Benefits and Challenges of Agro-Industrial Waste-Based Bricks

This table summarizes the key benefits and challenges associated with using agro-industrial wastes in brick manufacturing. It highlights the improvements in mechanical properties, cost savings, and durability, along with the challenges of processing and ensuring consistent quality and long-term performance [60].

5. CHALLENGES AND SOLUTIONS

5.1. Material Variability

The heterogeneity of agro-industrial wastes presents a significant challenge in achieving consistent brick quality. Agro-wastes such as rice husk ash, fly ash, sawdust, and coffee husk can vary widely in composition due to differences in their source, processing methods, and regional characteristics. For example, rice husk ash from one mill may contain different levels of silica compared to another, affecting its pozzolanic properties in brick manufacturing. Similarly, the size and distribution of particles in fly ash can differ based on its origin from different coal types, impacting its effectiveness as a partial replacement for clay [61].

Bricks made with this diversity may have uneven compressive strength, water absorption, and thermal conductivity, among other characteristics. The strength of bricks created using high-silica rice husk ash, for example, may be superior than that of bricks made with the same material from another source [62]. Standardised processing and quality control procedures are crucial to overcoming this obstacle. A homogeneous and consistent result is ensured by following procedures for grinding, drying, and homogenising agro-industrial wastes. Monitoring and managing the variability can be aided by

routine testing for characteristics including particle size, moisture content, and chemical composition. Quality control laboratories equipped with the necessary equipment are crucial to ensure the desired characteristics are consistently met across different batches of bricks. Standardization also involves setting up specifications for the acceptable ranges of chemical and physical properties of these waste-based materials [63].

5.2. Technological Barriers

Adopting new manufacturing technologies for waste-based bricks presents significant technological challenges. The incorporation of agro-industrial wastes requires specific processing techniques to prepare these materials adequately for use in brick manufacturing. For example, advanced milling systems may be needed to grind waste materials to the required fineness for uniform mixing with clay or other binding agents [64]. Similarly, drying technologies might be required to reduce the moisture content in waste materials before their incorporation into the brick mix, preventing issues like incomplete firing or poor durability.

These technological advancements often come with high costs, making the adoption of waste-based bricks a financial challenge for many manufacturers. Furthermore, these technologies might not be readily available in local markets, requiring investments in specialized equipment [65]. The financial burden can be a significant deterrent for manufacturers, especially small- and medium-sized enterprises (SMEs) with limited capital. To mitigate these challenges, support from governments and research institutions is crucial. Governments can provide subsidies, grants, or low-interest loans to encourage manufacturers to invest in the necessary technologies. Research institutions can play a key role by developing and demonstrating cost-effective, scalable technologies that make it economically viable to use agro-industrial wastes. These institutions can also help in training personnel and providing technical support to overcome the learning curve associated with new technologies [66]. Collaborations between industry, government, and academia can lead to innovations in processing techniques, such as improved methods for drying and milling, or the development of new binders that enhance the properties of bricks made from waste materials.

5.3. Regulatory and Market Acceptance

The lack of regulations and market skepticism poses significant barriers to the widespread adoption of waste-based bricks. Many regions do not have clear standards and regulations regarding the use of agro-industrial wastes in construction [67]. This creates uncertainty among builders,

architects, and consumers regarding the quality, safety, and durability of waste-based bricks. For instance, a lack of regulatory guidelines may result in inconsistent quality across different batches of bricks, leading to apprehension about their performance over the long term. Without standards, there is also the risk of introducing substandard products into the market, which could damage the reputation of the entire category of waste-based construction materials [68].

To overcome these barriers, policy interventions are essential. Governments need to set clear standards and regulations that define the acceptable properties of waste-based bricks. These standards should cover aspects such as compressive strength, water absorption, thermal insulation, and durability under various environmental conditions [69]. The establishment of such regulations can provide a level playing field for all manufacturers and ensure the safety and quality of the materials. In addition to regulatory measures, promoting awareness is crucial. Public awareness campaigns can educate stakeholders about the benefits of using waste-based bricks, such as their environmental advantages, cost

savings, and improved properties. These campaigns can highlight successful case studies and pilot projects that demonstrate the practical benefits of these bricks, fostering confidence in their use. Incentives like tax rebates or financial support for manufacturers using waste-based materials can also encourage broader market acceptance [70]. By integrating these strategies, the adoption of waste-based bricks can be accelerated, aligning with sustainable development goals and contributing to a circular economy in the construction industry.

In summary, overcoming the challenges associated with material variability, technological barriers, and regulatory acceptance requires a comprehensive approach. Standardization, government support, and public awareness campaigns are crucial to promoting the use of agro-industrial wastes in brick manufacturing [71]. Addressing these challenges will not only improve the sustainability of the construction industry but also support environmental protection and economic efficiency. Table 3 shows the Challenges in the Use of Agro-Industrial Waste-Based Bricks [72].

Table 3. Challenges in the Use of Agro-Industrial Waste-Based Bricks

Aspect	Challenges	Solutions
Material Variability	- Heterogeneity of agro-industrial wastes leading to inconsistent brick quality.- Variability in properties depending on the source and processing methods of the waste.	- Standardized processing and quality control measures.- Regular testing for properties such as particle size, moisture content, and chemical composition.
Technological Barriers	- High costs of adopting new manufacturing technologies.- Need for significant technical expertise.- Limited availability of necessary equipment.	- Support from governments and research institutions.- Investment in research and development for cost-effective technologies.- Training programs to build technical expertise.
Regulatory and Market Acceptance	- Lack of clear regulations and standards for waste-based bricks.- Market skepticism regarding quality and durability.- Inconsistent quality without guidelines.	- Policy interventions to establish standards and regulations.- Public awareness campaigns to promote the benefits of waste-based bricks.- Financial incentives for manufacturers.

This table summarizes the challenges faced in the use of agro-industrial waste-based bricks and the corresponding solutions to overcome them. By addressing these challenges, the industry can achieve consistent quality, economic feasibility, and broader market acceptance for waste-based bricks.

6. FUTURE PROSPECTS

6.1. Research and Development

Ongoing research is pivotal for enhancing the performance of waste-based bricks. This focus involves exploring innovative additives and processing techniques that can significantly improve the mechanical properties, durability, and cost-effectiveness of these bricks. For instance, the incorporation of pozzolans or nano-materials into

agro-industrial waste-based bricks can enhance their binding properties, leading to better compressive strength and reduced water absorption. Advanced processing techniques, such as novel drying methods or the development of new binders, are also critical [73]. Research institutions, universities, and industrial labs are instrumental in conducting experimental studies, pilot projects, and field tests to optimize these additives and techniques. The outcomes of such research can establish best practices in the production of waste-based bricks, ensuring their reliability and sustainability under various environmental conditions [74-78]. Ultimately, continuous research efforts are essential for maintaining the competitiveness of waste-based

bricks in the construction market, paving the way for broader adoption.

6.2. Policy Frameworks

Strong regulatory frameworks are essential to drive the transition toward greener construction practices. These frameworks provide the necessary support for the adoption of sustainable materials like agro-industrial waste-based bricks by setting clear standards and guidelines for their use [79]. Without such regulations, there may be hesitation among manufacturers and builders to incorporate waste-based bricks into their projects due to concerns over quality, safety, and performance. Governments can play a critical role by establishing standards for properties such as compressive strength, water absorption, and durability of these bricks [80]. Clear certification processes and guidelines assure quality and performance, making these materials more attractive to the market [81]. Moreover, offering incentives like tax rebates or subsidies for manufacturers using waste-based bricks can further promote their use [82]. Effective policy frameworks not only ensure the quality and safety of waste-based bricks but also stimulate their demand, ultimately leading to a more sustainable construction industry [83].

6.3. Global Collaboration

International collaboration is a key strategy for promoting the use of sustainable construction materials, including waste-based bricks. The global nature of sustainability challenges requires knowledge sharing, technology transfer, and market development across borders [84]. Collaborative efforts among countries, research institutions, and industries can facilitate the exchange of best practices, technologies, and research findings [85]. Joint research projects, technical assistance programs, and shared resources for testing and developing sustainable materials are crucial components of such collaborations. Global collaboration also aids in harmonizing standards and regulations across different regions, allowing manufacturers to access international markets and adopt best practices from around the world [86]. This can accelerate the adoption of waste-based bricks, promoting innovation and the development of a circular economy in the construction industry. By fostering an environment of cooperation, global collaboration supports the growth of sustainable construction practices and enhances the overall sustainability of the industry [87].

7. CONCLUSION

Agro-industrial wastes have significant potential to revolutionise brick manufacture by tackling urgent issues associated with waste management and resource sustainability. The incorporation of these elements into brick production aids in waste management, conserves natural resources, and

mitigates the environmental problems linked to conventional brick manufacturing methods. Notwithstanding hurdles including material unpredictability, technological obstacles, and regulatory concerns, there are evident avenues for progress via research, policy formulation, and industry implementation. Ongoing endeavours to develop standardised processing methodologies, build supporting regulatory frameworks, and promote worldwide cooperation are crucial to surmount these hurdles.

To increase the effectiveness of waste-based bricks and make them appropriate alternatives to conventional materials, research and development are crucial. Advancements in additives and processing techniques are essential to improve the strength, durability, and efficiency of these bricks. Furthermore, governmental frameworks that offer explicit standards and incentives might motivate manufacturers to utilise waste-based bricks, therefore guaranteeing their quality and safety. International collaboration promotes the exchange of information and technology, fostering broader implementation of sustainable practices across various locations.

Integrating environmental and economic factors, the use of waste-based bricks can substantially advance global sustainability objectives. These bricks facilitate the circular economy and aid in mitigating climate change by decreasing the carbon footprint of construction operations. The shift to sustainable construction methods by utilising agro-industrial waste in brick production corresponds with the overarching goals of sustainability, promoting a more robust and eco-friendly construction sector.

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IZVOD

PREGLED ODRŽIVE GRADNJE I UPRAVLJANJA OTPADOM: PROIZVODNJA CIGLE KORIŠĆENJEM AGROINDUSTRIJSKOG OTPADA

Građevinska industrija je veliki potrošač prirodnih resursa i značajan doprinos pogoršanju životne sredine. Održive građevinske prakse, posebno u proizvodnji cigle, postale su važne za ublažavanje ovih posledica. Upotreba agroindustrijskog otpada kao alternativne sirovine u proizvodnji cigle je inovativan pristup upravljanju otpadom i očuvanju resursa. Ovo istraživanje istražuje održivost korišćenja agroindustrijskog otpada kao što su pepeo od pirinčane ljuske, leteći pepeo, bagasa i drugi nusproizvodi za proizvodnju cigle. Procenjuje njihove ekološke, ekonomske i tehnološke prednosti, dok se suočava sa problemima kao što su varijabilnost materijala, metode obrade i poštovanje propisa. Ovo temeljno istraživanje ima za cilj da uspostavi okvir za korišćenje agroindustrijskog otpada u konvencionalnim metodama gradnje kako bi se postigli ciljevi održivosti.

Ključne reči: Prirodni resursi, održiva gradnja, agroindustrijski otpad, upravljanje otpadom

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