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Rice Husk Biomass Valorization in the Circular Bioeconomy: Energy, Soil, and Industrial Applications

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agricultural residue utilization, biomass conversion technologies, soil amendment strategies, carbon sequestration in soils, waste-to-resource systems, renewable material development, environmental remediation materials, sustainable resource management

Abstract. Rice husk is a high-volume lignocellulosic residue that remains underutilized despite its silica-rich composition, leading to environmental pollution and inefficient resource use. This review evaluates integrated valorization pathways within a circular bioeconomy, focusing on energy conversion, soil improvement, and industrial material applications. A systematic review of peer-reviewed studies published from 2000 to 2025 was conducted to synthesize evidence on rice husk utilization across sectors. Studies were screened for relevance and rigor, then grouped into three domains: thermochemical energy processes, agricultural and environmental applications, and industrial material development. Data were extracted and analyzed using thematic synthesis to identify trends, performance outcomes, and research gaps. Results show that one ton of rice husk can generate about 800 kWh of energy and reduce up to 1 ton of carbon emissions through gasification and combustion systems. In agriculture, biochar application increases soil cation exchange capacity by 20 to 30% in sandy soils and improves water retention, nutrient availability, and microbial activity. In industrial applications, rice husk ash contains 85 to 95% amorphous silica, which enhances strength and durability in cement and composite materials and supports pollutant adsorption in water and soil systems. Additional findings highlight its role in water purification, soil stabilization, and development of composites and nanosilica-based materials. Rice husk valorization improves resource efficiency and supports sustainable production across energy, agriculture, and industry. However, variability in processing methods, scalability constraints, and limited long-term validation restrict wider adoption. Integrated, standardized, and field-based approaches are required to enable practical and large-scale implementation.

Introduction

Rice (Oryza sativa L.) is one of the most important staple crops worldwide, particularly in Asia, where production and consumption exceed 90% of the global total (International Rice Research Institute [IRRI], 2020). Major rice-producing countries include China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Japan, Philippines, Republic of Korea, and Pakistan (IRRI, 2020). In the Philippines, rice serves as the primary staple food and a central driver of the agricultural sector, contributing significantly to rural livelihoods and national food security (Mutert & Fairhurst, 2002; Casinillo, 2022a). Government interventions such as the Rice Tariffication Law (Casinillo, 2020) and the Farmer Field School program (Red et al., 2021) support efforts to improve rice production and farmer capacity.

Rice milling generates substantial agricultural residues, mainly rice straw and rice husk (Tateda, 2016). Rice husk, the outer protective layer of the grain, is separated during milling after parboiling. This by-product is produced in large quantities globally, with Asia generating approximately 770 million tons annually (IRRI, 2017). In the Philippines, rice husk waste is estimated at 3.2 million metric tons per year (Sarong & Orge, 2015). Despite its abundance, rice husk is often treated as waste, with more than 90% disposed of through open burning or dumping. These practices release greenhouse gases and air pollutants, including carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), sulfur dioxide (SO2), nitrogen oxides (NOX), and particulate matter (PM2.5 and PM10) contributing to environmental degradation and public health risks (Junpen et al., 2018; Quispe et al., 2017; Singh, 2018; Golshan et al., 2002).

Rice husk contains valuable lignocellulosic components, including cellulose, lignin, hemicellulose, pentosans, and a high silica content (Mishra et al., 2023). These properties make it a suitable feedstock for multiple applications. In energy systems, rice husk can be converted into heat, syngas, and bio-oil through combustion, gasification, and pyrolysis (Li Zi, 2020). In agriculture, rice husk biochar improves soil fertility by enhancing nutrient retention, water-holding capacity, and microbial activity, particularly in nutrient-poor soils (Singh et al., 2018; Akumuntu, 2024). In industrial applications, rice husk ash provides a source of amorphous silica used in construction materials and environmental technologies (Santana Costa & Paranhos, 2018).

The global generation of rice residues is estimated at approximately 1.2 billion tons annually (Santana Costa & Paranhos, 2018; Medina Litardo et al., 2022), yet the utilization of rice husk remains limited. Most existing studies focus on isolated applications, with limited assessment of economic viability, environmental impact, and scalability across sectors. Variability in processing methods and husk composition also leads to inconsistent findings. Long-term field studies and integrated approaches remain insufficient, particularly in developing countries.

This review synthesizes current knowledge on rice husk biomass valorization within a circular bioeconomy framework, focusing on energy systems, soil management, and industrial applications. It evaluates environmental and economic implications, identifies research gaps, and outlines future directions for integrated and sustainable utilization. The study aligns with key Sustainable Development Goals, including SDG 2 (Zero Hunger) through improved soil productivity, SDG 7 (Affordable and Clean Energy) through biomass-based energy conversion, SDG 12 (Responsible Consumption and Production) through resource recovery and efficient material use, and SDG 13 (Climate Action) through emission reduction and carbon storage.

This review supports researchers, policymakers, and practitioners in advancing efficient, system-based utilization of rice husk biomass across multiple sectors.

Methodology

This section presents a structured description of the review approach and procedures used in the study. It outlines the scope and context of the review, the sources of literature, the selection criteria applied, the review design, the specific methods for screening and extraction, the data collection process from published works, the step-by-step procedure followed in organizing evidence, and the techniques used to synthesize and analyze findings across energy, soil, and industrial applications of rice husk biomass within a circular bioeconomy framework.

Research Design

This work follows a systematic literature review design. It synthesizes evidence on rice husk biomass valorization across energy, agricultural, environmental, and industrial domains. The approach supports structured evidence integration and minimizes selection bias through defined screening criteria.

Search Strategy and Data Sources

Peer-reviewed articles, conference papers, and institutional reports were retrieved from Scopus, Web of Science, ScienceDirect, and Google Scholar. Publications from 2000 to 2025 were included to capture both foundational and recent advancements. Keywords used included rice husk, biomass conversion, biochar, silica recovery, bioenergy, circular bioeconomy, and waste valorization.

Selection Criteria

Studies were included when they focused on rice husk utilization, reported experimental or applied findings, and provided measurable outcomes on energy, soil, or industrial performance. Exclusion criteria covered non-English sources, opinion papers without empirical basis, and studies unrelated to rice husk applications. Relevance and methodological clarity guided final inclusion.

Data Extraction and Synthesis

Relevant data were extracted into structured matrices covering application type, process conditions, outputs, and performance indicators. Studies were grouped into three domains: energy systems, soil and environmental applications, and industrial material development. Comparative synthesis was applied to identify trends, gaps, and converging findings.

Data Analysis

A thematic synthesis approach was used to integrate findings across studies. Patterns were identified based on application efficiency, material performance, and environmental outcomes. No statistical testing or significance levels were applied since this is a qualitative evidence synthesis. Reference management software supported organization and screening of literature.

Results and Discussion

CHEMICAL COMPOSITION OF RICE HUSK

Cellulose and Hemicellulose

Cellulose is the dominant structural polymer in rice husk, accounting for approximately 35-40% of its dry weight, along with 15-20% hemicellulose. Cellulose is a long-chain glucose polymer that forms the primary structural scaffold, while hemicellulose – a branched, shorter-chain polysaccharide – fills the spaces between cellulose fibers and contributes to the overall rigidity of the cell wall. Together, these polysaccharides form the bulk of the organic matrix. They are also the primary source of crude fiber, which makes rice husk relevant in livestock feeding as a dietary supplement that aids rumen digestion (Agriculture Institute, 2025).

Lignin

Lignin accounts for roughly 20-25% of rice husk by weight. The lignin content in rice husks can reach up to 22.5% and is notably higher than in rice straw. Lignin is a complex aromatic polymer that binds the cellulose and hemicellulose fibers together, acting as a natural adhesive. It is highly resistant to microbial and enzymatic degradation, which is one of the reasons rice husks decomposes slowly in soil and resists biodegradation. Lignin also contributes to the thermal stability of the husk, giving it fire-resistant characteristics that are useful in insulation application (Agriculture Institute, 2025).

Silica – the defining inorganic component

Of all the constituents of rice husk, silica (SiO_2) is the most distinctive. Silica is the main inorganic constituent of rice husk, with ultrafine particles and a suitable particle diameter. The silica content typically ranges between 16-22% of the total dry weight. Rice husks are composed of approximately 20% silica and 80% lignocellulose by weight, forming a unique lignocellulose-silica network. This silica is not randomly distributed – it is concentrated primarily in the outer epidermis and inner epidermis near the grain, forming a hard, abrasive surface coating.

The presence of silica is what gives rice husk its characteristic hardness and abrasiveness. It makes the husk resistant to wear, difficult to compost, and challenging to incorporate into biodegradable polymer systems without prior treatment. However, this same property is what makes it invaluable to industries requiring high-silica raw materials. When rice husk is burned, it generates rice husk ash (RHA) containing 85-95% amorphous silica, which has been widely used in manufacturing silicates, zeolites, catalysts, cement additives, and lightweight construction materials over the past two decades (Agriculture Institute, 2025).

PHYSICAL PROPERTIES OF RICE HUSK

The physical properties of rice husk flow directly from its composition and layered structure. These properties determine how the husk behaves during storage, processing, and end-use application.

Low bulk density

The bulk density of rice husk is low, lying in the range of 90-150 kg/m^3. This means the husk is lightweight relative to the volume it occupies. While this makes it easy to handle and transport, it also poses challenges for storage – large volumes are needed to store even modest quantities by weight. The low bulk density is, however, an advantage in applications requiring lightweight filler materials, such as lightweight concrete, insulation boards, and packing materials (Agriculture Institute, 2025).

High crude fiber content

The high cellulose, hemicellulose, and lignin content translates directly into a high crude fiber value. Rice husks are lignocellulose biomass composed of 35-40% cellulose, 15-20% hemicellulose, and 20-25% lignin, all of which contribute to the crude fiber fraction. This high fiber content gives rice husk its fibrous, tough texture. In animal nutrition, it is used as a roughage supplement for ruminants, where its fibrous structure aid's digestive function. However, the high lignin fraction limits digestibility, meaning its nutritional value as animal feed is limited unless subjected to chemical or physical pre-treatment (Agriculture Institute, 2025).

Low thermal conductivity and insulating properties

One of the most practically significant properties of rice husk is its low thermal conductivity. Rice husk-based insulation panels have demonstrated a thermal conductivity coefficient of 0.073 W/(m·K), which falls within the range of conventional thermal insulators. This value places rice husk in the same category as many commercially used natural insulation materials. Importantly, the sample with the highest silica content in its chemical composition yielded the lowest thermal conductivity, confirming that silica plays a fundamental role in the thermal insulation behavior of rice husk.

The insulating performance of rice husk is a result of multiple interacting factors: its porous, hollow fiber structure traps air; its low bulk density reduces heat-conducting mass; and the silica-rich outer layer adds a degree of thermal resistance. Studies show that increasing rice husk content in a composite can produce decreases in thermal conductivity due to the corresponding reduction in bulk density. These properties make rice husk a candidate for eco-friendly building insulation, particularly in tropical and hot-humid climates were keeping heat out is as important as retaining warmth (Agriculture Institute, 2025).

Abrasiveness and resistance to degradation

The silica embedded in the outer epidermis makes rice husk physically abrasive – a property that is immediately apparent when handling raw husk material. This abrasiveness is why rice husk is resistant to mechanical breakdown and slow to decompose in soil without microbial or chemical intervention. Efforts to utilize rice husks are limited due to their hard, woody, and abrasive nature, low nutrient content, resistance to degradation, large, generated quantities, and high ash content. Pre-treatment – whether acid leaching, alkali treatment, or thermal processing – is often required before the husk can be effectively used in composite materials or silica extraction processes (Agriculture Institute, 2025).

Furthermore, rice husk ash is an example of plant biomass that highly used in the making of materials. One of the main reasons is the high contain of silica (Si) and it is important in the making of ceramic nanocomposite. Besides that, rice husk ash is an important material in the silica nitride formation due to rice husk high Si content (Soltani et al., 2017c)

Component	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
Straw	32.0–38.6	19.7–35.7	13.5–22.3	10–17
Husk	28.6–43.3	22.0–29.7	19.2–24.4	17–20

Source: Mirmohamadsadeghi and Karimi (2020)

Table 1. Major components of rice straw and husks (%).

SUSTAINABLE ENERGY APPLICATIONS

Energy generation and techno-economic performance

Biomass energy is cheaper than other forms of renewable energy. Utilizing 70% of rice husk residues can generate about 1328 GWh of electricity annually. The cost of electricity from rice husk is about 47.36 cents per kWh, which is lower than coal at 55.22 cents per kWh (Mohiuddin et al., 2016). Converting rice husk into fuel is one of its most important uses (Hossain et al., 2018). Rice husk serves as an energy source due to its organic composition (IRRI, 2016). It undergoes thermal processes such as combustion, pyrolysis, and gasification (Sikarwar et al., 2016). These methods produce heat, electricity, syngas, and biofuels (Pradhan et al., 2013). Rice husk supports energy supply in countries with high production like China and India (Pradhan et al., 2013).

Rice husk is partially used as fuel in rice mills to generate heat to dry paddy and burning of rice residue may be practiced in the field (Shafie, 2015; Pode, 2016). Rice husk energy production often relies on gasification for small-scale systems. Gasification heats rice husk to produce combustible gases that drive turbines and generate electricity (Kumar et al., 2013). In rice mills, husk is used to produce steam for parboiling. A rice husk power system in India shows a practical setup where husk is fed into a gasifier, converted into gas, filtered, and used to run an engine for electricity generation (Pandey, 2011). Currently, two main methods produce energy from rice husk, gasification and direct combustion. Gasification uses about 1.86 kg per kWh, while combustion uses about 1.3 kg per kWh (Islam & Ahiduzzaman, 2013). A heating system study showed feasibility, emission reduction, and economic benefits (Asumadu-Sarkodie & Owusu, 2016b). Furthermore, rice husk has electrical and thermomechanical properties and shows promising electric resistivity (Bahrami et al., 2020). Rice husk produces electricity at a rate of 1.6 to 1.8 kg per kWh and shows lower CO2 emissions than coal and diesel (Lubis, 2018).

Thermochemical conversion processes and system performance

Rice husk gasification operates at high temperatures with limited air, producing combustible gas. This process is used in many Asian countries and supports engines, turbines, and fuel cells. One ton of rice husk can produce about 800 kWh and reduce about 1 ton of CO2 (Pode, 2016). An ideal process yields non-condensable gas and ash (Prasara-A & Gheewala, 2017). Gasifier studies show performance differences depending on feedstock (Susastriawan & Saptoadi, 2019). Rural electrification using biomass gasification has also been reported. Sustainable supply remains necessary for long-term use.
Rice husk is used for household fuel, but open burning contributes to air pollution and methane emissions. Methane has a higher global warming impact than carbon dioxide (Lubis, 2018).

Biofuel production and renewable fuel pathways

Given the rapid increase in worldwide energy demand, a growth of about 30% is projected by 2040 (OECD, 2016). Accordingly, substantial efforts have been made to replace fossil fuels with more sustainable renewable energy sources, such as agricultural wastes (Ge et al., 2016; Biswas et al., 2017). RH features a three-dimensional network structure composed of organic carbon and silica, which can be used to produce activated carbon, silica, syngas, and biofuel (Soltani et al., 2015). Although not sustainable, RH can serve as a coal replacement with fewer pollutants (Nayak et al., 2017).
Biogas can be obtained from lignin-rich materials such as RH in a reactor (Reaño, 2020). Gasification of RH to produce syngas has become a topic of interest in recent years (Bernardo et al., 2017). Reaño (2020) pointed out that RH can be used to produce green biohydrogen and used as a second-generation fermentative resource in bioethanol production due to its ability to deliver fermentable sugars such as glucose, xylose, arabinose, galactose, and mannose (Kaur & Singh, 2017; Tabata et al., 2017). RH is a suitable raw material for power plants, as it outperforms fossil fuels in terms of environmental emissions.

Energy-related materials and by-products

Rice husk produces energy-related materials such as biochar, activated carbon, silica, and silicon-based materials (Pode, 2016). Its porous structure allows adsorption of gases (Shen & Zhang, 2019). Additives from rice husk reduce pollutant gases and capture heavy metals during thermal processes (Wang et al., 2020a). Thermal decomposition shows stepwise degradation. Hemicellulose and cellulose degrade at 225–337 °C. Further degradation occurs at 332–380 °C, and lignin breaks down near 480 °C (Alaba et al., 2019).

Advanced energy materials and storage

Rice husk (RH) nanostructures are increasingly applied in modern energy technologies, including Li-ion batteries, supercapacitors, solar cells, and triboelectric nanogenerators (Wang et al., 2018). RH is also used to produce cost-effective carbon materials, which serve as efficient additives for Li-ion batteries (Zhang, Y. et al., 2020). Additionally, RH-derived silica can be converted into high-purity silicon to create uniform nanoporous silicon nanostructures, demonstrating excellent performance as anodes in Li-ion batteries (Cho et al., 2016). RHA has been utilized to produce a more affordable and environmentally friendly source of Si that can be used in solar cells to absorb sunlight (Putranto et al., 2021).

AGRICULTURAL AND ENVIRONMENTAL APPLICATIONS

Water purification and pollutant removal

Rice husk biochar (RHB) has demonstrated strong adsorption capabilities for removing contaminants from water. It effectively eliminates antibiotics such as levofloxacin and tetracycline from aqueous solutions (Yi et al., 2016; Bushra & Remya, 2020). Chemically modified rice husk, for example with 3-amino-propyl triethoxysilane, can remove metals such as scandium from wastewater (Salman et al., 2020). Mesoporous silica–polymer hybrids derived from rice husk and polyvinylpyrrolidone also show high efficiency in adsorbing divalent heavy metals (Betiha et al., 2020). RHB has also been shown to remove herbicides such as 2,4-D from agricultural drainage water (Amiri et al., 2018). Rice husk and rice husk ash are effective biosorbents for water purification and can remove nitrate ions, providing a cost-effective alternative to reverse osmosis, chemical precipitation, and membrane filtration (Dey et al., 2021; Afjeh et al., 2020). RHA has also been used to adsorb pharmaceutical contaminants including acid orange 7, amoxicillin, metformin, and carbamazepine (Swarnalakshmi et al., 2018). The high porosity and large surface area of rice husk enable efficient removal of heavy metals including manganese, nickel, and chromium from water (Batagarawa & Ajibola, 2019).

Dye removal from wastewater

Rice husk, rice husk biochar (RHB), and rice husk activated carbon (RHAC) are effective adsorbents for removing chemicals from industrial effluents (Prapagdee et al., 2016). The toxicity of certain dyes, some of which are mutagenic or diseasecausing, requires their removal from water (Chowdhury et al., 2011). Common removal methods include biological oxidation, chemical precipitation, and adsorption. Studies show that RH and RHB effectively remove color compounds such as methylene blue from aqueous solutions (Darabi et al., 2018).

Soil stabilization and geotechnical applications

The addition of rice husk ash (RHA) to soil improves performance by reducing shrinkage cracking and increasing compressive and shear strength as well as the California bearing ratio (Chen et al., 2021). Combining RHA with pozzolan cement enhances soil structural stability (Wibowo et al., 2023). The addition of RHA to clay soils reduces soil plasticity by about 90% and decreases free swell by nearly 70%, highlighting its potential as a cost-effective green technology to enhance soil strength (Karatai et al., 2017).

Soil amendment and fertility enhancement

Rice husk biochar acts as a soil amendment with positive effects on crop growth and soil biological quality (Akumuntu, 2024). It increases soil nutrient retention, water holding capacity, and microbial biomass in nutrient-poor soils (Singh et al., 2018). Application of rice husk biochar improves soil chemical properties by increasing cation exchange capacity, with increases of about 20 to 30% in loam sandy soils and 9 to 13% in clay soils, reducing nitrate leaching (Ghorbani et al., 2019). Proper processing of rice husk also improves soil quality by increasing silica bioavailability in paddy fields (Badar & Qureshi, 2014; Sekifuji & Tateda, 2019).

Soil physical properties and water dynamics

Rice husk biochar improves soil physical properties by increasing porosity and surface functionality, which enhances water retention and infiltration. Its porous structure increases soil surface area and improves water movement. Increased soil water holding capacity has been observed in Savannah Ochrosol, basalt, and grey soils (Duong et al., 2017). Combining RHB with waterlogged conditions improves rice growth, as shown by increased dry paddy biomass (Paiman & Effendy, 2020). These effects are more pronounced in coarse-textured and low-fertility soils (Ahmadi et al., 2020).

Crop productivity and agronomic performance

Rice husk biochar improves rice growth and yield, especially when combined with organic amendments. Higher application rates increase crop performance compared to untreated soils. The combined use of rice husk biochar and composted poultry litter produces higher rice productivity than single applications, with residual application of 20 Mg ha^{-1} biochar and 20 Mg ha^{-1} compost showing sustained benefits (Suswana, 2022). Rice husk mulch also improves crop performance. Application at 60 q/ha increased chickpea yield to 17.10 q/ha due to improved soil moisture, temperature, and weed suppression (Budhirani et al., 2025).

In commercial mushroom production, casings containing sawdust and RH are used as substrates to provide moisture and proper conditions for the initial growth of mushrooms, thereby improving quality and yield (Anyakorah and Dike, 2013).

Soil biological activity and microbial interactions

Rice husk biochar enhances soil biological activity and supports plant growth without toxicity. Application rates up to 1.5% increase enzyme activities such as alkaline phosphatase, beta-glucosidase, and dehydrogenase, which improve nutrient cycling (Akumuntu, 2024). It promotes beneficial microbial groups including Massilia, Bacillus, and Trichocladium, leading to improved plant growth. Rice husk-derived materials also enhance microbial growth, sporulation, and antifungal properties of Bacillus species (Ebe et al., 2019). The application of rice husk biochar with Bacillus pumilus improves rice productivity depending on genotype (Win et al., 2019).

Waste management, composting, and nutrient recycling

Rice husk improves composting efficiency and compost quality when added to organic waste. Its moisture absorption regulates temperature, moisture, pH, and carbon to nitrogen ratio, leading to faster decomposition and stable compost (Afrinata Riska et al., 2024). It also improves water holding capacity and aeration, which enhances microbial activity and increases composting temperature (Liu, 2018). Rice husk contributes to nutrient recycling and soil fertility in composting systems (Thiyageshwari et al., 2018). Farmers often apply rice husk and straw directly to fields to support nutrient cycling, although burning is still practiced due to low cost and ease of disposal (Ahmed et al., 2015).

When RH is used as mulch alone or combined with sawdust or paddy straw, it can maintain soil moisture, regulate soil temperature, preserve soil organic matter, improve soil structure, and prevent soil erosion, ultimately generating a proper microenvironment for the development of soil microbiota and improving crop yields (Lalruatsangi et al, 2018).

Environmental remediation and pollution control

Rice husk-based materials support soil remediation by removing contaminants such as sulfadiazine when combined with compost and mycorrhiza (Ahmadabadi et al., 2019). They also act as adsorbents for removing hormones and antibiotics from manure, improving fertilizer safety (Wan Ismail & Umairah Mokhtar, 2020). Conversion of rice husk into biochar and nanosilica improves soil pH, organic carbon, and nitrogen, leading to better plant growth and reduced reliance on inorganic fertilizers (Sarong et al., 2020). Biochar also acts as a carbon sink, contributing to climate change mitigation (Sarong et al., 2020).

Biomass utilization in agricultural systems

Rice husk is a lignocellulosic biomass widely available as agricultural waste and can be processed into pellets for use as fuel alternatives to diesel and coal (Defonseka, 2018).

INDUSTRIAL APPLICATIONS

Composite Production and Polymer Reinforcement

Rice husk (RH) is widely used as a reinforcement material in bio-composites due to its physical and chemical properties (Majeed et al., 2017; Suhot et al., 2021). Since the 1970s, it has served as a filler in hybrid composites with polymers such as polypropylene, polyethylene, resins, and natural rubber (Bisht et al., 2020). Polymer composites reinforced with natural fibers, including RH, offer advantages such as high specific strength, low density, biodegradability, low cost, and reduced tool wear. These characteristics make them suitable for both industrial applications and fundamental research (Arjmandi et al., 2015; Hemnath et al., 2021).

Studies show that adding RH to composites, for example with sugarcane bagasse fiber, improves mechanical properties like tensile and flexural strength by reducing void content (Hemnath et al., 2021). RH combined with wood particles and other materials is also applied in producing panelboards and various building and construction materials (Chalapud et al., 2020; Akinyemi et al., 2022).

In textile and fiber-based applications, fibers derived from rice husk serve as natural reinforcement in polymer and biocomposite materials. Suhot et al. (2021) found that incorporating these fibers enhances the physical, mechanical, and thermal properties of polymer composites, making them suitable for textile and fabric-like materials. The resulting composites exhibit improved strength and durability while retaining biodegradability. Recent research shows that rice husk fibers are increasingly used in composite boards and bio-based fabrics to improve mechanical performance, reduce weight, and support environmental sustainability.

Studies on rice husk reinforced polymer composites report enhanced strength and durability in these materials while maintaining eco-friendly characteristics. Incorporating rice husk fibers into bio composites supports efforts to reduce reliance on synthetic fibers and lowers environmental impact by utilizing agricultural by products in new material applications (Suhot et al., 2021).

Ceramic Materials

Rice husk (RH) and rice husk ash (RHA) are utilized in ceramic production. For instance, porous ceramics can be produced from composites of alumina and RHA (Ali et al., 2017). The typical process for producing ceramics from RH involves several steps: milling the RH, combining it with liquid phenol resin in a 3:1 ratio, drying at 150–180 °C, carbonizing the mixture, crushing the carbonized material, pressing the crushed mixture with powdered phenol resin into discs, re-carbonizing the discs, and finally cooling the finished ceramic discs (Shibata et al., 2014). Rice husk (RH) is rich in silica, making it a sustainable resource for the ceramic industry and reducing reliance on natural raw materials (Hossain et al., 2019).

Its derivative, rice husk ash (RHA), has been utilized in cement mortar production and in manufacturing glass-ceramics, demonstrating its versatility in construction and advanced ceramic applications (Danewalia et al., 2016; Abdul Wahab et al., 2020).

Concrete and Cement Applications

The durability of recycled aggregate concrete (RAC) can be enhanced using various additives, including rice husk ash (RHA) (Ali Qureshi et al., 2020; Hu et al., 2020). Incorporating RHA in onshore structures improves cement performance by increasing durability, reducing cracks, and enhancing anti-fouling properties, resulting in a green self-consolidating concrete (Lertwattanaruk & Makul, 2021). Additionally, a blend of 5% RHA, 5% sugarcane bagasse ash, and 90% cement have been shown to produce superior concrete mixtures (Channa et al., 2022).

Rice husk (RH) can be used as a slurry additive because its surface contains abundant silica nanoparticles, which enhance the hydration potential and workability of cement grouts (Berktas et al., 2021). In recent years, rice husk ash (RHA) has been widely used as a supplementary cementitious material, significantly improving the strength and durability of cement-based products (Ali Farid & Zaheer, 2023). For example, partially replacing cement with marble powder and sand with RHA enhances both the mechanical and microstructural properties of self-compacting concrete (Chaudhary et al., 2023).

Rice husk ash (RHA), a byproduct of rice milling, has gained attention as a supplementary material in concrete due to its contribution to both sustainability and structural performance. Studies show that incorporating RHA into concrete improves its physical properties by enhancing particle packing and reducing voids within the mixture. This leads to a denser and more cohesive matrix, which increases compressive strength and durability. As a result, concrete structures with RHA exhibit improved load-bearing capacity and reduced susceptibility to cracking and long-term structural damage. These characteristics make RHA a suitable material for various construction and architectural applications (Kumar et al., 2016).

Brick and Construction Materials

Bricks are basic building materials that account for 15% of the circumventing cost. The use of agricultural wastes such as bagasse ash and RH in brick production, alongside traditional cement, has significantly reduced costs. Additionally, the resulting bricks are more resistant and lighter than traditional clay bricks (Kumar et al., 2022). RH is a suitable combustible material with the potential to produce porous insulating firebricks (Hossain et al., 2021). RHA is also used to produce construction products such as cement and bricks (Jittin et al., 2020).

Industrial Silica and Chemical Applications

Rice husk is recognized as a sustainable and abundant source of silica, with its ash (RHA) showing significant variability in silica content due to factors such as soil type, climate, and agricultural practices (Chen et al., 2018; Bakar et al., 2016). Thermal degradation produces RHA with 85–95% amorphous silica making it suitable for substituting high-purity ground silica in industrial applications. In addition, RHA serves as a key precursor for valuable compounds like sodium silicate, enhancing its industrial and commercial relevance in fine chemical production (Vayghan, Khaloo, & Rajabipour, 2013).

Recent studies highlight rice husk as a valuable raw material for industrial applications due to its high silica and carbon content. Its abundant amorphous silica can be extracted for use in ceramics, glass, rubber, and coating industries. Additionally, this silica functions as a reinforcing agent in polymers and as a filler in paints and adhesives, expanding its applicability across multiple sectors (Nzereogu et al., 2023).

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Catalysis and Environmental Management

Rice husk and rice husk ash (RHA) have diverse applications across catalysis, environmental management, and construction. They serve as pozzolanic materials for soil stabilization and as adsorbents for wastewater and air pollution treatment (Moayedi et al., 2019). RHA also supports biodiesel production, with its pyrolysis-derived biochar acting as a catalyst for transesterification and esterification reactions (Li et al., 2014). In construction, rice husk and RHA reinforce mortars, concrete, and other rigid materials, improving strength and ductility due to their cellulose, hemicellulose, and lignin content (Wang et al., 2022). Additionally, incorporating these materials into cement reduces reliance on reagents that generate CO2, contributing to more sustainable building practices (Adetukasi et al., 2020).

Rice husk-derived silica is widely applied in construction due to its ability to improve the physicochemical and mechanical properties of cement, concrete, and fiber-cement products. Its pozzolanic characteristics allow partial cement replacement, resulting in stronger, more durable materials while reducing environmental impact (Gomez et al., 2023).

In advanced industrial applications, rice husk silica serves as a support material in heterogeneous catalysts for environmental remediation and chemical processes. It is also employed in the development of nanostructured materials, including nanosilica and single-atom catalysts, which improve efficiency in oxidation and purification processes (Peralta et al., 2024).

Wang et al. (2022) demonstrated that RHA can serve as an alternative cementitious material in cemented paste backfill, promoting cleaner production through solid waste reduction. RHA modifies the pore structure, with micropores dominating in number and secondary pores in volume, and higher dosages combined with longer curing times reduce overall porosity while improving unconfined compressive strength. The study observed a negative linear relationship between porosity and strength, with failure occurring primarily through tensile cracking. Increased RHA also enhances hydration products, including calcium silicate hydrate (C–S–H) and ettringite, which strengthen the material and reduce pore spaces. These findings highlight RHA's potential to improve mechanical performance and microstructure in cement-based materials, supporting its sustainable use in mining backfill and waste management.

Packaging and Biodegradable Materials

Ash and fibers from rice husk enhance the performance of biodegradable materials in packaging applications. Donati et al. (2022) reported that adding the ash to starch-based foams improves physical and mechanical properties, making the material more suitable for packaging while maintaining biodegradability. These composites overcome limitations of traditional bioplastics by increasing strength and reducing water sensitivity, supporting the development of eco-friendly packaging.

Conclusion and Recommendations

The direct utilization of rice husk (RH) and its derivatives reduce the cost of agricultural waste disposal while generating value-added products across multiple sectors. RH-derived materials such as rice husk ash (RHA), rice husk biochar (RHB), and activated carbon have shown strong potential in energy production, agriculture, environmental management, and industrial manufacturing. Current studies confirm that RH supports applications in the fuel industry through combustion, gasification, and pyrolysis, producing heat, electricity, syngas, and biofuels with lower emissions compared to fossil fuels. In modern energy systems, RH-derived carbon and silica materials are applied in Li-ion batteries, supercapacitors, and solar cells, demonstrating high efficiency and cost-effectiveness.

In the agricultural sector, RH improves soil fertility, water retention, and microbial activity, leading to increased crop productivity and better nutrient cycling. Its use in composting and mulching enhances soil structure and supports sustainable farming systems. In environmental applications, RH-based materials act as effective adsorbents for removing heavy metals, dyes, antibiotics, and other contaminants from water and soil. These functions provide low-cost and efficient alternatives to conventional treatment technologies.

In industrial applications, RH serves as a raw material for producing composites, ceramics, cement additives, and lightweight construction materials. The high silica content of RHA enables its use in manufacturing glass, coatings, catalysts, and nanostructured materials. Recent developments highlight its role in advanced technologies, including nanosilica production and catalyst support systems for environmental remediation. These applications show a transition from bulk, low-value uses to specialized, high-value products.

The increasing number of studies on RH reflects its expanding role in the bioeconomy. Its integration into agricultural, industrial, and energy systems supports resource efficiency, reduces environmental impact, and promotes rural development. However, challenges remain in terms of process standardization, scalability, and long-term performance validation.

Future research should focus on developing integrated utilization pathways that combine energy generation, agricultural improvement, and industrial processing. High-output and advanced characterization methods are needed to optimize RH properties for specific applications. Greater emphasis should also be placed on pilot-scale and field-based studies to ensure practical implementation. Expanding the use of RH in high-value sectors such as nanotechnology, energy storage, and advanced materials will further increase its economic impact. These developments position RH as a strategic resource not only in rice-producing countries but also in global markets where sustainable and renewable materials are in demand.

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study; all data used were obtained from previously published sources as cited in the reference list.

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Appendices

No appendices are attached to this study.