Rice Waste Feedstocks: A Review of Alternatives for their Conversion into High-Value Added Products

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The increase in global population, expected daunting energy demands, and scarcity of resources has driven the search for new sustainable sources of materials, energy, and chemicals. In this context, biomass valorization has emerged as a promising technology to obtain high-value products in recent years. This research focuses on the valorization of rice production waste including straw, husk, and bran, due to their abundance, underutilization, and potential in generating a wide range of valuable products such as biofuels and materials. A systematic review was conducted regarding the valorization of rice production waste. The characteristics of biomass obtained from post-harvest rice production were explored, as well as the primary products derived from each of the discussed biomass feedstocks. Furthermore, the economic viability of the obtained products in their respective fields of application was evaluated, providing a solid foundation for future research and industrial applications. Different rice waste materials studied hold significant potential to obtain high-value products including silica, adsorbent materials, biofuels, and various bioactive compounds.

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INTRODUCTION

The increase in global population has raised significant concerns about the availability of various products used by our society (Su and Xu 2022). Consequently, the scientific community is continuously exploring alternatives to replace currently utilized natural resources. Among these research efforts, biomass valorization to obtain high-value products stands out as one of the most promising approaches with potential to replace certain current end products. Biomass is defined as any organic material of plant or animal origin that can be used as an energy source or converted into useful chemicals or materials. Its key features include the ability to store solar energy through photosynthesis, its availability in various forms, and its potential to reduce greenhouse gas emissions as compared to fossil fuels (Núñez-Delgado *et al*. 2022; Stančin *et al*. 2023).

Numerous biomass feedstocks with interesting characteristics have been studied over the decades, demonstrating the potential to be converted into valuable products such as biofuels, biogas, high-purity chemicals, cosmetics, among others (Dessie *et al*. 2023; Drobniak *et al*. 2023). However, one biomass that has garnered significant attention within the scientific community is derived from waste products in rice production (Fig. 1). Due to its abundance and availability in many regions worldwide (economically and environmentally attractive option), rice waste has emerged as a promising alternative for the production of value-added products. It is estimated that approximately 1.2 billion tons of rice residues are generated annually worldwide post-harvest (Santana Costa and Paranhos 2018; Medina Litardo *et al.* 2022). The residues generated during rice production can be classified into three main types: straw, husk, and bran, each with distinct characteristics and potential for the production of different materials of interest. In general, they can serve as a source of bioenergy, raw materials for bioplastics production, construction materials, organic fertilizers, and high-value compounds, such as silica (Overturf *et al*. 2020).

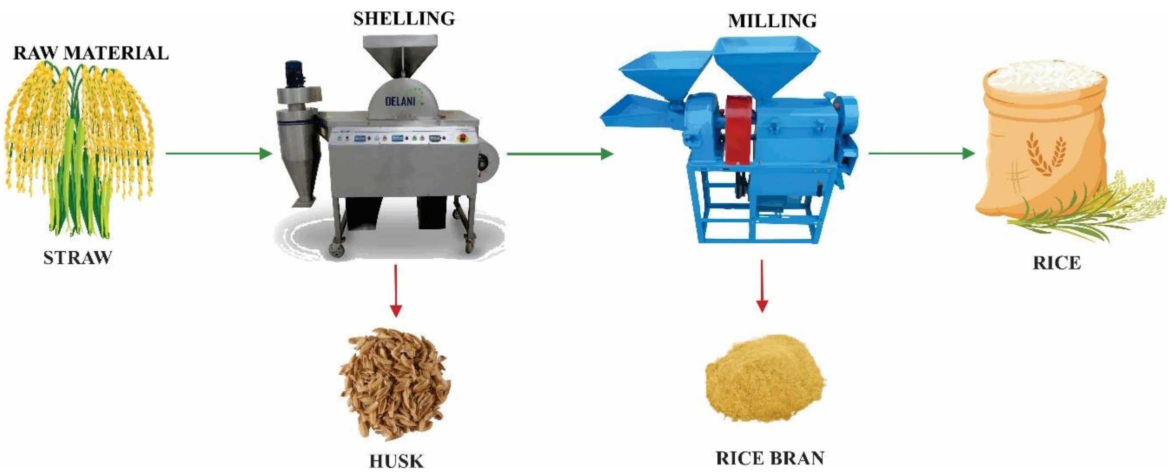

Fig. 1. Rice production waste generated during the process

Recent publications including those by Gupte *et al.* (2022) and Illankoon *et al.* (2023), have demonstrated the feasibility of using these types of residues to obtain high-value products. These studies covered various approaches found in literature, highlighting the potential of these biomass feedstocks. Therefore, the aim of this present research is to compile and analyze relevant information on the utilization of rice production residues. To achieve this objective, the main products derived from the three primary biomass sources mentioned will be described. The feasibility of these products will be analyzed based on the relationship between the obtained product and its market price, aiming to discuss which of these products holds prospects for higher profitability. This analysis will pave the way for future research to enhance our understanding of the products derived from rice production waste and their potential industrial applications, avoiding potential gaps in knowledge.

Rice Straw (RS)

Rice straw (RS) possesses interesting characteristics that allow it to be utilized in various technologies, such as raw material for composting, paper production, energy generation, mushroom cultivation, gasification, pyrolysis, construction material, pellet production, silica extraction, feed for ruminants, biofuel production, adsorbent, and biochar production (Zheng *et al*. 2023). Its chemical composition typically consists of approximately 35% to 45% cellulose, 25% to 35% hemicellulose, 15% to 25% lignin, 5% to 20% silica, 15% to 20% ash, and 3% to 8% proteins and fats (Tian *et al*. 2020). As a result, numerous studies have been conducted on these biomasses to enhance their profitability and expand their field of utility for waste products. In Fig. 2, the general production of two high-value products from rice straw can be observed.

Biofuels

Numerous research efforts have been directed towards RS for biocompound production, aiming to find cost-effective alternatives to traditional fuels and to utilize this biomass that is often burned (Michailos and Webb 2020). However, such endeavors can yield limited returns based on process profitability. An alternative approach to address these challenges involves biomass modification for biocompound production. In this regard, Saini *et al*. (2023) proposed modifications to RS biomass to produce bioethanol. They achieved an impressive increase in yield (>70%), reaching up to 7.28 $g*L^{-1}$ of bioethanol. Their method involved reducing lignin content and enhancing available carbohydrates, followed by subjecting the biomass to a cellulase cocktail to facilitate bioethanol production. Another avenue for biocompound production from RS biomass involves rice modification. Hu *et al*. (2023) focused on a mutant rice variety (cesa7), conducting a recalcitrance study of lignocellulose to enhance accessibility and biomass porosity. Consequently, they observed heightened bioethanol production compared to a wild-type variant subjected to the same process. The most intriguing finding, however, emerged during biomass saccharification, achieving hexose contents exceeding 96%. This allowed for application in the production of highly porous aerogels with a significant surface area, rendering the process not only economically viable but also enabling the utilization of these biomasses in various combined processes.

Similarly, RS has been involved in biodiesel production processes. This involves its modification with other materials such as graphene oxide as catalysts using a liquefaction process with supercritical ethanol for the conversion of oils into bioethanol. The results demonstrated the efficacy of such modified biomass for biofuel production. The optimal parameters used during the process led to a 33.4% conversion of the raw material into biofuel, all at a temperature of 320 °C and a catalyst weight percentage of 5% (Echaroj *et al*. 2021). Similar research focusing on biodiesel production was conducted by Saetiao *et al*. (2023). In this study, the authors converted palm oil using an RS ash support with varying amounts of calcium oxide (25 to 35% by weight) and calcination temperatures (600 to 800 °C) to produce biodiesel. The results of this study achieved a yield of 96.5% conversion to biofuel under optimal working conditions of 4.87% by weight of catalyst (35% by weight of calcium oxide treated at 600 °C), 175 minutes of reaction time, 65°C reaction temperature, and a methanol:oil ratio of 9.34:1. These findings demonstrate that different approaches to biomass can contribute to the production of biofuels using various raw materials. Despite the continuous evolution of RS conversion into biofuels, its high oxygen content limits its commercial application. However, proper pretreatment can help address current issues such as the treatment of waste oils from petroleum industries. Xu *et al*. (2022) proposed an innovative solution for treating petroleum sludge (OS) using RS to enhance the production of different hydrocarbons. In this process, RS underwent torrefaction and subsequent co-pyrolysis with OS. As a result, these processes synergistically improved gas production, significantly enhancing the formation of alkanes and olefins while reducing the generation of oxygenated compounds in the oil. This led to improved oil quality by increasing hydrocarbon concentration at the expense of oxygenated compounds.

Bio-Gas

Despite the significant advances achieved in biomass modification and pretreatment for its lignocellulosic content, these processes come with certain drawbacks that diminish process profitability. As a result, new research endeavors have emerged to address these issues. An example of this is the utilization of N_2, CO_2, and O_2 nanobubbles, which were employed as soaking agents and catalysts to enhance anaerobic digestion performance. This led to a 21.4% increase in methane production compared to pristine RS, with a maximum production of 313.9 ml*g^{-1} VS (volatile solids). Nanobubbles demonstrated a promising alternative for two-step biogas production processes (Wang *et al*. 2023a). Similarly, other approaches for this biomass in biocompounds production have been proposed. The production of clean hydrogen was proposed by Pan *et al*. (2023). In this study, wood chips and RS were subjected to an innovative multi-generation energy system based on co-firing with an air electrolysis membrane exchange agent, a supercritical carbon dioxide Brayton cycle, and a humidification-dehumidification system. Results showed that hydrogen production from RS reached 1.96 kg*h^{-1} with a CO_2 production rate of 10.41 g*kWh^{-1}. The cited research validated the potential use of a system ensemble for energy production. The obtained results underscore the capacity of this biomass to contribute to future energy generation.

Combining different processes has demonstrated a significant improvement in the yield of various biofuels. Dong *et al*. (2023) proposed the feasibility of a study for the continuous production of a mixture of CH_4 and H_2 (denoted as *biohythane*) from RS using an anaerobic bioreactor integrated under thermophilic conditions. The results showed yields of up to 612.5 ml*g^{-1} VS with a composition of approximately 17% H_2 and 83% CH_4. The viability of this study is highlighted by *biohythane* production rates, as this process significantly increases the production of both gases by up to 13% more than if the production processes are carried out separately. Furthermore, the utilization of energy employed increases by up to 167% in terms of conversion of the target products, making the study an intriguing perspective for RS utilization.

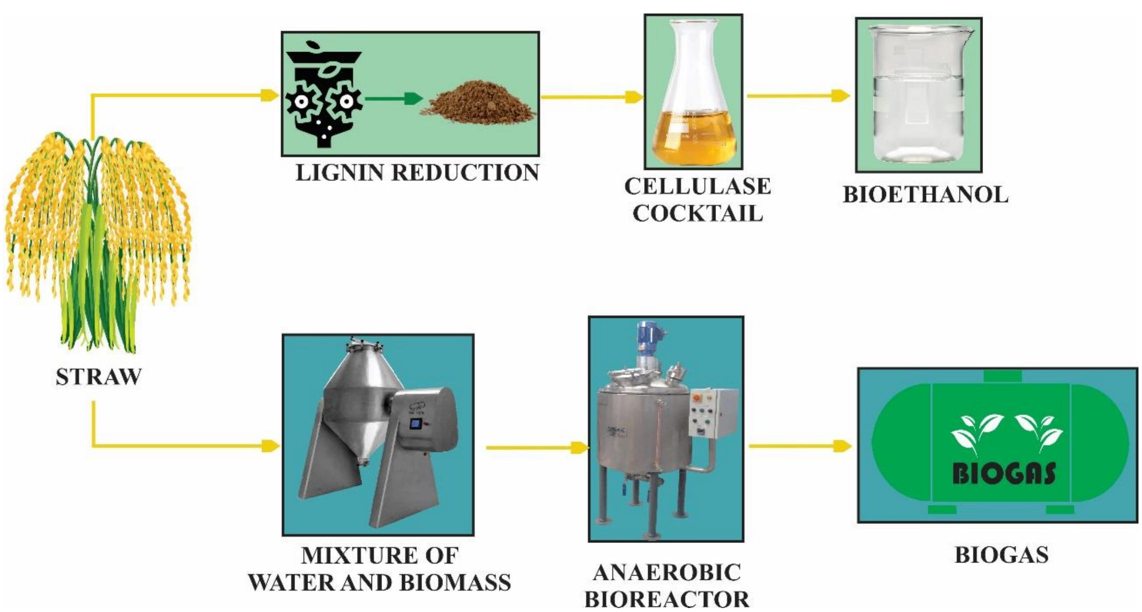

Fig. 2. General scheme for obtaining biofuels and biogas from rice straw

Materials

The use of RS in reclaimed soils increases nutrient content and potential crop production. Although this technology has not yet been developed to provide clear operational concepts, several studies have demonstrated that incorporating these biomass feedstocks can degrade various contaminants present in the soil. Tian *et al.* (2023) conducted research to measure the emergence of antibiotic resistance in soils contaminated with norfloxacin, to which RS, biocarbon and ashes were added. The results of this study showed an increase in nutrient content in the soil upon the addition of RS as compared to the control soil, as well as a significant increase in the resistance attributed to straw and biocarbon. This soil modification allowed for the degradation of norfloxacin, while ash content inhibited drug degradation. However, the authors suggested optimizing the process to enhance biodegradation and more effectively inhibit antibiotic resistance in the soils. Narzary *et al.* (2023) pointed out that producing briquettes from rice straw can be a complex task due to the properties of this biomass despite the favourable calorific value. In this regard, they used binders with RS in a carbonization drum to alter the physical properties of this carbonized biomass. The results showed that density, tear resistance, and calorific value increased compared to biomass without binders, allowing for the formation of stable briquettes with improved characteristics. These briquettes, with respect to those made from paper, tars, or starch, require less energy for production, indicating a potential for burning this material and providing an alternative energy source. The proposed concept demonstrate that various carbonaceous materials can be obtained from RS depending on the methodology. This has also been evidenced in Wang *et al.* (2023), where modified biocarbon with $Ca(OH)_2$ was synthesized and employed to remove methylene blue from contaminated water. The morphological characterization of the material and its physical characteristics (Fig. 3) demonstrated the presence of carbon and oxygen within the RS matrix, as well as the presence of functional groups OH, CO, Si-O that can be modified with other compounds, along with a porous structure that allows for effective material functionalization. All of this resulted in an adsorption capacity of 333.3 $mg*g^{-1}$.

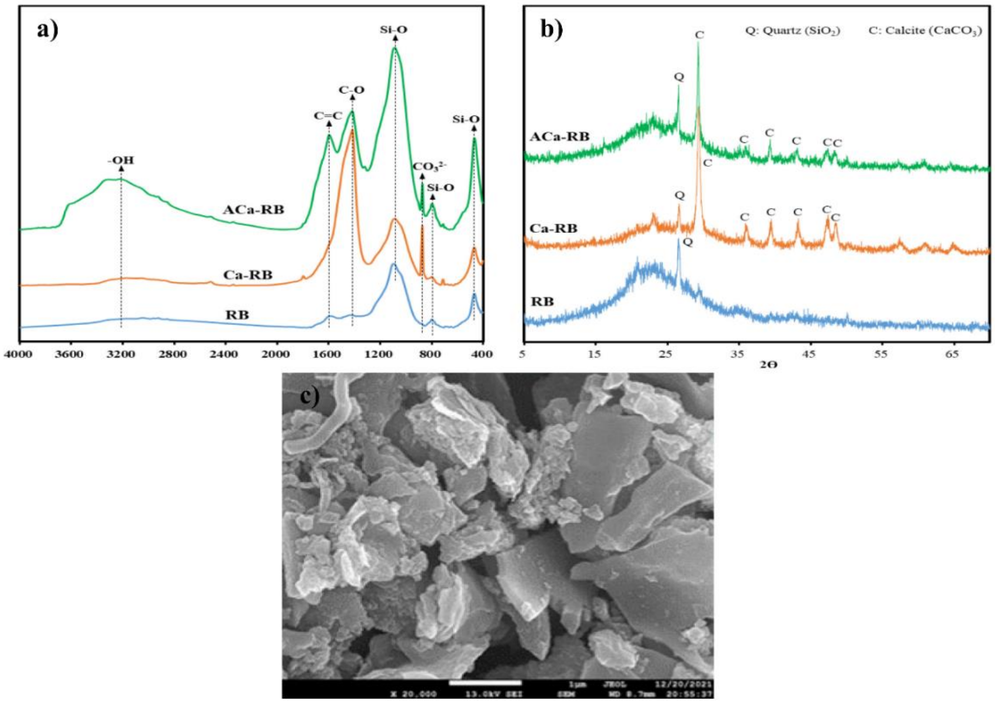

Fig. 3. Morphological and physical characterization of biochar (RB) from rice straw: a) FTIR, b) XRD, c) SEM. Reproduced by permission from Elsevier, Wang *et al.* 2023b.

Hydrogels were also synthesized from RS and subsequently applied to sandy and calcareous soils at a ratio of 0.2% by weight. The results showed that the application of these hydrogels to soils improves their hydrophysical, physicochemical, and biological properties, being an excellent addition during drought times, as it enables optimal conditions for crop growth with a reduced volume of irrigation (Solieman *et al.* 2023). Bangar *et al*. (2023) presents a different approach to the applications of RS, where their research focuses on developing biodegradable packaging materials from this biomass. This approach is promising, as it allows for the conversion of these waste materials into packaging materials, offering an alternative to traditional plastic waste and addressing the associated environmental issues. The researchers extracted cellulose using unconventional methods such as ultrasonication or microwave irradiation, and then modified the properties of this cellulose to form nanostructures, ultimately creating bioplastics. The results of this study indicated that the material’s properties make it suitable for various plastic-related applications such as food packaging, biodegradable containers, edible films/coatings, active packaging, and more. This innovative and sustainable approach provides a new solution to the plastic waste problem. Similarly, biomass modification has demonstrated increased yields and applicability in various fields. Saini *et al*. (2023) proposed modifications aimed at delignifying the biomass and increasing the percentage of available carbohydrates. This modified biomass was subsequently subjected to a cellulase cocktail for application in bioethanol production. Moreover, the lignin extracted from the pretreatment streams exhibited the ability to act as a biopesticide and biofertilizer. It showed promising results against *H. armigera* larvae, implying that the findings from this research offer a promising strategy for reutilizing pretreatment streams, making processes more cost-effective and expanding their application.

Rice Husk (RH)

Rice husk has been the subject of various uses and applications due to its properties. Among the rice production residues, it is the most studied, as studies have reported its use as a substrate for edible mushroom cultivation, livestock feed, manufacturing of ceramic and refractory materials, as well as production of active silica, among other value-added compounds (Yaghoubi *et al*. 2019). Several studies reported various characterization experiments for rice husk, which have allowed researchers to identify its main components. Research results including those from Morales-Paredes *et al.* (2023) and Zambrano-Intriago *et al.* (2022) pointed to porous structures and irregular fragments with holes for rice husk as determined using SEM. EDX analyses also confirmed a high presence of silicon, carbon and oxygen. Furthermore, FTIR spectra revealed the presence of various functional groups such as OH, COOH, Si-OH, CHO, and C=O.

This makes rice husk applicable in various fields, with a strong emphasis on adsorbent materials. Although the chemical composition of rice husk may vary depending on the region where it is produced, in general, it consists of 25 to 35% cellulose, 18 to 21% hemicellulose, 26 to 31% lignin, and 15 to 25% silica (Rajamani *et al*. 2023). Despite the great potential for various applications of rice husk, determining the most economically profitable or beneficial uses is of significant importance.

Silica

Silica is a compound with numerous applications in the field of chemistry, owing to its versatility and unique physicochemical properties. However, it is not freely available in nature, and conventional processes for obtaining it are considered unsustainable due to the involved procedures (Villota-Enríquez and Rodríguez-Páez 2023). Hence, discovering new methods and sources that require fewer treatments for its extraction could be an intriguing proposition. In this context, research has been conducted to obtain silica from biomass derived from RH. Shrestha *et al*. (2023) synthesized biogenic silica nanoparticles from rice husk ash through a process involving leaching with hydrochloric acid, followed by pyrolysis at 600 °C, and a sol-gel method. The sol-gel method is widely employed to create inorganic materials and thin films. In this method, a solution with inorganic or metallic compounds is treated with a precursor solution to form a colloidal dispersion. These dispersions are then hydrolyzed and condensed with the metal precursors to form inorganic polymers, allowing for the synthesis of materials and thin films at lower temperatures as compared to solid-state methods (Innocenzi 2023). The results of this study demonstrated highly pure amorphous silica, containing approximately 86.5% of heterogeneous amorphous silica nanoparticles with particle sizes around 50 to 60 nm, mesopores ranging from 10 to 30 nm, and the presence of Si-OH polar bonds. This material was employed as a chromatography column filler for the separation of ortho and para-nitroanilines, as well as ortho and para-nitrophenols, effectively accomplishing the task with a mobile phase composition of 80% hexane and 20% ethyl acetate, as shown in Fig. 4.

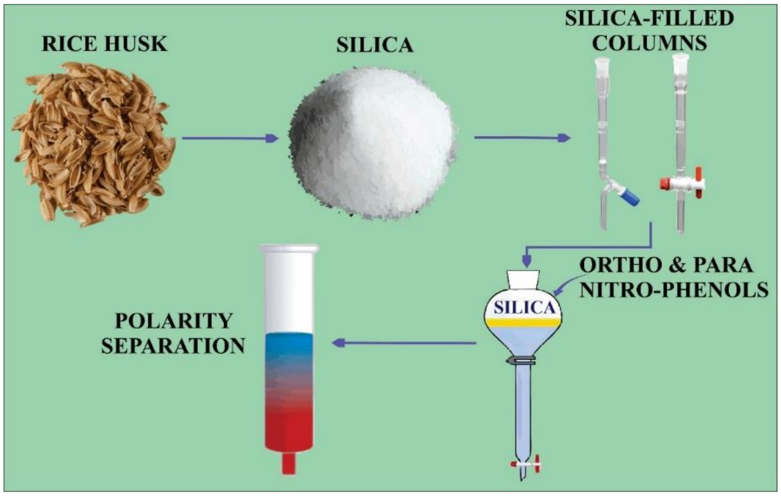

Fig. 4. Silica-filled chromatographic column for ortho and para-nitrophenol separation

These findings illustrate that waste materials can be transformed into valuable products, such as a chromatography column stationary phase. A similar study was conducted to obtain silica from rice husk ash using various alkaline methods (KOH and NaOH) with sol-gel precipitation. The outcome yielded irregularly shaped amorphous silica particles with an average particle size ranging from 10 to 50 µm, depending on the type and concentration of alkali used. Given the substantial amount of ash resulting from combustion, this study enables the transformation of such waste into a highly value product (Aprilia *et al*. 2023).

Research such as that conducted by Haider *et al.* (2022) demonstrated the applicability of such materials. In that study, silica was derived from treating RH with sulfuric acid using various calcination and combustion processes. The resulting silica was then employed for the removal of dyes (methylene blue). The findings of this investigation revealed that the obtained silica was amorphous and mesoporous with purity exceeding 94%, and a yield conversion of over 72% without the need for additional calcination. These characteristics allowed for the adsorption of 107 mg of methylene blue per gram of silica in one hour of adsorption. This not only presents an environmentally friendly approach for the reuse of waste generated from rice husk but also offers a solution for treating dyes present in water. Due to the promising results yielded by the extraction of silica from RH, various approaches have been developed to obtain such silica. Franco *et al*. (2018) designed a method for obtaining high-purity silica (>95%) using a mechanochemical/microwave approach. They employed a ball mill in which RH was combined with an acidic solution, followed by microwave treatment to obtain silica. This approach not only facilitated the extraction of high-purity silica but also allowed for the mechanochemical incorporation of metals onto the silica surface to create nanocatalysts. These nanocatalysts exhibited excellent catalytic activities, enabling the selective quantification of monoalkylated products. Once again, this showcases the significant value of this biomass and its potential application as supports for nanocatalyst development.

Noori *et al*. (2023) coupled zirconia with the silica obtained from RH, which was used as a catalyst for carbon-carbon bond formation through the Heck reaction under solar irradiation. In this study, they first synthesized silica nanoparticles and then modified the surface through trimethoxysilane grafting. Thiol-ene free radicals were subsequently reacted with zirconia alkenes using azobisisobutyronitrile as an initiator. The catalytic capacity of the nanocomposite was tested in the arylization of olefins under concentrated solar irradiation and conventional thermal conditions. The results of this research demonstrated that utilizing solar irradiation for the arylization of olefins using modified silica as a catalyst offers a more efficient alternative route due to its high energy savings and achieved yield. Therefore, this investigation presented a viable strategy through the utilization of a renewable energy source as an irradiation method, a non-volatile solvent, a straightforward methodology, catalyst recovery, and good yields within short reaction times.

Composite/Adsorptive Materials

Due to the mentioned properties of RH, its use as a base for the development of adsorbents can result in new materials with unique and enhanced properties. Fernández-Andrade *et al*. (2023), through an in-situ growth process, designed a hybrid (MOF@Biomass) using rice husk and microwave-synthesized Mil-53(AL) particles. This process involved pre-treating the RH, adsorbing Al onto RH, and an *in-situ* growth reaction with the MOF. This led to a significant size increase up to 400 times compared to Mil-53(AL) crystals and utilization of the product in the removal of oxytetracycline at 139 $mg*g^{-1}$, diclofenac at 93 $mg*g^{-1}$, and glyphosate at 162 $mg*g^{-1}$, achieving removal rates of 91%, 80%, and 97%, respectively. This demonstrated that MIL-53(AL) maintained its contaminant-degrading properties after hybridization compared to pristine MOF adsorption. Similarly, the development of Fe_3O_4 nanostructures using rice husk was achieved through a microwave-assisted combustion process. Analysis of the material revealed polycrystalline Fe_3O_4 structures with a size of 5 to 10 nm decorated with amorphous SiO_2 nano-spheres with a size of 50 nm, resulting in the obtained material $Fe_3O_4@SiO_2$. This transformed the non-magnetic material into a ferromagnetic state, which is not inherent to Fe_3O_4. The product had a saturation magnetization of 45 $emu*g^{-1}$. Moreover, using 100 mg of this adsorbent for 20 minutes could remove over 90% of Hg^{2+} ions at a concentration of 100 $mg*L^{-1}$. This demonstrates the potential of such RH-based materials for the removal of contaminants from water. However, the recovery of the adsorbent after treatment remains challenging, and different approaches may be needed. This material holds promise for cost-effective treatment of waters containing heavy metals. (Araichimani *et al*. 2022)

Various studies for the removal of emerging and hazardous contaminants using RH-modified adsorbents have been proposed, with highly promising results. Wang *et al*. (2022) developed a CO_2 adsorbent by impregnating KOH onto rice husk-based activated carbon (DKOH-AC), showing improved physicochemical characteristics of the material. The adsorption process was shown to be controlled by intraparticle diffusion. Adsorption tests in a chamber demonstrated promising results for the rapid reduction of CO_2 from 2000 ppm to less than 1000 ppm in approximately 100 minutes, with good regenerability and reusability. Similarly, Yang *et al*. (2022) developed an adsorbent (RHB-ZnO_3) based on rice husk-derived biochar and ZnO nanoparticles for batch adsorption of Reactive Red 24 in an aqueous solution. The material’s surface area was 13.84 $m^{2}*g^{-1}$, with an adsorption capacity of 174 mg per gram of adsorbent in 60 minutes, which was 4 times higher than the results obtained with ZnO particles. In addition, the low ZnO requirement of 3% (w/w) demonstrated the feasibility of RHB-ZnO_3 synthesis, considering the achieved yields during the research and reusability after multiple absorption-desorption cycles. A similar approach was used to develop multi-walled carbon nanotubes (MWCNTs) from rice husk and study their different functionalized forms with HNO_3/H_2SO_4 (MWCNT), NaOCl

(MWCNT), and H_2O_2 (MWCNT), which were subsequently employed in the adsorption of benzene and toluene. The results of this research demonstrated efficient integration of functional groups into carbon nanotubes, along with good adsorption capacities for the studied aromatic compounds. MWCNTs exhibited better adsorption capacity, while MWCNTs with functionalization by H_2O_2 represented the lowest capacity (Le *et al*. 2023). Therefore, it is evident that the use of this biomass in the production of different adsorptive materials presents a significant opportunity for the valorization of rice husk waste generated during rice production.

Rice Bran (RB)

Rice bran (RB) is the final product of the outer covering of rice after dehusking and milling, representing approximately 9% of the total weight during rice production. Despite this, due to its significant nutritional value, bioactive compounds, and substantial health benefits, its utilization can be profitable (Manzoor *et al*. 2023). In their research, Hong and Wang (2017) conducted a characterization of the morphological and physical properties of rice bran. This allowed them to demonstrate that this biomass has a cellular fiber structure with hexagonal or pentagonal shapes and lacks an appreciable porous structure. EDX analysis also showed the presence of magnetic particles, and functional groups NH and OH were observed through FTIR analysis. These results show that this type of biomass has favorable properties for various applications. Additionally, its chemical composition consists of 15% to 25% fats, 10% to 15% proteins, 10% to 20% dietary fiber, 45% to 60% carbohydrates, and 6% to 8% ash, in addition to vitamins and minerals. This has led to its use in various industries, including oil production, nutritional supplements, cosmetics, pharmaceuticals, fuels, among others. (Wancura *et al*. 2023)

Bioactives

Rice bran (RB) is highly nutritious and rich in bioactive compounds such as phenols with antioxidant activities. However, developing a cost-effective extraction method using solvents is crucial for its practical application. Bunmusik *et al*. (2023) optimized the ultrasound-assisted extraction process of bioactives from pigmented rice using solvents. The extraction parameters included temperatures of 20 to 60 °C, time intervals of 20 to 40 minutes, and a sample-solvent ratio of 1:10 to 1:30 mg*mL^{-1}. The results demonstrated that extraction conditions significantly affected bioactive compounds, as evidenced by the total content of anthocyanins, phenols, flavonoids, and antioxidant activities measured by DPPH (1,1-diphenyl-2-picrylhydrazyl) radical scavenging capacity. Optimal extraction conditions were achieved using 60% (v/v) aqueous methanol with 0.1% citric acid as the solvent, applying ultrasound at 30 °C for 30 minutes with a 1:20 mg*mL^{-1} sample-solvent ratio. These parameters minimize the cost-effective extraction of phytochemical bioactives and their potential use in various applications. However, solvent recovery can pose challenges. To address this, Moirangthem *et al*. (2021) conducted a similar investigation for anthocyanin extraction from RB. In this case, supercritical water-assisted microwave extraction was employed at 90 °C for 5 minutes. The obtained results demonstrated an extraction efficiency of 85.8% for anthocyanins, surpassing yields achieved by traditional solvent-based methods for rice bran bioactive extraction. Moreover, the potential to inhibit colorectal cell formation and the lack of cytotoxicity in Jurkat cell lines make this approach applicable in the field of biomedicine.

The combination of rice bran (RB) with other materials has also been studied in the conversion of RB into value-added products. The development of a controlled release system for bioactive graphene oxide, tailored to the target environment, was investigated using simulated intestinal fluid (SIF) and a surfactant solution. The material was prepared using lipid nanoparticles, obtained from nanostructured lipids (NLC) encapsulating bioactive γ-oryzanol (GO) from RB oil. The fabrication involved a hot homogenization process using sunflower oil and stearic acid as the encapsulating lipid matrix, RB phospholipids, and polysorbate 80 (Tween 80) as a stabilizer. The fabricated GO-NLC demonstrated a high encapsulation efficiency of 95%, with spherical morphology and an average particle diameter of 143 nm. As a result, the material exhibited an 18-fold increase in free radical scavenging activity, a 200-fold increase in anti-inflammatory activity, and a twofold increase in hyaluronidase inhibition. Furthermore, this characteristic was preserved by over 90% after 60 days under light and ambient temperature conditions. The obtained results indicate that this material functions as a rapid-triggered release system, as well as a colloidal nanocarrier for prolonged GO release (Villar *et al*. 2022).

Another approach to utilizing this biomass was proposed by Sapna and Jayadeep (2022). They suggested the optimal combination of cellulolytic-xylanolytic enzymes (CXC) with RB to enhance the release of nutraceuticals and bioactivities. This was achieved by using enzyme ratios of 1.5:3 (CXC1), 3:2 (CXC2), and 4.5:1 (CXC3) per 2g of RB. This led to a significant increase in ferulic acid in soluble phenols by 253%, p-coumaric acid in combined phenols by 66%, and γ-oryzanol fractions ranging from 41% to 743% for the CXC2 assay. These material properties exhibited higher ferric reducing power and DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity, nitric oxide and superoxide anion elimination, inhibition of human LDL oxidation, and hydroxyl radical scavenging. As a result, this combination improved the nutraceutical profile and antioxidant potential of RB. This opens up possibilities for utilizing the characteristics present in rice bran within the fields of phytochemistry and biotechnology, with various perspectives and applications.

Li *et al*. (2023) developed an intelligent film for monitoring various parameters of interest in the food industry. They investigated the effect of incorporating barley prolamins (HBP) on the properties of barley β-glucan films (HBBG), aiming to enhance the anthocyanins of black rice bran (BRA). The addition of HBP reduced the water vapor and oxygen permeability of the HBBG film. It also improved mechanical, thermal, optical properties, and water contact angle. This allowed for rapid color changes in the films (HBBG/HBP/BRA) observed under different pH solutions and ammonia atmosphere due to the anthocyanins in BRA. Moreover, it enhanced the stability of anthocyanins through hydrogen bonds formed by the materials used. These results enabled the monitoring of pork freshness at 4 ◦C and demonstrated the potential of using these films in packaging materials to extend the shelf life of foods. Additionally, these films showed high sensitivity to ammonia and significant color changes in a pH range from 2 to 13, making them suitable for monitoring food freshness.

Bioplastics

The high content of starch and proteins present in rice bran allows its use as a macromolecule in bioplastic production. This abundant resource from the agri-food industry has garnered interest in bioplastic production due to its abundance and low cost. Bioplastics are made from biopolymers, which can be found in residues generated by agricultural industries because of their protein, lipid, and polysaccharide content. Among the various sources used for bioplastic production, rice bran has emerged as a great option for obtaining bioplastics.

In this context, Alonso-González *et al*. (2021) developed bioplastics from a homogeneous mixture of RB, glycerol, and water, which was subsequently processed through injection molding. During this research, different mixtures were evaluated, yielding varying rheological behaviors during and after drying. However, the ratio of 55% RB and 45% plasticizing mixture (33% glycerol and water) at 80 °C exhibited the best results during experimentation, as the other mixtures had to undergo a drying process before injection molding. Moreover, it was demonstrated that temperature is a highly significant factor as it aids in starch plasticization and thus affects its properties. Nevertheless, even though higher temperatures result in improved mechanical characteristics compared to lower temperatures, they present poor physical integrity during water immersion due to stable properties generated at high temperatures, which has been primarily attributed to the loss of soluble matter. For this reason, developing a technique that enables greater medium stability will be essential for producing bioplastics with improved characteristics.

In one study, glycerol was mixed with rice bran and used to analyze the effect of three different molding temperatures (100, 130, and 150 °C) on the mechanical properties, microstructure, and water adsorption capacity of the final matrices. The results indicate that the combination of RB with glycerol leads to the disruption of hydrogen bonds, resulting in increased processability and enabling thermomechanical methods to be used in the fabrication of desired bioplastics. Additionally, it was demonstrated that although the Young’s modulus increases proportionally with the rise in temperature during injection molding, leading to a more compact structure, the water adsorption capacity decreases (Alonso-Gonzalez *et al*. 2021)

Alonso-González *et al*. (2022), in a preliminary investigation, focused on bioplastic production from rice bran after treating the raw material with water and different proportions of glycerol and sorbitol. The researchers aimed to deeply incorporate plasticizers by subjecting starches to shear forces at high temperatures and excess water (gelatinization). During this research, results obtained using different plasticizers with water were compared. The outcomes showed that while water is necessary for producing stiffer specimens, an excess of water hinders the injection molding process, leading to brittle bioplastics. The 2:1 glycerol/water ratio was the highest that could be processed, while the sorbitol/water mixture could achieve higher proportions of up to 4:1, demonstrating sorbitol as a better plasticizer. This illustrates the correct selection of plasticizers and water, producing stiffer bioplastics with viscoelastic modulus, maximum stress, Young's modulus, increased elasticity, and water absorption capacities. Additionally, the effectiveness of RB for bioplastic production is showcased. Despite the results obtained from these studies, the combination of various waste sources, such as rice bran as a biopolymeric material, and chitin found in shrimp shells, holds significant potential for the production of bioplastics. Chitin can be transformed into chitin nanowhiskers (CNW), which can reinforce the biopolymeric materials present in rice bran. Therefore, to enhance the starch properties, an investigation was conducted using CNW from shrimp shell waste along with the addition of glycerol as a plasticizer. Figure 5 shows a scheme of the combination of these wastes and their application in the production of bioplastics. The results of this study suggest that the combination of these two waste materials emerges as a promising alternative for bioplastics production. The bioplastics obtained during the research exhibited outstanding degradation properties in soil burial tests, with a degradation of 50.7% in sandy soil, 86.2% in humus, and 100% in compost over a period of 15 days. Despite this, mechanical properties such as tensile strength and water adsorption, while doubling compared to bioplastics produced solely from rice bran, still fell below standard parameters. This demonstrates that combining different waste materials can yield bioplastics with improved alternatives, and it is anticipated that future research will lead to process enhancements and better outcomes (Setiawan *et al*. 2022).

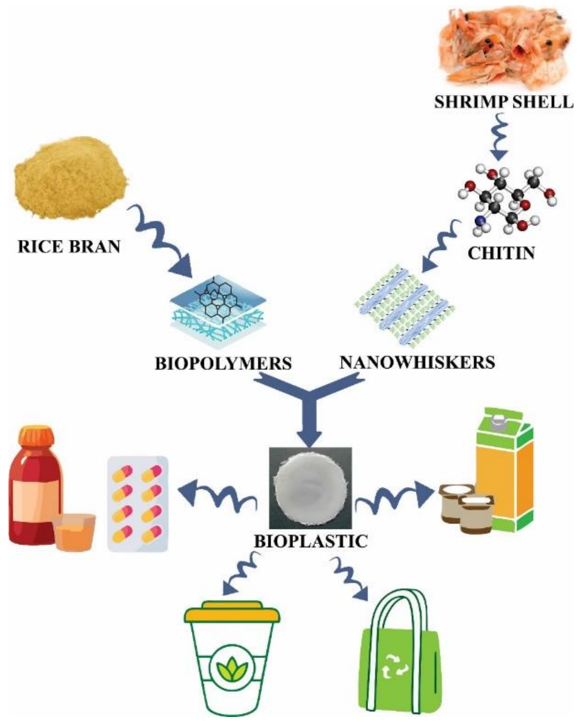

Fig. 5. Production of bioplastics from rice bran polymers and chitin nanowhiskers and their application fields

Another approach was proposed by Adnan *et al*. (2023), where they obtained polyhydroxybutyrate (PHB), a macromolecule produced by bacteria as part of their metabolism, using various agricultural residues as nutrient sources, including rice bran. In the study, ten bacterial strains were evaluated, and the *B. flexus* strain showed the highest PHB production after 48 hours of incubation using glucose as a carbon source and peptone as a nitrogen source. This was achieved through response surface methodology (RSM) using a Box-Behnken design (BBD). The results indicate that this methodology can be highly effective in optimizing PHB production yield, with optimal conditions leading to up to 1.3 times increased polymer production compared to non-optimized incubation methods, significantly reducing bacterial production costs. These macromolecules can be considered an alternative for bioplastics production due to their rapid degradation properties under natural environmental conditions. Moreover, the process is scalable for large-scale bioplastics production, with applications in various industrial sectors such as packaging, agriculture, and medicine. Therefore, improving process conditions and investigating PHB production in fermenters could be a promising alternative in the field of bioplastics, meeting the growing demand for environmentally-friendly plastics.

Economic Analysis of the Valorization of Rice Production Residues

Conducting a comprehensive economic analysis of rice waste for obtaining value-added products is a complex task given the properties and applications of each of the waste products generated during rice production. Additionally, the increasing research and existing methods for obtaining each product discussed in this work affect not only the economic performance of the different products but also their application in other industrial fields. Other waste from corn, sugarcane, or wood industry waste has also demonstrated significant potential in waste valorization. However, making a comparison with other waste can be a complex task. It is estimated that only 25% of all generated waste is recycled/valorized, while the rest is dumped in landfills or burned (Kee *et al*. 2022). Annually, 1102 million tons of corn crops (Aghaei *et al.* 2022), over 2000 million tons of sugarcane (Torres de Sande *et al.* 2021), and more than 1000 million tons of wood waste are generated (Xu *et al.* 2023).

Numerous research studies have shown the applicability of these biomass types for the production of (bio)materials, chemicals, and fuels. For example, Collard *et al.* (2022) obtained high-quality liquid fuel and gases from pine wood waste, while Xu *et al.* (2023) obtained modified bitumen with good mechanical properties and a porous structure through hydrothermal carbonization of wood. Zheng *et al.* (2022) generated high yields of H_2 from various straws, and Vaštyl *et al.* (2022) obtained gases, biochar, and oil through fast pyrolysis of cocoa pod husks and used tires. Moreover, Sica *et al.* (2023) achieved high ethanol yields from sugarcane waste. Each of these approaches demonstrates that other biomass feedstocks can also lead to high-value-added products. However, despite the similarities in the amounts of waste produced between rice production and other biomass sources, the content and diversification of rice waste allow for a wider range of applications and products such as the extraction of silica or bran during processing (Alan and Köker 2023; Torres-Mayanga *et al.* 2019). Additionally, other unexplored approaches in this contribution such as the use of carbonaceous materials as supercapacitor electrode materials (Ray *et al*. 2023; Wang *et al.* 2023), anode materials for lithium-ion batteries (Wu *et al.* 2022; Kumchompoo *et al.* 2023), the synthesis of materials for adsorption of heavy metals (Liu *et al.* 2022; Xu *et al.* 2022) or organic dye (You *et al*. 2022; Hu *et al.* 2023) pointed to the utilization of rice waste being more economically feasible as compared to other potential biomass sources. This section aims to provide a general overview of the profitability of utilizing biomass generated during rice production and identify which of these options would be the best choice for large-scale applications. Table 1 presents a comprehensive analysis of market prices for each material obtained from various biomass sources, along with the fields in which they can be applied. This demonstrates the approaches and feasibility of producing each of these materials and which of the different biomass sources is economically viable due to the variety of products or benefits they offer.

The various discussed biomass feedstocks show significant economic viability for obtaining value-added products, as shown in Table 1. While RS enables the production of biofuels, biogases, and different materials, the profitability and scalability of biofuels stand out in the RS-derived product spectrum. This, combined with the growing demand for alternative fuel sources and their industrial applications, positions biofuels as the most promising option to explore and research among the developed technologies for utilizing rice straw generated during rice production. The projected market value is $154 billion by 2024. Another material of consideration from RS is carbon-based materials. Data obtained suggests that such materials currently generate around $22.9 billion annually. Additionally, more cost-effective methods for their production make the utilization of RS for carbon-based material production a significant opportunity.

Table 1. Cost Analysis and Applications of Biomasses from Rice Residues

Biomass	Product obtained	Classifi-cation	Employed Configuration	Results Obtained	Market Value	Fields Used	References
Rice Straw	Biofuels	--	Fermentation of enzymatic hydrolysates pretreated with alkaline, oxidative, and enzymatic process (Saini *et al.* 2023)	The RS pretreatment led to significant sugar release, achieving fermentation yields of 73.0% to 85.3% with *S. Cerevisiae* strains. Furthermore, RS lignin showed pesticidal activity against *Helicoverpa armigera* larvae.	$US 154 billion to the end of 2024	Industrial Transport., Chemical Energy	(Jayakumar *et al*. 2023; Yoon 2022)
			The fermentation of a rice mutant created using the CRISPR/Cas9 method (Hu *et al.* 2023)	The mutant cesa7 had reduced lignocellulose recalcitrance, improving bioethanol production efficiency. Additionally, it enabled the synthesis of cellulose aerogels with high oil adsorption capacity.			
			Alcoholic liquefaction for biofuel production (Echaroj *et al*. 2021)	Alcoholic liquefaction enhanced biofuel yield from biomass such as RS, with temperature increase being a key factor. Moreover, higher acid concentrations led to improved cracking activity and increased biofuel yield.			
			Calcium oxide catalyst supported on RS ash for biofuel production (Saetiao *et al.* 2023)	The catalyst, with irregular particle shape and 42% calcium content, displayed robust catalytic activity for biodiesel production. It could be recycled up to 5 times, yielding biodiesel ranging from 96.49% to 65.30%. These significant yields show promise for its technology application.			
	Biogas	--	Anaerobic digestion for biogas production using nanobubbles with high-	Nanobubble application in anaerobic digestion notably boosted methane production, with CO_2 nanobubbles delivering the best results. Thus,	$US 4.2 billion per year	Chemical Energy	(Emmanuel *et al*. 2022; Kwon *et al.* 2022)

			purity gases (N_2, CO_2, O_2) (Wang *et al*. 2023)	incorporating this method in anaerobic digestion processes can be advantageous.			
			Anaerobic fluidized bed acidogenic reactor for biohythane production (Dong *et al.* 2023)	The results showed an impressive biohythane yield of 612.5 ml/g VS, comprising roughly 17% H2 and 83% CH4. The study's value is in its remarkable biohythane production rates, achieving a 13% increase over separate H2 and CH4 production processes.			
	Materials	Carbon Materials	Briquettes made from rice straw and starch as a binder (Narzary *et al*. 2023)	Results indicated that briquettes containing 15% taro starch by weight displayed excellent performance in calorific value and fixed carbon content, establishing it as a high-quality fuel source.	$US 22.9 billion per year	Medical Pharma-ceutical Agriculture Chemical Petro-chemical	(Li *et al.* 2023; Rojas *et al.* 2023; Roux & Varrone 2021; Yan *et al.* 2023)
		Packaging materials	Nanocellulose from RS, Starch, polyvinyl alcohol, and polylactic acid (Bangar *et al*. 2023)	The obtained packaging materials showed outstanding biodegradability, low production costs, and the integration of nanocellulose notably enhanced their mechanical and barrier properties, positioning them as a promising alternative in this field.	3,13 USD/kg		
Rice Husk	Silica	--	The Sol-Gel method was used to synthesize silica nanoparticles from rice husks (Shrestha *et al.* 2023)	Implementing this method enabled the production of highly pure amorphous silica nanoparticles. These nanoparticles can serve as filler material in chromatographic columns, facilitating the separation of ortho and para-nitroanilines and ortho and para-nitrophenols.	7.3 USD/kg	Glass Ceramics and paints Construct-ion Foundry	(Nandiyanto *et al*. 2020; Yadav *et al.* 2022)

			The effect of alkalinity on the synthesis of amorphous silica using the sol-gel method (Aprilia *et al*. 2023)	Using NaOH and KOH as alkaline solutions yielded silica nanoparticles with comparable functional groups, including siloxane, C-H, and silanol. Additionally, both amorphous and crystalline surfaces were observed, making this method suitable for obtaining such material from RH-Ash.		Electronics Food Pharma-ceutical Cosmetics Filtration	
			Synthesis of biogenic catalysts using a microwave-assisted mechanochemical approach (Franco *et al.* 2018)	The mechanochemical approach enabled mesoporous silica nanoparticle synthesis from rice husk. The cost-effective microwave-assisted process yielded highly pure amorphous silica. Subsequently, employing the same method, metallic particles were integrated into the matrix, resulting in the production of highly pure biogenic catalysts with fascinating properties.			
			The acid and alkaline treatments of rice husk ash were performed using NaOH, HCl, and H_2SO_4 (Haider *et al.* 2022)	The results demonstrated high-purity silica with structural variations depending on the washing type. Acid washing yielded a uniform, well-structured surface, whereas water washing resulted in a porous, rough surface. Both surfaces contained Si-O-Si functional groups. Furthermore, a substantial methylene blue adsorption capacity was observed, suggesting a combination of pseudo-first-order and pseudo-second-order kinetic models, implying both physisorption and chemisorption processes.			
			Catalyst based on silica functionalized with NaOH and 3-	The research yielded the nanocatalyst SiO2-S-Cin.Pd, employed in Heck coupling reactions. This material had a			

			mercaptopropyl (Noori *et al.* 2023)	spherical shape, featured Si-O-Si functional groups and C-H bonds, and contained 2.42% Pd by weight. It effectively catalyzed Heck coupling reactions with alkyl iodides and alkenes, exhibiting high recyclability.			
	Adsorptive Materials	MOF	MIL-53(Al)@RH using microwaves (Fernández-Andrade *et al.* 2023)	Functionalizing rice husk into the MOF matrix resulted in a material with substantial surface area and mesoporosity. Analysis confirmed the presence of functional groups and a high adsorption capacity. This facilitated the efficient removal of OTC, GLY, and DCL, with removal efficiencies exceeding 90%.	1200 USD/kg	Medical Environ-mental Treatment Pharma-ceutical Food Chemical and Petro-chemical Agriculture	(Hou *et al*. 2018; Rojas *et al.* 2023; Sukatis *et al.* 2022; Yan *et al.* 2023; Yashni *et al.* 2021; Yieh *et al.* 2019; Zeghoud *et al.* 2022; Zhang *et al.* 2023)
		Fe_3O_4	The $Fe_3O_4@SiO_2$ nanostructures using $FeCl_3.6H_2O$, $FeSO_4.7H_2O$, $Hg(NO_3)_2$, RH, NH_4OH (Araichimani *et al.* 2022)	The results indicated mesoporous and magnetic properties. The surface area of the nanostructure was 175 m^{2}*g^{-1} with an average pore size of 1.89 mm. Additionally, it showed significant efficiency in the removal of Hg^{+2}.	200 USD/kg		
		Carbon Nanoparticles	Activated carbon from RB treated with KOH. (Wang *et al.* 2022)	The analysis revealed irregular lumps and the presence of micropores after activation. Adsorption tests also showed a significant reduction in CO_2 from the air.	$US 22.9 billion per year		
			Nanotubes derived from RB functionalized with solutions of HNO_3/H_2SO_4, H_2O_2, or NaOCl (Le *et al*. 2023)	It was found that the different results had different characteristics depending on the solutions used. Furthermore, each of the products obtained from the functionalizations, MWCNT, MWCNT, and MWCNT, showed a great capacity for the removal of benzene and toluene.			

		ZnO	Electrochemical synthesis of ZnO nanoparticles loaded with rice husk biocarbon (Yang *et al.* 2022)	The results show proper impregnation of biocarbon into ZnO nanoparticles. Furthermore, it exhibited high adsorption performance after modification and could be recycled for up to 5 adsorption-desorption cycles. This modification also improved the adsorption capacity by up to 4 times compared to using ZnO nanoparticles alone.	100 USD/kg		
Rice Bran	Bioactive	--	Rice bran, aluminum chloride, solvents, and sodium bicarbonate (Bunmusik *et al.* 2023)	It was demonstrated that a 1:20 g/mL solvent ratio showed optimal operating conditions. Furthermore, the analyses determined significant concentrations of anthocyanins, phenols, flavonoids, and a 50% inhibition in the radical scavenging assay.	$US 65.6 billion to the end of 2028	Food Pharma-ceutical Medical Cosmetics Agriculture Biotech-nology	(Essien *et al.* 2021; Mounika *et al.* 2022)
			Subcritical water assisted by microwaves (Moirangthem *et al.* 2021)	This technique showed a great alternative for the extraction of anthocyanins from black rice compared to the traditional solvent extraction method, allowing for the recovery of more than 85% of the theoretical anthocyanin content.			
			Lipid nanoparticles with stearic acid, sunflower oil, and rice bran oil (Villar *et al.* 2022)	The GO-NLC nanoparticles exhibited efficient encapsulation of rice bran oil (GO), and the analyses demonstrated various bioactive properties such as antioxidant, anti-inflammatory, and hyaluronidase inhibitory activity.			
			Optimal combination of cellulolytic-xylanolytic enzymes through different methods	Combining enzymatic hydrolysis, solvent application, and acid treatments optimized the release of nutraceuticals and bioactivities. This led to notable			

			(Sapna & Jayadeep 2022)	changes in the phenolic profile, vitamin E content, and antioxidant capacity.			
			Intelligent Film Barley prolamins and black rice bran (Li *et al.* 2023)	The preparation of these smart films allowed for optimal monitoring of the freshness of pork, indicating changes in its color based on the state of the meat.			
	Bioplastics	--	RB, water, and glycerol (Alonso-González *et al.* 2021)	Bioplastics made from RB required the right mixing temperature for their production. They exhibited a high water absorption behavior and significant loss of soluble material.	$ 31,22 billion to 2027	Packaging Agriculture Auto-motive Electronics Disposable Tableware Toy industry Medicine	(Adnan *et al.* 2023; Djouonkep *et al.* 2023)
			RB, Water, glycerol or sorbitol (Alonso-Gonzalez *et al.* 2021)	The results indicated that glycerol yielded stronger bioplastics with greater thermosetting potential but poorer mechanical properties, while sorbitol exhibited higher properties and more rigid structures.			
			RB, water and glycerol (Alonso-González *et al.* 2022)	It was demonstrated that a water-glycerol ratio of 2:1 yields better results in terms of the strength and elasticity of the bioplastic. Furthermore, the processing temperature has a significant impact on the bioplastic properties.			
			Biopolymers, nanowhiskers, glycerol and water (Setiawan *et al.* 2022)	The obtained bioplastics showed a smooth, bubble-free surface, along with significant tensile strength and a high degradation rate.			
			Landfill bacteria for production of Polyhydroxybutyrate film (Adnan *et al.* 2023)	The results indicated an optimal production of up to 5.45g/L of PHB with ideal characteristics for use in the field of bioplastics.			

Similarly, products derived from Rice Bran (RB) also possess substantial potential for application across various fields, and they are estimated to become a significant part of industries' economies working with such compounds within a couple of years, as depicted in Table 1. Despite the projected $65.6 billion market value for bioactive by 2028 and $31.22 billion for bioplastics by 2027, the latter is particularly promising due to the growing demand for plastics and the environmental pollution they cause. Utilizing this biomass for bioplastics production or further advancing their technology may offer better profitability in the future, given the current issues associated with petroleum-derived plastics.

In summary, RH stands out as the most promising biomass to obtain high-value products as compared to other materials derived from the different biomass feedstocks showcased in this contribution. This is not only due to the extensive applicability of adsorbent and silica materials across numerous industrial sectors within our society but also the favorable pricing, the substantial quantities of reclaimable waste materials, and the developed technologies surrounding them, making these processes highly profitable and scalable. Coupled with material modification technologies that can be applied and the potential for combining them with other materials to enhance effectiveness, this makes it a compelling avenue. Therefore, labeling the different RH-based materials as superior to silica might not be the optimal choice. Hence, considering the general potential of this type of waste as a source for various adsorbent and synthesis materials provides a more accurate understanding of how this raw material could influence diverse environmental treatments, fields like medicine, filtration, cosmetics, food, and more. Nevertheless, each of the discussed biomasses presents significant potential in their application for producing value-added products. This not only enables the synthesis of diverse materials but also offers alternatives for managing the waste generated during rice production processes, thereby fostering a more circular economy and reducing environmental impact on our surroundings.

Future Perspectives and Conclusions

The utilization of residues generated in rice production and their conversion into high value-added products offer relevant potential for the valorization of such raw materials. The three primary biomass feedstocks derived from rice production (straw, husk, and bran) enabled the extraction of various products of great current interest. These products can find applications across a spectrum including (bio)fuels, the development of active compounds and plastics, as well as materials including silica or other adsorbents. These high value-added products can find applications in environmental remediation, biomedical applications, filtration, cosmetics, foodstuffs and various others. Furthermore, the combination of these materials with other technologies or substances not only broadens their field of application but also can potentially provide more economically feasible processes while enhancing the added value of such residues. Intriguing approaches including integrating MOFs with RH into nanohybrids, combining cellulose from RB with chitin for bioplastic production or merging modified RS with petroleum sludges for various hydrocarbon production, represent just a few of the remarkable possibilities offered by rice-derived waste fractions.

Each of the diverse approaches to obtain value-added products from selected fractions in this work exhibited potentially remarkable applicability within their respective fields of use, with potentially promising economic prospects. Based on these premises, researchers are prompted to continue studying and developing more cost-effective processes and novel products derived from various rice production residues as well as combining these fractions with others to expand their applications scope. This expansion is pivotal for a circular economy around these residues while respecting the environment.

We believe that this contribution can stimulate further studies focused on the development of new products as well as a future pilot-scale implementation of some of the aforementioned processes, which possess considerable potential but have not yet been studied for scaling up, *e.g.*, bioactives or bioplastics production. The future utilization of new waste feedstocks has the potential to play a substantial role in the economy and products used by our society, thus making them an integral, sustainable component of energy and material solutions. This, in turn, can foster the design of greener and cleaner processes and technologies for a more sustainable future.

Rice waste can be consequently considered a compelling alternative in the quest for new resources, also having potentially relevant valorization strategies towards the production of a number of valuable end products.

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