The Pharma Innovation Journal 2020; 9(6): 634-638

www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.03
TPI 2020; 9(6): 634-638

www.thepharmajournal.com
Received: 16-04-2020
Accepted: 22-05-2020

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Mini review on paddy straw biomass: A potential renewable resources

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Abstract

Rice straw biomass is a significant renewable resource for our country, primarily composed of complex organic polymers, including carbohydrates. These carbohydrates consist of cellulose and hemicellulose linear polysaccharide polymers made up of numerous glucose monosaccharide units as well as lignin, which contains phenylpropane units derived from hydroxyl and methoxy substituted phenylpropane. Rice straw presents a valuable opportunity for the industrial production of important medicinal fungal products and biofuels. However, there are several limitations to the industrial production of metabolites from existing resources. Rice straw serves as an alternative source for various pharmaceutical compounds, typically synthesized with the aid of microorganisms (bacteria and fungi). Utilizing rice straw can address significant challenges, such as reducing field burning, thereby contributing to climate change mitigation through the involvement of commercially important microorganisms. In this review, we summarize the advantages and challenges associated with various industrial methods for producing metabolites from rice straw biomass in a cost-effective manner. This approach not only has the potential to enhance pharmaceutical production but can also contribute to doubling farmers' incomes.

Keywords: Rice straw biomass, cellulose, hemicellulose, lignin and delignification

1. Introduction

Rice is one of the most widely cultivated cereal crops, producing 494.9 million metric tonnes globally in the 2017-18. China leads production with 148.9 million metric tonnes, followed by India at 112.8 million metric tonnes [1]. Rice straw, the residual material left after grain harvesting, is traditionally used for various purposes, including animal feed, mushroom cultivation, energy generation, and compost preparation. It is composed of approximately 38% cellulose, 25% hemicellulose, and 12% lignin [2]. Cellulose consists of C-6 sugars, while hemicelluloses primarily contain C-5 sugars such as xylose and arabinose. In rice straw biomass, cellulose, hemicellulose, and lignin are encased in a dense matrix that makes them resistant to degradation [3]. Rice straw is abundant, inexpensive, and a valuable feedstock for the pharmaceutical industry. Notably, rice crops generate straw that can account for up to 45% of their total weight, much of which is often burned to clear fields for subsequent planting. This open-field burning in India significantly contributes to greenhouse gas emissions [4]. Utilizing paddy straw for metabolite production can help mitigate climate change associated with straw burning while providing a renewable fuel source. Suitable fungi have already been identified to effectively utilize the cellulose and hemicellulose in rice straw biomass [5].

Overall, the use of rice straw biomass represents a major opportunity for producing industrial products through the action of fungi and bacteria. The most widely available wastage in India is rice straw biomass. Rice straw is separated from the grains after the plants are threshed either manually, threshers or, more recently, by using combine harvesters. Each kg of milled rice produced results in roughly 0.7–1.4 kg of rice straw depending on varieties. Conventionally in rural part of India Rice straw are used as a animal feeding, pot preparation, mushroom production or compost preparations (Fig.1). In recent years the researchers explored the importance of rice straw biomass bioethanol production, electric production and also can be utilized in the paper industry.

1.1 Rice straw biomass constitutions

Rice straw is a lignocellulosic biomass that can be fractionated through various pretreatment methods, including mechanical, chemical, and biological processes. It contains approximately 38.7% cellulose, 19.7% hemicellulose, and 13.5% lignin (w/w). Both cellulose and hemicellulose are polysaccharides:

Cellulose is a long, straight-chain polymer made exclusively of β-glucose monomers, while hemicellulose is a shorter, cross-linked polymer composed of various sugars, including xylose, galactose, mannose, rhamnose, and arabinose. Lignin, on the other hand, is an aromatic structural polymer formed through the oxidative combination of 4-hydroxyphenylpropanoids, primarily including p-coumaric, coniferyl, and sinapyl alcohols [6]. In plant cell walls, these polymers create stable, complex three-dimensional structures known as lignocellulose, where cellulose is surrounded by a layer of hemicellulose and embedded within a matrix of hemicellulose and lignin. Additionally, rice straw contains notable amounts of silica and other minor components. While cellulose and hemicellulose are organic fibres, lignin serves as a crucial structural element in the cell wall [7]. According to Wu *et al*., (2018), the sugar composition of rice straw includes rhamnose, fucose, arabinose, xylose, mannose, galactose, and glucose, with cellulose-derived glucose being the most abundant sugar present [8].

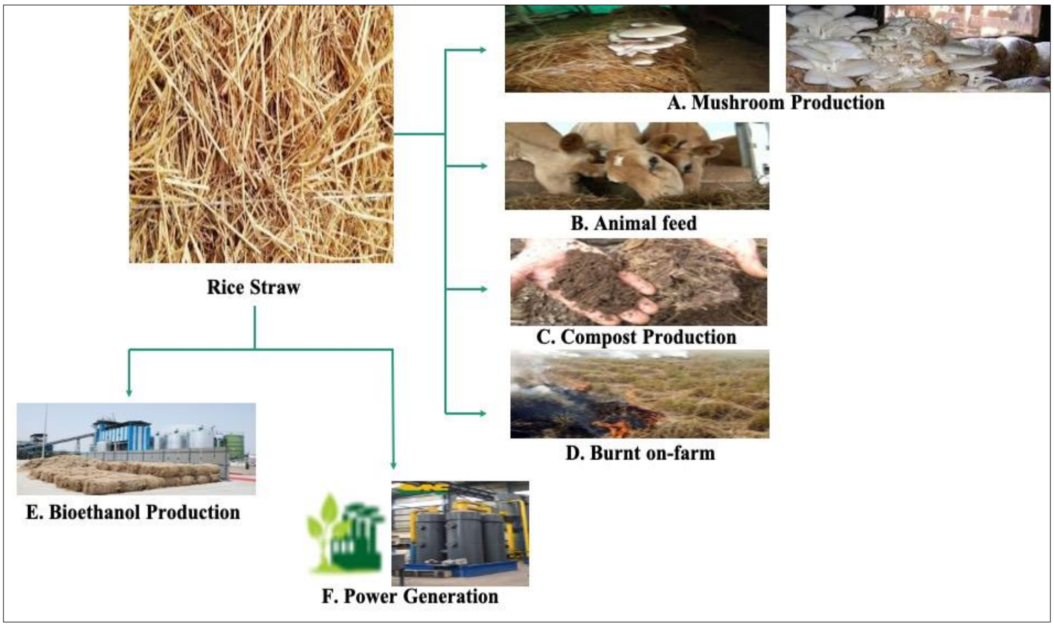

Fig 1: Applications of rice straw for various utility

1.2 Pre-treatments of rice straw

1.2.1 Physical pre-treatment of rice straw

Physical pre-treatment enhances the accessible surface area and pore size while reducing the degree of crystallinity and polymerization of cellulose. Common methods for physically treating lignocellulosic residues include steaming, grinding, irradiation, and thermal treatments. Combining grinding with other pre-treatment techniques effectively reduces the particle size of biomass and helps to isolate the glycosidic bonds in cellulose molecular chains, especially in the presence of lignin. Microwave treatment is particularly effective, as it degrades lignin and hemicellulose in lignocellulosic materials, thereby increasing their enzymatic sensitivity [9].

1.2.2 Chemical pre-treatment

Chemical pre-treatment increases the accessible surface area and pore size while decreasing the crystallinity and polymerization of cellulose in lignocellulosic materials. Commonly employed chemical treatments for degrading lignocellulosic residues include acidic and alkaline methods. These treatments effectively break the glycosidic bonds in cellulose molecular chains, resulting in reduced particle size [10, 11].

1.2.3 Biological pre-treatment of rice straw

Biological pre-treatment is one of the simplest and most cost-effective methods, utilizing lignocellulolytic fungi or enzymes. White-rot, brown-rot, and soft-rot fungi are commonly employed to degrade rice straw. Research indicates that white and soft-rot fungi can attack both cellulose and lignin, while brown-rot fungi primarily target cellulose [12]. This method is considered eco-friendly as it does not produce toxic by-products. However, the hydrolysis rate is influenced by the substrate's nature, treatment duration, and temperature, which can limit its widespread use. Fungal hyphae penetrate the rice straw cell wall, degrading lignin and enhancing digestibility, depending on the composition of the cell wall [13].

1.2.3.1 Bacteria

Bacteria are a diverse group of prokaryotic microorganisms, primarily consisting of single-celled organisms. They interact with plant cell walls through three main morphological forms: tunneling, erosion, and cavitation, particularly in waterlogged conditions [14, 15]. Previous studies have shown that Streptomyces viridosporus can degrade softwood lignin into low molecular weight fragments [16]. Additionally, enzymes such as peroxidases, ligninases, and manganese peroxidases, which are similar to those produced by fungi, its also play a role in bacterial biomass delignification [17, 18]. *Rhodococcus jostii*, found in soil and other natural environments, is capable of transforming lignin one of the most abundant polymers in the biosphere into various monocyclic phenolic compounds[19]. Notably, some bacteria can also utilize hardwood, which is typically resistant to fungal decay [20]. However, bacteria are generally less efficient than fungi for lignocellulosic pre-treatment. Recent studies comparing the efficacy of fungi and bacteria for pre-treating sugarcane demonstrated that the most significant reduction in the carbon-to-nitrogen (C:N) ratio was achieved using *Aspergillus terreus*, followed by *Cellulomonas* *uda*, *Trichoderma reesei*, and *Zymomonas mobilis* [21].

1.2.3.2 White-rot fungus

White-rot fungi are a diverse group within the agaricomycetes, basidiomycetes, and some ascomycetes that decompose lignin and various environmental pollutants, converting them into carbon dioxide and water. Pretreatment with white-rot fungi enhances the biodegradability of lignocellulosic biomass, leading to improved quality of animal feed. For instance, Okano *et al*., (2005) reported that cedar wood treated with white-rot fungi showed significant improvements in rumen digestibility [22]. Similarly, treating grasses, oat straw, and alfalfa stems with *Ceriporiopsis subvermispora* resulted in notable enhancements in digestibility [23].

The use of chemicals in the pulping industry can be reduced through the application of white-rot fungi in biological pulping (bio-pulping), which also decreases environmental hazards [24]. The bio-pulping process effectively removes lignin, hemicellulose, and some wood extractives, thereby improving paper quality while significantly reducing the time and energy required for pulping wood chips [25]. Additionally, the white-rot fungus *Trametes hirsuta* has been utilized to produce fiber board through microbial pre-treatment, enhancing the properties of the biomass for bio-composite production using hot pressing without the need for adhesives [26].

1.2.3.3 Brown-rot fungi

Brown-rot fungi are a class of basidiomycete fungi that differ from white-rot fungi in their method of lignocellulose degradation. They primarily utilize enzymes to break down cellulose and hemicellulose while minimally affecting lignin. Brown-rot fungi completely hydrolyse polysaccharides without significantly removing lignin [27]. This process results in an increased volume of pores in the wood cell wall and leads to rapid depolymerization of holocellulose during the early stages of decay, resulting in extensive degradation of holocellulose in wood [12].

1.3 Industrial application of rice straw

Rice straw has a potential source for many industrial applications such as metabolites production. Biofuel production, Mushroom Production and Power generation etc.

1.3.1 Metabolites productions

The recombinant lysine-producing strain utilizing pentoses in media with acid-treated rice straw or wheat bran hydrolysate as a carbon and energy source demonstrates that acid hydrolysates from agricultural waste can serve as an alternative feedstock for large-scale amino acid production by *Corynebacterium glutamicum* [28]. Optimization of the fermentation process through conventional methods resulted in a two-fold increase in laccase production. Statistical optimization further enhanced laccase yield, achieving a three-fold increase compared to non-adapted media. This investigation highlights the effectiveness of statistical methods in boosting laccase production by this strain and confirms the viability of using rice straw for laccase production in solid-state fermentation, making it a cost-effective and readily available agro-industrial waste.

Rice straw (1.0% alkali-pretreated) underwent enzymatic hydrolysis using thermostable Fe_3O_4/alginate nanocomposites treated crude fungal cellulase obtained from Aspergillus fumigatus AA001. This process released approximately 54.18 g/L of monomeric sugars in the form of rice straw hydrolysate, which served as substrates for hydrogen production via dark fermentation by *Clostridium pasteurianum* using a simultaneous hydrolysis and fermentation (SHF) process. A total of 2580 ml/L of cumulative hydrogen was produced over 144 hours, accompanied by an increase in bacterial biomass [29].

1.3.2 Biofuel production

Rice straw holds significant potential as a raw material for bioethanol production. Popping pre-treatment of rice straw before downstream fermentation has been shown to enhance the conversion efficiency of cellulose to glucose. In contrast, lignocellulosic biomass such as residues from rice straw or dedicated energy crops (2nd generation) represents an attractive alternative. This approach helps prevent air pollution associated with burning rice straw in the fields, which contributes to climate change, and these materials are generally cheaper than traditional biomass sources [30, 31]. However, the high cost of biofuel production is often due to intensive labour and multiple processing steps, which present economic and technical challenges that must be addressed for efficient and cost-effective biological conversion of lignocellulosic biomass into biofuels.

Rice straw is one of the largest biomass feedstocks, with the potential to produce approximately 600-800 billion liters of bioethanol annually from the available biomass. This volume represents the highest yield from a single biomass source. Globally, rice straw production is around 600-800 million tons per year, with significant contributions from Africa (20.9 million tons), Asia (667.6 million tons), and Europe (3.9 million tons) [32].

Furthermore, the efficiency of the process indicates that using this hydrolysate, *C. pasteurianum* (MTCC116) can yield a cumulative hydrogen production of 2580 ml/L over 144 hours, with a maximum production rate of 23.96 ml/L/h achieved within 96 hours. The maximum dry bacterial biomass recorded was 1.02 g/L after 96 hours and 1.51 g/L after 144 hours, with initial pH values of 6.6 and 3.8, respectively, suggesting favourable conditions for higher hydrogen production [33].

The effectiveness of white-rot fungi, including *Phanerochaete chrysosporium*, *P. ostreatus*, and *Trametes versicolor*, has been evaluated for their ability to break down various polymers. Pre-treatment of rice straw with *Aspergillus* and other fungi has yielded the highest ethanol production.

1.3.3 Compost preparation

Compost can be used as fertilizer for growing vegetables and other crops or as a direct soil conditioner. As a soil conditioner, it enhances the nutrient and organic matter content of the soil. The carbon-to-nitrogen (C:N) ratio of composting materials plays a crucial role in determining both the quality and duration of the composting process. For optimal results, a C:N ratio between 20 and 30 is recommended. Ratios that are too high can prolong the composting time, while those that are too low may lead to excessive nitrogen loss. To achieve the ideal C:N ratio, rice straw can be combined with nitrogen-rich organic materials, such as manure. Paddy straw, which has a C:N ratio of approximately 84.56, is particularly suitable for this purpose. After 90 days of composting, the C:N ratio of rice straw can range from 16.6 to 34.5, indicating effective breakdown [34].

1.3.4 Mushroom production

Rice straw mushrooms, such as *Volvariella volvacea and Pleurotus spp*., are among the easiest mushrooms to cultivate, with a short incubation period of just 14-21 days. These tropical and temperate species thrive best at temperatures between 30-35 °C for mycelial growth and 28-32 °C for fruiting body production. Mushroom cultivation is a popular practice due to its low investment costs and good yields [35, 36].

1.3.5 Power Generation

Global rice production has seen a notable increase from 2012 to 2018, with the Asian region being the largest producer, accounting for approximately 90.5% of total global output, according to FAO reports. Rice straw is regarded as a valuable resource for second-generation biofuel production. The fibre residue is often burned to generate heat and electrical energy, contributing to a carbon-neutral or at least energy-efficient biofuel facility. Additionally, grinding rice straw enhances its surface area for subsequent chemical reactions, and combining the straw with alkalis and acids further improves its digestibility [37]. The European Union is actively promoting the use of energy from renewable sources (EC, 2009) and has set a target for achieving a significant share of energy from renewables by 2020, which includes biogas produced from the anaerobic digestion of agricultural residues. The urgent need to mitigate climate change and enhance energy security is driving increased interest in renewable energy sources, leading many regions and countries worldwide to establish ambitious targets [38].

2. Conclusion

Our review paper concludes that alternative uses of rice straw can help farmers double their income while addressing the waste produced in the fields. There are numerous opportunities to utilize this agricultural residue in various sectors, including nutraceuticals, biofuels, food additives, and pharmaceuticals. These applications can also contribute to reducing the increasing environmental pollution associated with rice straw disposal.

3. Acknowledgement

We extend our gratitude to our team members for their invaluable assistance, as well as to the Department of Plant Molecular Biology and Biotechnology, the Department of Plant Biochemistry, the Department of Plant Pathology, at Indira Gandhi Agricultural University and the Department of Biotechnology.

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