A Review on Sustainable Approaches towards Pulp Production from the Paddy Straw

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***Abstract*- The global community is confronting environmental issues associated with the rapid increase in commercial and urban development, including waste management challenges, elevated emissions of greenhouse gases, pollution, deforestation, and depletion of non-renewable resources. India, with its predominant agricultural economy, generates a large quantity of agricultural waste post-farming operations. The common practice of combustion of this waste for disposal purposes among farmers is a significant environmental concern. Despite efforts to utilize agricultural waste for various applications such as feedstock, chemical recovery, and dye adsorption, a substantial amount remains unutilized. The burning of agricultural waste for disposal contributes to air pollution and the release of toxic and greenhouse gases. Therefore, it is imperative to implement a system that minimizes waste generation or utilizes it for productive purposes.**

The present paper highlights a method for converting rice straws into paper and composite boards through a simple process. Wood, due to its cellulose and hemicellulose content, is commonly considered as the ideal material for paper production, however, its limited availability and negative environmental and ethical impacts associated with its harvesting, make it an unsustainable option. Agricultural waste, such as rice straw, contains cellulose, hemicellulose, and lignin. The presence of lignin impedes the process of transforming rice straw into paper, but it can be removed through chemical means. After the removal of lignin, rice straw can be processed into pulp and utilized for paper and paperboard production. The purpose of this review is to promote sustainable development by reducing the amount of agricultural waste burned and substituting wood with agricultural waste as the primary raw material for paper and paperboard production.

Keywords: Paddy Straw, Pulp, Pollution, Agricultural waste, Environmental, cellulose, Lignin.

I. INTRODUCTION

Stubble burning is a prominent source of greenhouse gas (GHG) emissions that contribute to the warming of the environment and climate change. The release of GHG emissions into the atmosphere due to the burning of stubble has been a concern since the industrial revolution, as it has led to a decline in air quality, environmental degradation, and negative impacts on human health [1], [2].

The agricultural sector in India is a major contributor to the economy, and as a result of regular crop cultivation, there is a significant amount of agro-residual biomass generated as waste. This waste includes various types of agricultural residues such as rice straw, wheat straw, sugarcane bagasse, and other organic matter [3]. While these residues can be a valuable resource, they are often treated as waste and not utilized effectively. Inappropriate disposal of this waste can lead to environmental pollution and health hazards, making it crucial to find sustainable solutions for managing agricultural waste in India.

India is a major builder of sugarcane, cuisine grains, oil seeds, and additional agricultural items. As a result of periodic crop cultivation cycles, a large amount of agro-residual biomass is generated through various agricultural activities [4]. According to studies, the total agricultural production in India includes 341.20 million tonnes of sugarcane [5], 93.51 million tonnes of wheat [6], 105.24 million tonnes of rice, 22.26 million tonnes of maize [7], 16.03 million tonnes of millets (jowar, bajra, ragi, and small millet), 7.79 million tonnes of fiber crops (jute, mesta, cotton), 18.34 million tonnes of pulses, and 30.94 million tonnes of oilseed crops.

Over 30% of the world's population depends on domesticated rice, one of the five major crops grown worldwide [8]. Rice farming appears to have started in the middle Yangzi Valley approximately 8500–8000 years ago (BP), and it then spread to south China and Southeast Asia, according to archaeological and archaeobotanical discoveries [9]. More than 70% of Indians depend on rice as their primary source of food, and rice grows on 40–45% of the country's total acreage used for cereal crops [10].

Along with the grains nearly 50% or more non-edible biomass is produced in rice plant as straw which includes stem, leaf blades, leaf sheaths and post-harvest remains of panicle [11]. In India the rice straw production is not lesser than 126.6 million tonnes considering harvest index of 0.45 (Singh, Srivastava et al. 2016).

With lack of economically viable alternative option to utilize the straw, the rice farmers in India especially from the northern states, Punjab and Haryana choose to burn the straw in their fields. Nearly 16% crop residues are burnt on farm in India and out of which 60% is rice straw (Anandan et al., 2018).

As a result, there are significant environmental concerns like air pollution, smoke generation, and soil moisture loss. These issues can have negative impacts on human health, such as respiratory problems, and can also harm local ecosystems and contribute to climate change [13], [14]. Therefore, finding sustainable alternatives for utilizing agricultural waste is crucial for mitigating these concerns. This article reviews to discover a viable strategy for utilizing agricultural waste that is profitable for farmers and other industries, while also being environmentally and economically feasible.

The Ecological Ramifications of Agricultural Straw Combustion

Burning straw is a prevalent environmental issue that negatively affects soil fertility, pH level, microbial population, and organic matter. Studies have shown that 1 ton of rice straw contains a considerable amount of nitrogen, phosphorus, potassium, and sulfur, which have the potential to act as micronutrients for the soil [15]. Farmers tend to burn paddy straw to exploit these nutrients, but this practice ultimately results in soil infertility in the long run [16].

Figure 1: Schematic representation of Impacts of Straw Incineration on the Environment and Public Health

Burning of agricultural residue has deleterious impacts on both soil quality and air quality. The release of toxic greenhouse gases, including carbon dioxide, carbon monoxide, nitrogen oxides, methane, and nitrous oxide, during crop burning season leads to significant air pollution [17]. This pollution has been documented to have adverse effects on human health, causing respiratory issues, cardiovascular disease, and other disorders as illustrated in figure 1. The spread of smog, a key consequence of burning, is not limited by geographical boundaries and can travel long distances via wind.

The combustion of crop residues during field burning releases fine particulate matter into the atmosphere, which is a major source of concern due to its adverse impact on human health and the Earth's climate [18], [19]. The environmental and health effects of atmospheric particulate matter are contingent upon its composition and size. The presence of distinct chemical signatures within the particulate matter can be utilized for receptor modelling to indirectly quantify the source contribution, particularly in situations where emission inventory data is not readily available [20]. This is particularly pertinent for crop residue field burning, as quantifying emissions directly is challenging due to the short duration and dispersed nature of these burning events.

The Established Approach for Transforming Rice Straw into Pulp

Rice straw is a plentiful agricultural waste product that has the potential to serve as a valuable raw material in the paper industry [21]. However, converting rice straw into paper pulp is a complex process due to its short fiber length and the need for efficient delignification. To address this challenge, several conventional or traditional methods have been developed, including soda pulping, kraft pulping, and semi-chemical pulping, mechanical, semi-mechanical pulping as represented in figure 2[22].

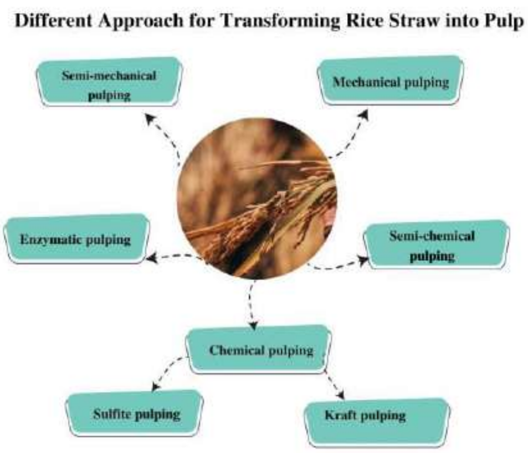

Figure 2: Schematic representation of different method of converting rice straw into pulp

Each of these methods involves different conditions and chemicals to break down the lignin in rice straw and extract the cellulose fibers, resulting in a pulp suitable for papermaking.

- **Mechanical pulping** is one method of processing rice straw. In this process, the straw is first dried and cut into small pieces. The pieces are then fed into a grinder or refiner, which uses mechanical force to break apart the fibers [23], [24]. The lignin that binds the fibers together is destroyed, but not removed, and the resulting pulp still contains significant amounts of impurities. Mechanical pulping is less expensive than other pulping methods, but the resulting pulp is not suitable for high-quality papers [25].
- **Semi-mechanical pulping**, also known as chemi-mechanical pulping or CMP, is a pulping process that combines mechanical and chemical methods to produce pulp. This process is typically used to produce pulp from wood, but it can also be used for other fiber sources such as rice straw. In semi-mechanical pulping, the raw material is first mechanically processed to remove the bark and any other impurities. The remaining wood or straw is then chipped or ground into small pieces. These pieces are then cooked in a chemical solution, usually consisting of sodium sulfite and sodium hydroxide. The chemical solution helps to soften the wood fibers and break down the lignin, making it easier to separate the fibers. The softened wood pieces are then mechanically processed again, usually in a disk refiner or a conical refiner, to further separate the fibers and improve the quality of the pulp. The refining process also helps to remove any remaining impurities and reduces the fiber size. Semi-mechanical pulping is often used to produce pulp for paper products that require high strength and durability, such as paperboard and packaging materials. The resulting pulp has a higher yield and is less expensive to produce than fully chemical pulps, such as kraft and sulfite pulps.
- **Semi-chemical pulping** is another method of processing rice straw. This process uses a combination of mechanical and chemical treatments to remove impurities. The straw is first soaked in a solution of sodium hydroxide and sodium sulfite, which softens the fibers and dissolves some of the lignin. The pulp is then mechanically refined to further separate the fibers. The resulting pulp contains less lignin than mechanical pulp, but still retains a significant number of impurities. Semi-chemical pulping produces a pulp that is suitable for making low-grade papers, such as newsprint.
- **Chemical pulping** is the most effective method of removing lignin and other impurities from rice straw. This process uses harsh chemicals, such as sodium hydroxide and sodium sulfide, to break down the lignin and separate the fibers [26]. There are two major processes used in chemical pulping:
  - ➢ Kraft Pulping
  - ➢ Sulfite Pulping.
  - ✓ **Kraft pulping** is a chemical pulping process that is widely used in the paper industry due to its ability to produce high-quality pulp with excellent physical and chemical properties. The process starts by chipping the rice straw into small pieces and then cooking them in a digester vessel with a mixture of sodium hydroxide and sodium sulfide at high temperatures and pressures [27]. The combination of high temperature and pressure, along with the strong alkali solution, breaks down the lignin in the rice straw, allowing the fibers to separate and form a highly pure pulp. The lignin that is removed during the process is usually burned as fuel to provide energy for the pulping process.

    Kraft pulp has several desirable properties that make it ideal for making high-quality papers. The pulp is strong, durable, and has a high tear resistance, making it ideal for use in printing and writing papers, as well as in packaging materials. Additionally, kraft pulp is very bright and has a high opacity, making it ideal for printing and writing applications that require excellent print quality [28]. Kraft pulping is also relatively efficient in terms of the amount of raw material needed to produce a given amount of pulp. This is because the process is able to remove a high percentage of lignin from the raw material, leaving behind a relatively pure pulp that requires less refining [29]. However, the kraft pulping process has some drawbacks. It is a harsh process that requires large amounts of chemicals, energy, and water, making it expensive and environmentally demanding. Additionally, the process can produce waste products that must be disposed of properly to avoid negative environmental impacts.
  - ✓ **Sulfite pulping** is a chemical pulping process that involves the use of calcium bisulfite and sodium sulfite to cook rice straw at lower temperature and pressure compared to kraft pulping. This process is less harsh on the fibers and produces a pulp that retains more of the original strength and flexibility of the fibers. The resulting pulp is suitable for

making specialty papers such as tissue and filter papers.

The sulfite pulping process involves the cooking of rice straw in a solution of calcium bisulfite and sodium sulfite, which breaks down the lignin in the straw and separates the fibers [22]. This process is milder than kraft pulping and requires less energy and fewer chemicals. The resulting pulp has a lower degree of delignification than kraft pulp, but it also retains more of the original strength and flexibility of the fibers [30].

After the pulping process, the resulting pulp may be further refined in a refiner or fibrator to improve its quality. This refining process helps to increase the fiber bonding and decrease the fiber length, which results in improved pulp properties. Well-cooked pulps are classified as "soft" and have good tearing strength, while poorly cooked pulps are classified as "hard" and have high bursting strength and high bleach consumption [30].

Sulfite pulping has several advantages over kraft pulping, including the ability to produce a pulp that retains more of the original fiber strength and flexibility, as well as the lower energy requirements and fewer chemicals needed for the process [31]. However, sulfite pulping also has some disadvantages, including lower pulp yield and higher costs associated with the use of calcium bisulfite.

Advanced methodologies for turning rice straw into pulp

The traditional methods of rice straw pulping, especially chemical pulping have been recognized for their adverse environmental impacts, attributed to the use of harsh chemicals and high energy requirements. Consequently, there is a growing interest in the development of alternative, sustainable methods for producing pulp from rice straw. The new approaches strive to minimize energy consumption and eliminate the use of hazardous chemicals, while still producing high-quality pulp. These innovations are crucial as they provide an environmentally friendly and economically feasible substitute

Enzymatic pulping represents a promising strategy for depolymerizing lignin in plant biomass, such as rice straw. This approach involves the use of selective enzymatic reactions to cleave the interunit linkages of lignin macromolecules, while leaving the cellulose fibers intact for downstream processing into paper and other products [32]. Compared to conventional pulping methods, enzymatic pulping operates under mild conditions of temperature, pH, and pressure, and requires less energy input and fewer hazardous chemicals, thereby reducing the environmental impact of the process. Furthermore, the enzymes utilized in enzymatic pulping are often derived from renewable resources and exhibit high specificity and efficiency, which contribute to their sustainable and eco-friendly nature [33].

The utilization of supercritical carbon dioxide (CO_2) for lignin extraction from rice straw fibers presents a significant opportunity for advancing the sustainability of pulp formation processes. By leveraging supercritical CO_2 as a solvent, lignin can be selectively extracted from the fibers, leading to a higher cellulose content in the resulting pulp [34]. This can translate to improved paper quality and reduced demand for bleaching chemicals, thereby minimizing the environmental impact of the pulp formation process. The process of extracting lignin from rice straw fibers using supercritical carbon dioxide (CO_2) involves several key steps [35]. Initially, the rice straw biomass is pre-treated to remove impurities and enhance the accessibility of the lignin molecules. The pre-treated biomass is then loaded into an extraction vessel and exposed to supercritical CO_2 at high pressure and temperature. Under these conditions, the supercritical CO_2 acts as a solvent and selectively dissolves lignin from the fibers. The temperature and pressure conditions are adjusted based on the type of lignin being extracted and the desired degree of extraction. Following extraction, the lignin-rich CO_2 solution is depressurized, causing the CO_2 to revert to its gas state, and resulting in the precipitation of lignin. The lignin can be separated from the CO_2 and purified using a range of techniques. The extracted lignin can then be utilized for the production of biofuels, chemicals, and materials, as well as a source of renewable energy [36]. Meanwhile, the remaining cellulose-rich fibers can be further processed into pulp for use in papermaking or other applications.

Overall, the process of supercritical CO_2 extraction of lignin from rice straw fibers is a promising and environmentally-friendly alternative to traditional methods, as it eliminates the need for harsh chemicals and high temperatures and produces a valuable byproduct.

The Road Ahead:

Paddy straw has the potential to serve as a crucial precursor in the paper and pulp industry, however, there have been significant efforts to enhance the efficiency of pulp generation from paddy straw, which has resulted in elevated costs. Annually, a staggering 5 billion mega-grams of crop residues are produced, with limited economic viability, often utilized for animal feed, mushroom substrate, bioenergy, charcoal, and domestic fuel purposes. Nevertheless, a small fraction of crop residue is employed in the agricultural sector to satisfy operational requirements, while the remaining surplus creates logistical challenges necessitating laborious collection, packing, and transportation for further processing [37]. And even if farmers try to do all the things, it won't be financially beneficial for them as operational costs of utilizing crop residue are very high. As a results, farmers tend to safe their time and money by burning the crop residue which tends to cause air pollution and soil pollution [38]. The proper use of this vast quantity of crop residues on the farm is a significant challenge. Pre-treatment process demands a copious number of chemical compounds and water which tends to hinders the application in large scale and cause a substantial increase in the operational costs [39]. Pre-treatment process also leads to variety of environmental concerns as it needs a continuous supply of water, a proper disposal of Alkali black liquor (ABL) and a cost-effective recycling methodology [40]. Alkali black liquor contains soluble lignin, hemicellulose, silica and toxic chemicals which is quite harmful for the water bodies if not treated properly [41]. Despite the efforts made by farmers to utilize crop residues, the utilization of these residues remains financially unfeasible due to the high operational costs involved (Liska et al., 2014). Consequently, farmers often resort to burning crop residues, leading to significant air and soil pollution. The proper utilization of the vast quantity of crop residues remains a significant challenge. The pre-treatment process requires a copious number of chemical compounds and water, making its large-scale application difficult and leading to an increase in operational costs (Kim et al., 2018). Additionally, the pre-treatment process raises various environmental concerns, including the need for a continuous supply of water, the proper disposal of Alkali black liquor (ABL), and the implementation of cost-effective recycling methods (Kumar et al., 2019). ABL contains soluble lignin, hemicellulose, silica, and toxic chemicals, which pose a significant threat to water bodies if not treated appropriately (Minu et al., 2012). To address the negative environmental impact of the pre-treatment process, there have been efforts to make it more efficient and eco-friendlier. Collaboration between industry and research institutions is necessary to conduct more studies on recycling alkali liquor, increasing the mechanical durability of paper, and developing sustainable ways to reduce the environmental impact of the fabrication process (Singh, Srivastava et al., 2016). To improve the efficiency and yield of traditional compounds, it is necessary to explore alternatives to chemical compounds and focus on technological improvements, reducing human dependency on the entire operation. Lignin-degrading enzymes represent one such alternative, which has been studied in various applications such as the paper industry (Janusz et al., 2017). The identification of a wide range of known bacterial peroxidases and laccases that may be involved in lignin degradation has grown remarkably over the last two decades (Abdel-Hamid et al., 2013). Lignin-degrading enzymes have attracted attention for their valuable biotechnological applications, especially in the pre-treatment of recalcitrant lignocellulosic biomass, becoming a sustainable way to reduce dependency on harmful chemicals. Investigation can also be done on different chemical solutions to improve the breakdown of the lignocellulosic structure and develop chemicals with better biodegradability and less environmental harm. There may still be undiscovered enzyme types involved in bacterial lignin degradation that require further investigation (de Gonzalo et al., 2016).

Conclusion

In conclusion, the production of paddy straw during paddy grain production results in the generation of substantial amounts of lignin and cellulose residue, which is typically disposed of through burning due to inadequate resources for proper management. This leads to severe air pollution and health issues in specific regions. However, rice straw exhibits promising potential as a viable raw material in the pulp and paper industries. Utilizing rice straw as a raw material can aid farmers in managing their straw, while also presenting an eco-friendly alternative to wood as a raw material. Although rice straw contains undesirable components like ash and silica, it also consists of advantageous constituents for papermaking, paperboard, and composite board production. Therefore, exploring the application of rice straw as a raw material for the paper and board industries has the potential to minimize environmental pollution and promote a more sustainable and efficient utilization of resources in the paper and board industry.

Future Prospect

In the future, the potential widespread use of rice straw as a raw material for the pulp and paper industries may provide a sustainable and cost-effective alternative to traditional wood-based pulp and paper production. Advances in technology and processing methods may facilitate the extraction of valuable components from rice straw, while also reducing the undesirable effects of ash and silica. Additionally, raising awareness among farmers and incentivizing them to sell their rice straw residue for use in the pulp and paper industries may further promote the adoption of this sustainable solution. Overall, the future prospects of using rice straw as a raw material in the pulp and paper industries are promising, and further research and development in this field may lead to significant environmental and economic benefits.

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