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A Comprehensive Study on the Valorisation of Rice Husk Hemicellulose for Sustainable Biodegradable Films and Bioadhesives: Extraction, Functional Properties, and Future Perspectives

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ABSTRACT:
Rice husk is a rich lignocellulosic agricultural waste produced in large amounts by rice milling sectors and poses a problem and an opportunity of biomass valorisation. Hemicellulose is one structural component, which has been gaining more interest because of its amorphous structure, chemical availability, and possible role in the development of sustainable materials. This review paper is a summary of the current developments in the extraction, characterization, and use of hemicellulose extracted out of rice husk. Different methods of extraction such as alkaline, dilute acid, hydrothermal, enzymatic, and hybrid processes are critically analysed with reference to conditions of the process, efficiency of the extraction process, and structural integrity of the extracted polymer. Alkali concentration, temperature, extraction time and solid to liquid ratio are also key parameters that are discussed on their effect on the yield and purity of hemicellulose. Moreover, the film forming capacity, bioadhesive properties of rice husk hemicellulose are also investigated and the material would work well as a biodegradable substitute of traditional synthetic polymers in packaging, coating and in adhesive wood use. Although improvements have been made, issues of moisture sensitivity, mechanical strength, and scalability of the process continue to be major hurdles to the industrial application. The review mentions the emergent strategies such as green modification, nanofiller reinforcement and integrated biorefinery as the way forward in improving performance and commercialization opportunities. Altogether, rice husk hemicellulose is a promising renewable platform of sustainable material growth in a circle bioeconomy.

KEYWORDS: Rice Husk, Hemicellulose, Alkali Extraction, Biodegradable film, Biomass valorisation, Bioadhesives, circular economy, sustainable processing, waste to value, Lignocellulosic biomass.

I. INTRODUCTION:

India is one of the major rice producing countries in the world and the state of Tamil Nadu provides approximately about 7-8 million tonnes annually, particularly from delta regions Thanjavur and Nagapattinam.Rice milling results in large volumes of rice husk, which constitutes nearly 20-22% of paddy weight, resulting in approximately 1.5-1.7 million tonnes of husk each year within the state. Due to the absence of comprehensive utilization plans, a large portion of this biomass has been discarded either by open burning or by landfilling and around the major milling plants, such as Chennai, which allows the release of harmful particulate matters and greenhouse gases resulting in various environmental problems such as soil degradation, air pollution etc. This urges the need for finding out the eco-friendlier way of utilisation.

Rice husk is a lignocellulosic biomass that is mainly made up of cellulose (35-38 %), hemicellulose (21-25%), lignin (17-20 %), and silica-based ash (15-17 %)[1].· These compositional fractions give sufficient abundance and cheap acquisition price, making rice husk a promising feedstock to biorefinery processes. Despite the usefulness of the carbohydrates fraction in various applications of the materials, the large-lignin matrix helps create a stiff, hydrophobic barrier that prevents the infiltration of solvents, along with the accessibility of enzymes6. At the same time, the high silica content that is typical of rice husk may lead to dislocation of alkaline extraction by forming colloidal or gel-like silicate complex, which in turn decreases filtration efficiency and affects the purity of the product.

Hemicellulose is one of the structural components that is a relatively amorphous and chemically accessible fraction that can be solubilised under controlled conditions. Alkaline, hydrothermal or enzymatic extraction methods allow the extraction of branched polysaccharides including arabinoxylans and xyloglucans, which have desirable adhesive and film-forming properties. biomaterials. Traditional synthetic adhesives, especially Urea-formaldehyde resins and Phenol-formaldehyde resins are widely used in the composite industries made of wood due to their strength and permanency. Although these benefits exist, the release of volatile formaldehyde into the environment during the production and use of the product has been associated with various health hazards as well as water bodies contamination[2]. Thus, it is vital to identify a better renewable adhesive system. As a result, hemicellulose can be used as an effective intermediate to create biodegradable films and bioadhesive formula, which will lead to the conversion of this agricultural residue into value-added biomaterials.

This review will discuss the existing methods to extract hemicellulose in rice husk, methods to optimise the extraction yield and material characteristics and subsequent biofilm and bioadhesiveformulations. Focus is put on the possibilities of hemicellulose-based substances as alternatives to traditional synthetic adhesives as sustainable solutions, which would play a dual role in ensuring resource efficiency and the creation of the circular bioeconomy.

II. STRUCTURE AND PROPERTIES OF HEMICELLULOSE FROM RICE HUSK:

Hemicellulose is found in the lignocellulosic matrix of rice husk in a content of around 21-25 % and occurs mostly as arabinoxylans and xyloglucans. After partial delignification, the hemicellulose could be selectively isolated by either alkaline, hydrothermal, or enzymatic processes, and made an accessible, versatile biopolymer to the creation of films and adhesive materials.Hemicellulose is more chemically reactive than cellulose, and due to its heterogeneous and amorphous structure it can easily be modified and processed as a material.

2.1. Chemical structureof rice husk hemicellulose:

Rice husk hemicellulose is structurally made with a backbone of 2-4 linked D-xylopyranose units that are substituted with different side-chain groups such as 4-O-methyl-D-gulucronic acid, acetyl, and 4-O-methyl-D-galactose groups in minor quantities[3]. These branched and relatively short polysaccharide chains generally having a lower degree of polymerisation than cellulose, establish a heteropolymer net that in controlled conditions provides its flexibility as well as solubility. The literature of spectroscopic studies generally reveals that the absorption bands at about 1730 cm^{-1}indicative of the carbonyl groups of acetyl or uronic linkage of the extraction product are found, and that the Xylan structure peaks are observed at about 1040cm^{-1} to confirm the presence of hemicellulose fractions. The chemical composition of rick husk lignocellulosic biomass is shown in Table 1.

TABLE 1: Chemical Composition of Rice Husk Lignocellulosic Biomass

COMPONENT	STRUCTURE	KEY TRAITS	ROLE IN RICE HUSK
Cellulose	Linear beta 1,4-linked glucan chains.	Highly crystalline, insoluble.	Provides structural rigidity.
Hemicellulose	Branched Xylan/arabinoxylan heteropolymers.	Amorphous, partially soluble.	Matrix filler linking cellulose and lignin.
Lignin	Phenolic crosslinked polymer.	Hydrophobic, Calcitrant.	Barrier against chemical penetration.

2.2. Differences between hemicellulose, cellulose and lignin:

As compared to cellulose, which is a highly structured crystalline microfibril, which gives it mechanical strength and thermal stability, hemicellulose is mostly amorphous and branched, giving it a low degree of crystallinity and increased sensitivity to hydrolysis at relatively mild chemical

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conditions. Lignin is a complex phenolic polymer that is found in the rice husk and adds rigidity to the structure and creates a protection scaffold around the carbohydrate to restrict the penetration of solvents and accessibility of enzymes[4]. The alkaline pretreatment process helps in removing part of the lignin to increase the availability of hemicellulose, which can be extracted. Furthermore, the existence of silica in rice husk paves the way to challenges in processing because it affects filtration and separation efficiency, even though it does not cause a dramatic change in the primary chemical structure of hemicellulose.The lignocellulosic structure of rice husk before and after pretreatment is depicted in Figure 1.

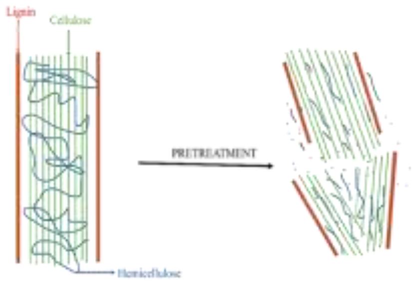

Figure 1: Lignocellulosic Structure of Rice Husk

2.3. Film-forming natureof rice husk hemicellulose:

The hemicellulose possesses the film-forming ability because it has numerous hydroxyl and acetyl functional groups that have the capacity to form intermolecular hydrogen bonds[9].Hemicellulose is capable of creating flexible and transparent films under appropriate conditions of processing, including the solvent casting or extrusion. According to the previous research, addition of plasticisers, such as glycerol, increases flexibility and ductility by weakening the intermolecular interactions, but without causing a high crystallinity level[5]. Such properties make the hemicellulose-based materials appealing in biodegradable film and coating.

2.4. Adhesion mechanismof rice husk hemicellulose-based bioadhesives:

Hemicellulose based systems are reported to adhesive because of the polar hydroxyl group which facilitates the formation of hydrogen bonding with lignocellulosic materials especially the wood surfaces. Hemicellulose exhibits a branched structure which adds to mechanical interlocking and increased wetting behaviour[6]. Several studies have shown that cross-linking agents, citric acid, and other biobased crosslinkers have the potential to enhance adhesive properties by undergoingesterification reaction and network formation during thermal curing. These are the changes that increases the bonding strength but retains the less toxic nature and this is what makes it better than the traditional adhesives.

III. EXTRACTION METHODS FOR HEMICELLULOSE FROM RICE HUSK:

The hemicellulose recovery of rice husk requires the utilization of appropriate pretreatment plans to overcome the difficulty of lignin as well as the silica processing issues that are associated with lignocellulosic biomass. In majority of the studies, delignification is followed by selective hemicellulose solubilisation by chemicals, hydrothermal or enzymatic method. The selection of extraction methodology has a significant effect on the hemicelluloseoutput, molecularintegrity, purity and environmental impact, and defines its use in final products including biodegradable films and adhesive systems. Recovery of hemicellulose has been reported ranging between 15-25 % of total amount of hemicellulose in rice husk, which depends on the conditions of processing and the efficiency of pretreatment.

3.1. Alkali extraction of hemicellulose from rice husk:

Alkali extraction is one of the most commonly used processes of hemicellulose recovery because of its high rate and ease of operation. The saponification of ester bonds that hold lignin and hemicellulose by sodium hydroxide solution (2-8 wt.%) at room temperature of 60-100℃, between 2-4hrs causes the solubility of hemicellulose as sodium hemicellulosate.Precipitation followed by neutralisation can produce yield of about 20-22% with impurities of over 85% under optimised conditions which include 4% NaOH at 80℃ in 3hrs[7].However the process yields alkaline effluents to be treated later, and dissolved silica might cause gel formation when recovering. Alkaline extraction has disadvantages but can be used in large scale biorefinery due to its economic value and scalability.

3.2. Acid extraction of hemicelluloses from rice husk:

Dilute acid extraction uses mineral acids likeH_2SO_4 or HCl (0.5-2%) at higher temperatures

(120-160 ℃) to hydrolyse the glycosidic bonds present in hemicellulose. The harsh treatments favour the depolymerisation to oligomers and monosaccharides, whereas mild treatments in which the reaction is controlled such as 1N H_2SO_4at 140 ℃ in 90 min allow partial recovery of polymeric hemicellulose with a yield between 18-20 %[8].Silica is solubilised well with acid extraction, butchallenges of the technique include corrosion of equipment, lower selectivity and degradation of cellulose with time exposure makes it a difficult method to use. As a result, dilute acid processes are better suited to manufacture of low molecular weight products like sugars or oligomers than to high molecular weight products like hemicellulose film or adhesive formation.

3.3. Hydrothermal methods for hemicellulose extraction:

Hydrothermal extraction employs hot, pressurised, compressed water at temperatures of about 180-220℃, and pressure of 10-40 bar. It takes advantage of the fact that hemicellulose is relatively less thermal resistant than cellulose. In this case, hemicellulose is subjected to autohydrolysis where acetyl groups dissociate to acetic acid in situ and as a result, the selective solubilisation is achieved without the use of external reagents. Efficacies of solubilisation have been reported as high as 66-97% with little loss of cellulose at optimum conditions. Hydrothermal treatment has also been enhanced to two steps, which enhances the recovery of holocellulose. Even though hydrothermal processing is energy intensive, it is environmentally favourable and uses specialised equipment. This technique is especially suitable when it comes to the production of Xylooligosaccharides and partially depolymerised hemicellulose fraction[9].

3.4. Enzymatic methods for hemicellulose extraction:

Enzyme extraction is usually conducted after physical or chemical pretreatment (Alkali treatment or steam explosion) to facilitate the exposure of substrates. Xylanase and Beta - xylosidase enzyme systems are mild work systems (pH 4.5-6,45-55 ℃) that allow the selective hydrolysis of hemicellulose components without affecting polymeric structure. Most yields of up to 90-95 % relative recovery were reported, and high molecular weight hemicellulose fractions were obtained with a molecular weight higher than 10kDa[10].The specificity of enzyme methods are high, making them applicable to food grade or high purity demands. But high enzyme prices and longer processing duration make the method inapplicable so far to large scale industrial applications.

3.5. Hybrid extraction approaches for hemicellulose recovery:

The combination of hydrothermal pretreatment with mild alkaline or enzymatic treatment is an emerging trend of hybrid extraction methods with an aim of enhancing the recovery of hemicellulose as well as reducing structural degradation[11]. This has made possible yields of over 25% without compromising the molecular properties of film-forming and adhesive use. Optimisation of the processes through the help of statistical software, response surface methodology, has also enhanced the extraction efficiency through the fine-tuning of parameters such as temperature, residence time and reagent concentration. The strategies are combined to help in the valorisation of rice husk as a renewable source of sustainable material development and bioadhesive production.

IV. PARAMETERS USED TO OPTIMISE HEMICELLULOSE EXTRACTION OF RICE HUSK:

Optimisation of Alkali based extraction parameters is critical for the recovery of the maximum hemicellulose and also for the maintenance of the molecular integrity needed in the downstream usage of the material. Alkali treatment is considered as one of the most scalable strategies of processing the rice husks among the extraction strategies available. Response Surface Methodology (RSM) has widely been used to determine the interactive impacts of process variables on the yield, the purity and the molecular weight of hemicellulose, and also to reduce lignin contamination and energy usage simultaneously. The major extraction parameters, such as alkali concentration, temperature, extraction time, pH, and solid to liquid ratio, are highly interdependent on which too much severity might maximise solubilisation, and in the process degrade polysaccharide.

4.1. Effect of NaOH concentration on hemicelluloses extraction:

Sodium hydroxide at concentration between 1 and 8% is usually used in extraction of hemicellulose. These have been reported as optimum concentrations of 4 %, allowing effective delignification and solubilisation of hemicellulose, and preventing over-solubilisation of cellulose.The partial removal of lignin at low concentrations limits the recovery of hemicellulose leading to low yields: less than 15 %[12]. On the other hand, the concentrations of more than 6 % can facilitate cellulose solubilisation and lower purity of extract. The alkali concentration and yield in RSM-based optimisation studies have always shown a quadratic relationship with the maximum recovery usually recorded in the 4-5% range.

4.2. Effect of temperature on hemicellulose extraction:

The temperature of extraction has a great impact on the mass transfer and reaction kinetics.Temperatures 60-100 ℃ are usually explored, and about 80 ℃ has been reported to have good results at 20-22 % yields with moderate severity of extraction[13].Reduced temperature conditions are more favourable to preserve the higher-molecular-weight fractions and leads to slower diffusion and less extraction efficiency.However, higher temperatures than 90℃ can cause a hydrolytic reaction, resulting in the depolymerisation of hemicellulose into oligomeric fractions and consequently, a reduction in the yield of polymer.

4.3. Effect of extraction time on hemicellulose extraction:

The extraction time is generally between 1-4 hours with a maximum of about 3 hours often documented at 80 ℃ and 4 % NaOH[14].Reduced extraction times can lead to incomplete solubilisation where longer extraction times after 4 h can lead to polymer degradation and low molecular weight. RSM procedures tend to show a non-optimal yield curve after the optimal extraction period and thus extended processing increases energy use instead of recovery efficiency.

4.4. Effect of pH conditions on hemicellulose extraction:

The process of extracting alkali is performed in extremely alkaline (pH 13-14) conditions, which enables swelling of fibres and breaking of the ester bonds between lignin and hemicellulose. After extraction, hemicellulose can be precipitated by acidification to a pH of about pH 2 with the use of mineral acids with recovery efficiencies as high as 90 % [15].Neutral washing to almost neutral pH follows to remove any remaining salts and impurities without causing much damage to the polymer structure.

4.5. Effectof solid-to-liquid ratioon hemicellulose extraction:

The solid to liquid ratio affects the efficiency of mass transfer, as well as solvent utilisation. Ratios between 1:6 and 1:16(S: L) have been explored, although intermediate ratios between these extremes tend to give an efficient balance between extraction efficiency and economy of the process.Reduced ratios lead to increased diffusion and solubilisation, but increased solid loadings lead to reduced use of solvents but possibly lower extraction yield because of reduced mass transfer.

4.6. Optimization of hemicellulose extraction from rice husk:

In general, theory-driven RSM-based optimization of extraction conditions of rice husk hemicellulose involve a generally convergent profile of 4 % NaOH concentration, 80 ℃ temperature, 3 hrs extraction duration and solid-to-liquid ratio of 1:10, with the yield of 20-25% hemicellulose of 85% purity.Strategies of pretreatment Two-step pretreatment approaches that include preliminary delignification and alkali extraction have also enhanced recovery by increasing the accessibility of hemicellulose.These optimised conditions are more or less applicable in the process that involves a high-molecular-weight hemicellulose, like in the formation of biodegradable films and the development of bioadhesives. Table 2 illustrates the optimized extraction conditions of hemicellulose from rice husk.

TABLE 2: Optimization of Hemicellulose Extraction from Rice Husk from different sources

S.No.	Source	Method used	Optimised Conditions	Yield	Reference
1.	Sugarcane bagasse	Organic Acid treatment	p-toluenesulfonic acid 3%, 80°C, 120 mi	36.02%	[16]

2.	Wheat straw	Hydrothermal process	170°C, 120 min	28%	[17]
3.	Bagasse	Mineral acid extraction	Naphthalene 1 boronic acid 0.25%,	85 mol% of xyloses	[18]
4.	poplar	Organic acid treatment	Benzoic acid 2%, 160°C, 0.75h	93.1%	[19]
5.	Corn fibre	Hydrothermal process	Citric acid 0.8%, 150°C, 3 h	49.5% ± 1.3%	[20]
6.	Poppy stalk	Alkali extraction with instant Controlled pressure drop	KOH 22.17%, steam pressure 5 bar, 7 h	26.27% (relative to dry mass)	[21]
7.	Sugarcane bagasse	Mixed Alkali treatment	NaOH plus NH4OH 10%, 120°C, 1 h	Xylose 68.32%, Arabinose 17.34%	[22]
8.	Bamboo	One step freeze thawed assisted alkali treatment	Freezing at −40°C, 10 h; NaOH 5%, 2h	56.12%	[23]
9.	Sugarcane bagasse pith	Ultrasonic assisted Alkali treatment	Ultrasonic treatment 28 min; KOH 3.7%, 53°C;KOH 3.7%, 2h	23.05%	[24]

V. HEMICELLULOSE FILM FORMATION AND BIOADHESIVE PROPERTIES

5.1. Film-forming ability of rice husk hemicellulose

Hemicellulose derived by rice husk, is primarily arabinoxylan with an innate ability to form a film that can thereby be attributed to the abundance of hydroxyl and acetyl functional groups that can form intermolecular hydrogen bonding.Solution casting is normally used to prepare films producing biodegradable and non-toxic matrices that can be used in sustainable applications in adhesives.

5.2. Effect of plasticizers and polymer blending

Plasticizers like glycerol are regularly added to relieve flexibilities and reduce brittleness developed as a result of strong polymer-polymer interactions. Intermediate amounts of plasticizer will improve chain mobility and break elongation, but the extreme amounts can lower tensile strength and make the product more susceptible to moisture[25]. The addition of hemicellulose to starch also intensifies the level of mechanical strength and resistance to the barrier property by increased intermolecular interactions, photo-enhancing film stability as compared to pure hemicellulose systems.

5.3. Crosslinking for structural stability and water resistance

The crosslinking strategies can be instrumental in increasing the water resistance and the structural stability. Esters, like citric acid, are useful in enhancing the formation of ester bonds between chains of the polymer during thermal conditioning resulting in enhanced tensile strength and dimensional stability. Crosslinked networks inhibit mobility of polymer and add strength to counter degradation caused by moisture, which is necessary to adhesive applications.

5.4. Adhesion mechanism and bioadhesive performance

Hemicellulose based systems mainly depend on hydrogen bonding with the lignocellulosic substrates and mechanical interlocking on porous structures to determine adhesion mechanism.The bonding performance is also enhanced through crosslinking which strengthens the internal polymer network.Optimised hemicellulose formulations exhibit mechanical and adhesive properties comparable to traditional synthetic adhesives, indicating their potential as sustainable bioadhesive systems derived from agricultural residues.

VI. APPLICATIONS OF RICE HUSK HEMICELLULOSE IN SUSTAINABLE MATERIALS

The agricultural residues are converted into valuable biomaterials with the help of rice husk hemicellulose, which is isolated through optimized alkali or hydrothermal treatment. Its property of forming a film intrinsically, biodegradability, and adhesive properties make it compatible with the concept of a circular economy.

6.1. Packaging films based on rice husk hemicellulose:

Mixed with plasticizers, such as glycerol and starch, the hemicellulose provides transparent and flexible films with an improvement of mechanical strength and barrier properties10. The oxygen-barrier films exhibit good performance with regard to oxygen-barrier and biodegradability, thus making them sustainable food packaging. The cross-linking also increases moisture resistance capacity, and the shelf life of perishable products.

6.2. Wood Adhesives based on Rice Husk Hemicellulose:

Bioadhesives based on hemicellulose that are produced through thermal curing and cross-linking display equal wet-shear strength to standard urea-formaldehyde adhesives, but do not produce any volatile organic compounds[26]. The use of starch improves tack and bonding capability, which can find its way in the manufacture of plywood and particleboard.

6.3. Coating applications of rice husk hemicellulose:

Formulations based on hemicellulose can be used as biodegradable surfaces to paper and wood substrates, which enhances resistance to grease and increases surface stability. Blended or Hemicellulose, a component of the matrix of biocomposites and hydrogel systems, increases mechanical properties and water absorbing ability. The complete biodegradability of it reduces environmental impact and preconditions the creation of sustainable material value chains based on agricultural residues.

VII. CHALLENGES AND RESEARCH GAPS IN RICE HUSK HEMICELLULOSE UTILIZATION

Regardless of being a good film forming and binding material, application of rice husk hemicellulose in industry is limited by various technical and process related barriers. The need to overcome these restrictions is critical to move the laboratory-scale extraction and material development to the commercial implementations.

7.1. Moisture sensitivity of rice husk hemicellulose-based materials:

Hemicellulose films and adhesives exhibit high sensitivities to moisture that can be attributed to the large hydrophilic hydroxyl groups on the polymeric backbone. Moisture intrusion causes swelling, plasticization and relative reduction of mechanical performance and adhesive performance in high humidity. Although the addition of plasticizers helps in increasing flexibility, it can raise the absorption of moisture. The current cross-linking and surface-modification methods have a moderate effect on water resistance increase. Future studies should focus on hydrophobic modification techniques that are environmentally friendly like fatty-acid esterification or green surface modification to strengthen moisture resistance without compromising biodegradability[27].

7.2. Limited mechanical strength of rice husk hemicellulose-based materials:

Hemicellulose films are usually homogeneous and thus weaker in tensile strength as compared to standard biodegradable polymers which limits their application in load-bearing or wet environments. Mechanical performance is enhanced through blending with starch or other biopolymers; however, long-term phase stability and durability is an issue. The addition of strengthening nanofillers such as cellulose nanocrystals, silica nanoparticles, or bio-derived nanofillers is a strategic research direction.

Many of the existing modification and cross-linking techniques involve high processing temperatures or have expensive additives, which may not be industrial viable. Besides, left inorganic constituents, including silica, may be a factor influencing the stability of materials during processing[28]. This has led to a growing need of low-energy, eco-friendly methods of modification including bio-based cross-linkers, enzyme-based grafting and naturally occurring phenolic compounds, hence making scalable adhesive formulations free of formaldehyde.

7.4. Scale-up and process integration challenges

Optimisations achieved on the laboratory level do not always scale to industrial systems. Difficulties such as alkaline wastewater treatment, complications in silica-mediated processing, and variations in the composition of raw-material may affect the efficiency of extraction and economics of the processes. Therefore, techno-economic evaluation, combined biorefinery strategies, and standardization of pre-processing procedures should become the focus of the future studies to ensure the quality of materials and improved scalability.

VIII. CONCLUSION:

Rice husk is a highly abundant by-product of the agricultural industry that can be valorised by extracting hemicellulose by employing optimised alkali and hydrothermal processes. Due to its typical film-forming capacity, biodegradation ability and functional versatility of functional groups, rice husk-derived hemicellulose can be strategically adjusted through plasticization, blending, and cross-linking to achieve the generation of biodegradable films and bioadhesive systems bearing a comparable mechanical and bonding performance to traditional synthetic adhesive. The resulting innovations make hemicellulose a viable and biologically harmless substitute of formaldehyde-based resin systems and, at the same time, alleviate the concern relating to the management of agricultural waste.

Although these benefits exist, the issues such as moisture sensitivity, mechanical stability in humid environments, and scale-up challenges are the main barriers to the industrial implementation. Green modification strategies, better integration of processes as well as pilot-scale validation will be necessary in addressing these issues and will contribute to further commercial feasibility. Altogether, the rice husk hemicellulose shows good promise as a renewable platform material in the implementation of a circular bioeconomy in the packaging, coating, and wood adhesive application.

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