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Research Paper

BIOPLASTICS DERIVED FROM RICE HUSK AND RICE STRAW

A Review of Fabrication Routes, Material Properties, and Application Potential

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Abstract: Rice husk and rice straw are among the largest lignocellulosic residues generated by global agriculture, yet a substantial share of this biomass is still burned or landfilled rather than valorized. Over the past decade, researchers have explored these residues as feedstocks for bioplastics intended to displace petroleum-based polymers in packaging, disposable products, and even building materials. This review synthesizes findings from six primary studies that convert rice husk or rice straw into bioplastic materials through distinct routes: fiber reinforcement of commercial bioplastics, starch-flour film casting, regenerated cellulose film casting, starch-filler composites, chemical esterification of cellulose, and simultaneous cellulose-silica co-extraction. Across these studies, mechanical strength, water sensitivity, and biodegradation rate consistently trade off against one another, and the natural silica present in both residues repeatedly emerges as a functional component rather than a mere impurity, contributing to flame retardancy, reinforcement, and barrier performance. The review compares the processing conditions and resulting properties of each approach and discusses the remaining obstacles to scaling rice-residue bioplastics toward commercial packaging and disposable-product applications.

Keywords: Rice husk, lignocellulosic, valorized, petroleum-based polymers, co-extraction.

1. INTRODUCTION

The accumulation of conventional, petroleum-derived plastics in landfills, waterways, and oceans has become one of the defining environmental problems of the past several decades, prompting sustained research into biodegradable alternatives produced from renewable biomass rather than fossil feedstocks [1,2]. Bioplastics manufactured from polysaccharides such as starch and cellulose are attractive because these biopolymers are abundant, inexpensive relative to other biopolymer classes, and capable of being broken down by soil microorganisms after use [1].

Rice cultivation generates two major lignocellulosic by-products at enormous scale: rice husk, the hard protective hull removed during milling, and rice straw, the stem and leaf residue left in the field after harvest. Global rice production has been estimated at roughly 503 million metric tons for 2021 [1], while total cereal production worldwide reached approximately 2577 million tons in the 2016/17 season, a figure used to illustrate the enormous volume of straw fiber renewed annually that could, in principle, be diverted from open-field burning toward higher-value uses [3]. Improper disposal of both residues, whether through open burning or accumulation as agro-industrial waste, contributes to air pollution and represents a lost opportunity to recover a renewable source of cellulose and reactive mineral content [1,3].

This review draws together six studies that each convert rice husk or rice straw into a bioplastic material through a different processing route, ranging from simple physical blending of milled fiber into commercial thermoplastics to the chemical esterification of purified cellulose [1–6]. The aim is to compare how feedstock preparation, plasticizer or filler choice, and processing method influence the resulting mechanical strength, water and oil resistance, thermal behavior, and biodegradation rate, and to identify the practical trade-offs that currently separate these materials from mature commercial polymers.

2. RICE HUSK AND RICE STRAW AS FEEDSTOCKS

Although rice husk and rice straw originate from the same crop, their chemical compositions differ somewhat depending on plant part, variety, and analytical method, but both are characterized by a lignocellulosic matrix combined with an unusually high mineral silica fraction compared with wood. Rice straw has been reported to contain silica levels of up to roughly 20% of dry weight, considerably higher than wheat straw (4–10%) and far higher than wood (below 1%) [3]. In one study's own ashing experiments, rice straw ash represented 14.8% of the original straw mass, and silicon made up about 73.3% of that ash, corresponding to roughly 11.1% of the whole untreated straw [3]. Rice straw fiber has also been described, citing earlier work, as composed of approximately 28–36% cellulose, 23–28% hemicellulose, 12–14% lignin, and 14–20% ash [4]. A somewhat different breakdown has been reported for straw pulp specifically, at about 31.37% cellulose, 18.14% hemicellulose, and 7.76% lignin, reflecting the influence of variety and pre-treatment on measured composition [5].

Rice husk shows a broadly comparable profile: husk composition has been summarized as roughly 35% cellulose, 25% hemicellulose, 20% lignin, and 15–20% silica [1], while husk has also been reported to consist of about 28–30% inorganic material, chiefly silica, and 70–72% organic material, of which cellulose accounts for roughly 44.32% on a dry basis [2]. This shared characteristic, an inherently high native silica content, recurs throughout the studies reviewed here as a functional feature rather

than an inert impurity, variously acting as a natural flame-retardant filler, a source of reinforcing biogenic silica once extracted and calcined, and an indicator of the degree of purification achieved during cellulose isolation.

3. FABRICATION ROUTES FOR RICE-RESIDUE BIOPLASTICS

3.1 Fiber-Reinforced Thermoplastic Composites for Building Products

One study took a comparatively simple physical approach, incorporating untreated, mechanically chopped rice straw fiber (0.5–2 mm) at a 20 wt.% loading into two bio-based thermoplastics, poly (lactic acid) (PLA) and a synthesized lignin thermoplastic (Arbo form), with a conventional polypropylene (PP) composite prepared at the same fiber loading as a fossil-based reference [3]. No chemical fiber treatment or added flame retardant was used; instead, the native silica content of the straw was deliberately exploited as a partial substitute for conventional mineral flame retardants. The three bio composites were compounded in a twin-screw extruder, injection molded into test specimens, and evaluated for density, morphology, and flammability using a small-flame test based on the UL 1694 standard, after which one formulation (rice straw–PLA) was further extruded into sheet and vacuum-thermoformed over custom molds to demonstrate architectural cladding panels [3].

The PP-based reference composite melted completely under flame exposure and continued burning without self-extinguishing, failing to meet a defined fire class [3]. The rice straw–PLA composite performed markedly better, approaching the UL1694-TC2 classification, while the rice straw–lignin composite achieved the best result of the three, reaching the self-extinguishing SC-1 class with no dripping and short after-flame times [3]. Scanning electron microscopy indicated that the lignin matrix formed a more homogeneous, tightly bonded interface with the straw fibers than PLA did, attributed to a favorable interaction between the straw's native silica and the lignin present in both the fiber and the matrix [3]. The rice straw–lignin and rice straw–PLA composites were also denser (1.2–1.3 g/cm³) than the PP reference (0.9 g/cm³) [3]. Because the approach avoids added flame-retardant chemicals and uses fiber that would otherwise be considered agricultural waste, these bio composites were proposed as a partially bio-based, lower-cost alternative to conventional wood–polymer composites for interior cladding, acoustic absorption, and thermal insulation applications [3].

3.2 Starch-Flour Based Biodegradable Drinking Straws

A second study targeted a specific single-use product, the drinking straw, using a much simpler and more accessible feedstock: flour milled from unused, leftover cooked rice together with rice bran, both classified as food-processing residues in Indonesia, where an estimated 93 million plastic straws are used daily [6]. Six combinations of the two flours were tested, ranging from rice-flour-dominant blends (2.5–3.5 g rice flour to a fixed 0.5 g bran) to bran-dominant blends (0.5 g rice flour to 2.5–3.5 g bran), each plasticized with glycerin recovered from used cooking oil and stabilized with chitosan [6]. The starch fraction was gelatinized, combined with a chitosan–acetic acid solution, cast into sheets, dried, and then rolled into a straw shape before a final drying step, and the resulting straws were benchmarked against a conventional plastic straw [6].

Mechanical performance fell well short of the plastic control across every combination: tensile strength ranged from only 0.21 to 6.19 MPa against roughly 40.5 MPa for the plastic straw, and elongation ranged from 0.43% to 1.71% against roughly 16% for the control [6]. The rice-flour-dominant blend containing 3.0 g rice flour to 0.5 g bran gave the best mechanical results of the biodegradable series, attributed to its comparatively higher amylose content [6]. Water uptake was essentially complete (about 100%) for every biodegradable sample, compared with roughly 2% for the plastic straw, reflecting the intrinsic hydrophilicity of starch [6]. On the positive side, biodegradation in soil was rapid: rice-flour-dominant straws fully degraded within four days and bran-dominant straws within a single day, whereas the plastic control showed no degradation over a seven-day test [6]. Despite full biodegradability, none of the formulations yet reproduced the mechanical strength or water resistance needed to functionally replace a plastic straw [6].

3.3 Regenerated Cellulose Films Plasticized with Glycerol

A third study pursued a cellulose-based film rather than a starch-based one, first pulping rice straw by cooking it in a 50% ethanol solution with sodium hydroxide as a catalyst to isolate a cellulose-rich pulp, and then forming a film by the phase-inversion method: pulp and chitosan were dissolved together in dilute acetic acid, glycerol was added at concentrations of 25%, 30%, or 35% relative to pulp weight, and the mixture was cast and dried [5]. Fourier-transform infrared spectroscopy confirmed that no new chemical bonds formed during blending, consistent with glycerol acting purely as a physical plasticizer rather than a reactive additive [5].

Increasing glycerol content produced a consistent and physically intuitive set of trade-offs. Water swelling rose from 83.85% at 25% glycerol to 86.87% at 35% glycerol, while oil swelling fell from 38.89% to 29.11% over the same range, reflecting glycerol's hydrophilic character [5]. Elongation at break rose sharply from 45.9% to 65.0% as glycerol increased, while tensile strength fell from 11.2 MPa to 6.0 MPa, a pattern explained by glycerol molecules inserting themselves into the polymer network and weakening the intermolecular hydrogen bonding that otherwise stiffens the film [5]. Soil burial biodegradation over 15 days followed the same direction: the highest-glycerol film lost 18.5% of its mass in dry soil and 21.3% in wet soil, both higher than the lower-glycerol formulations, indicating that greater water affinity accelerates microbial attack [5]. The 35% glycerol formulation was identified as the best-performing bioplastic in the series, on the basis of its combination of workable tensile strength, high elongation, and favorable oil resistance for potential food-contact use [5].

3.4 Starch Bioplastics Reinforced with Rice Husk Powder

A fourth study took a comparative approach, producing parallel series of bioplastic films from rice starch and corn starch, each combined with glycerol, sorbitol, or a 1:1 glycerol–sorbitol mixture as plasticizer, and reinforced with a natural filler, rice husk powder for the rice-starch series and eggshell powder for the corn-starch series, at loadings of 0%, 5%, or 10% by weight relative to the starch solution [2]. Across a wider screening range, 5 mL of plasticizer was identified as optimal, since lower amounts produced brittle, inflexible films and higher amounts produced excessively moist, sticky films, while filler loadings above roughly 10% led to rough, cracked, and easily crumbled films because higher filler content disrupted the starch matrix's intermolecular interactions [2].

For the rice-starch series specifically, adding rice husk powder increased water absorption rather than decreasing it, the opposite of the trend observed for eggshell-filled corn starch films, a difference attributed to the hydrophilic cellulose that dominates rice husk composition versus the largely insoluble calcium carbonate that dominates eggshell [2]. Rice husk filler also reduced both tensile strength and Young's modulus of the rice-starch films, again contrasting with the corn-starch series, where eggshell filler increased both properties; this was linked to poor filler dispersion and weak adhesion between the husk particles and the starch matrix [2]. Among plasticizers, sorbitol-plasticized films consistently showed higher tensile strength and modulus than glycerol-plasticized films, while glycerol produced greater flexibility, moisture content, and water/alcohol solubility, consistent with its smaller molecular size and stronger affinity for water [2]. Soil burial biodegradation testing over five days showed that, for the rice-starch series, the unplasticized, filler-free control biodegraded fastest, while both plasticizer and filler addition slowed biodegradation [2]. In a separate experiment on the corn-starch series, coating a bioplastic sample with room-temperature-vulcanizing (RTV) silicone reduced water solubility to essentially zero and reduced five-day soil biodegradation from about 16% down to 0% for an intact coated sample, illustrating a direct trade-off between imparting water resistance and preserving biodegradability [2].

3.5 Chemically Esterified Cellulose Films

A fifth study pursued a chemical modification strategy rather than a physical blending one. Rice straw was first delignified and bleached to isolate cellulose, which was then esterified with lauroyl chloride in a toluene/pyridine system to produce cellulose laurate, a hydrophobic long-chain fatty acid ester of cellulose [4]. Reaction temperature and time were both varied, and weight increase from esterification rose with both variables up to an optimum of 60 °C for 10 hours, beyond which excessive reaction conditions caused visible browning attributed to cellulose degradation rather than continued esterification [4].

Infrared spectroscopy confirmed the reaction: the hydroxyl stretches characteristic of unmodified cellulose diminished while a new ester carbonyl peak and stronger alkyl C–H peaks appeared, consistent with substitution of hydroxyl groups by lauroyl side chains [4]. This chemical change had a marked effect on solubility, since unmodified rice straw cellulose is insoluble in common organic solvents, whereas the esterified cellulose laurate dissolved readily in toluene, chloroform, and dichloromethane, allowing the material to be solution-cast into a film [4]. The resulting film had a tensile strength of 7.29 MPa, elongation at break of 9.04%, and elastic modulus of 206.73 MPa; these values remained well below those of common commercial polymers such as low-density polyethylene or polypropylene, indicating that the esterified rice straw film, while processable and more hydrophobic than native cellulose, remains comparatively brittle [4].

3.6 Cellulose–Silica Composite Films via Simultaneous Co-Extraction

A sixth study proposed extracting both cellulose fiber and crystalline biogenic silica from the same batch of rice husk in a single integrated process, rather than treating the silica as waste after cellulose isolation [1]. Acid and alkali treatment released a cellulose-rich solid together with a sodium silicate-rich filtrate; the cellulose was subsequently bleached, while the filtrate was acidified, gelled, dried, and calcined at 800 °C to yield crystalline silica particles with an average diameter of about 5.6 micrometers [1]. Cellulose and silica yield from the husk were approximately 24% and 10%, respectively [1]. In a step highlighted as novel, the extracted cellulose fiber (average diameter 9.45 micrometers) was dissolved in aqueous zinc chloride, a recyclable inorganic solvent not previously reported for rice husk cellulose, and cast into films reinforced with the biogenic silica at loadings of 0%, 1%, 2%, or 3% by weight relative to cellulose [1].

Structural analysis showed that dissolving and regenerating the cellulose converted its native crystalline form into a less-ordered cellulose type with markedly reduced crystallinity, which silica addition partly reversed at loadings above roughly 1% [1]. Moisture content, water vapor transmission, and water vapor permeability of the films all decreased progressively as silica content increased, indicating improved barrier performance attributable to the dense network formed between silica and the cellulose matrix [1]. Tensile strength increased from 311 kN/m² for the unreinforced film to a maximum of 1347 kN/m² (roughly 1.35 MPa) at 2 wt.% silica, before declining at 3 wt.% silica as excess silica caused particle agglomeration, phase separation, and visible surface cracking; elongation at break declined steadily as silica content rose, reflecting the stiffening effect of the rigid filler [1]. Thermal analysis showed that silica addition increased the proportion of solid residue remaining at high temperature, indicating improved thermal stability [1]. Soil burial testing over 21 days showed that the unreinforced film lost 55.7% of its mass, while the most heavily silica-reinforced film lost only 25.5%, since the denser silica–cellulose network was harder for soil microorganisms to penetrate; even the slowest-degrading formulation, however, still degraded considerably faster than conventional plastics [1]. On the basis of the combined tensile, barrier, and biodegradability results, the 2 wt.% silica formulation was identified as the best candidate among those tested for green packaging applications [1].

4. COMPARATIVE DISCUSSION

Table 1 summarizes the feedstock, base material, key additives, best-reported mechanical performance, biodegradation outcome, and intended application for each of the six studies reviewed. Several cross-cutting patterns emerge from this comparison. First, mechanical strength and water resistance tend to move together and both tend to move opposite to biodegradation rate: the starch-

flour straws [6] and the glycerol-plasticized cellulose films [5] degrade fastest but are also the weakest and most water-sensitive, whereas the silica-reinforced film [1] and the esterified cellulose film [4] achieve higher strength or greater hydrophobicity at the cost of slower, though still substantial, biodegradation.

Table 1 summary of the feedstock

Feedstock / Route	Matrix or Base Material	Key Additive(s)	Best Mechanical Result	Biodegradability Outcome	Primary Target Use	Ref.
Rice straw fiber (20 wt.%) in thermoplastic	PLA / Lignin (Arbo form)	None (natural silica in straw acted as flame retardant)	Density 1.2–1.3 g/cm³; UL1694 fire class SC-1 for lignin composite	Not evaluated (durable building product)	Interior cladding, acoustic/thermal insulation panels	[3]
Unused rice flour + rice bran flour	Gelatinized starch film	Chitosan, glycerin from used cooking oil	Tensile strength up to 6.19 MPa; elongation up to 1.71%	Fully degraded in 1–4 days (soil burial)	Drinking straws	[6]
Rice straw pulp	Regenerated cellulose film	Chitosan, glycerol (25–35%)	Tensile strength 6 MPa at 35% glycerol; elongation 65%	18.5–21.3% weight loss after 15 days soil burial	Food packaging film	[5]
Rice starch + rice husk powder	Starch film	Glycerol/sorbitol, rice husk filler (5–10%)	Highest tensile/modulus with sorbitol and no filler	Reduced by filler and plasticizer; RTV coating suppressed it almost entirely	Food-contact / flexible packaging	[2]
Rice straw cellulose	Cellulose laurate ester	Lauroyl chloride (esterifying agent)	Tensile strength 7.29 MPa; elongation 9.04%	Not evaluated directly (esterified cellulose expected to degrade more slowly than native cellulose)	Solvent-cast biodegradable film	[4]
Rice husk cellulose + biogenic silica	Regenerated cellulose (ZnCl2-dissolved)	Biogenic silica (1–3 wt.%)	Tensile strength up to 1347 kN/m² (≈1.35 MPa) at 2 wt.% silica	25.5–55.7% weight loss after 21 days soil burial	Green packaging film	[1]

Second, the native silica content shared by rice husk and rice straw is exploited in markedly different ways across the six studies, ranging from a completely passive role, where untreated straw fiber's mineral content happens to confer flame retardancy [3], to an actively engineered role, where silica is deliberately isolated, calcined into a crystalline reinforcing phase, and reintroduced at a controlled loading [1]. This suggests that the mineral fraction of these residues, often discussed mainly as an obstacle to pulping or combustion, is itself a resource that can be recovered rather than discarded.

Third, the choice between a starch-based and a cellulose-based strategy shapes the practical ceiling on performance. The starch-flour and starch-filler systems [6,2] are simpler to process, requiring no chemical pulping or esterification, but their tensile strengths remain in the low single digits of megapascals and their water sensitivity is severe. The cellulose-based systems [5,4,1] generally require more extensive feedstock preparation, such as pulping, bleaching, or chemical modification, but achieve somewhat better mechanical performance and, in the case of esterification or silica reinforcement, meaningfully improved water or moisture resistance. None of the six studies, however, reported bioplastics from rice husk or rice straw that matched the tensile strength or elastic modulus of commercial polymers such as PLA, LDPE, or PP; reference values cited for commercial PLA (about 59 MPa tensile strength, 3500 MPa modulus) and for polyhydroxyalkanoates (11–40 MPa tensile strength) remain well above the rice-residue bioplastics discussed here [2].

5. CHALLENGES AND FUTURE DIRECTIONS

Several practical challenges recur across the literature reviewed. Water sensitivity is the most consistent limitation: starch- and cellulose-based films alike absorb water readily because of their abundant hydroxyl groups, which restricts their use in humid environments or for liquid-containing products unless a barrier or coating strategy is applied. An RTV silicone coating trial demonstrated that hydrophobic surface treatments can suppress water uptake almost entirely, but at the cost of also suppressing

biodegradability, since a continuous hydrophobic coating prevents microbial access to the underlying biopolymer [2]. Reconciling water resistance with end-of-life biodegradability, perhaps through coatings that themselves degrade or through reinforcement strategies such as the biogenic silica approach, which improved barrier properties while still allowing substantial biodegradation, appears to be a more promising direction than simple hydrophobic encapsulation [1].

A second recurring challenge is brittleness and comparatively low tensile strength relative to commercial plastics, even after optimization of plasticizer type and content. Increasing plasticizer content reliably increases flexibility but reduces strength [5,2], so plasticizer choice functions as a trade-off rather than a straightforward improvement, and the useful range for any given formulation appears to be fairly narrow, as shown by the deterioration in film quality observed outside a 5 mL optimum [2]. Reinforcement with rigid fillers can raise strength, as silica did up to 2 wt.% [1], but excessive filler consistently caused agglomeration, phase separation, and cracking across multiple studies [2,1], indicating that filler dispersion, rather than filler quantity alone, is a key process variable that would benefit from further optimization, for example through surface treatment of the filler or improved mixing methods.

Scale-up and feedstock variability represent a further obstacle largely unaddressed within the individual studies reviewed. Rice husk and rice straw composition varies with variety, growing region, and harvest conditions, which could affect the consistency of extracted cellulose, silica, or starch fractions and, in turn, the reproducibility of bioplastic properties at industrial scale. Several of the routes described also involve energy- or chemical-intensive steps, such as high-temperature calcination for silica [1] or organic solvent use for esterification [4], that would need life-cycle and cost assessment before these materials could be considered genuinely more sustainable than the petroleum-based plastics they are intended to replace. Future work that couples mechanical and barrier optimization with such assessments, alongside continued exploration of the residues' native mineral content as a functional rather than incidental component, would help clarify which of these fabrication routes is most likely to reach practical application.

6. CONCLUSION

Rice husk and rice straw are versatile, widely available feedstocks for bioplastic production, and the six approaches reviewed here demonstrate that they can be converted into materials ranging from flame-retardant building composites to compostable drinking straws and reinforced packaging films [1–6]. Across all of the routes examined, a consistent trade-off links mechanical strength, water resistance, and biodegradation rate, and the natural silica content of both residues repeatedly proves useful, whether left in place as a passive flame-retardant filler or deliberately extracted and reintroduced as a reinforcing phase. While none of the reported bioplastics yet rival the mechanical performance of commercial petroleum-based polymers, the combination of full or substantial biodegradability, low feedstock cost, and the diversion of an abundant agricultural residue from open burning makes continued development of rice-residue bioplastics a worthwhile direction for sustainable materials research.

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