Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

ENERGY-EFFICIENT PRODUCTION OF PULP FROM RICE STRAW USING SUSTAINABLE CHEMICAL AND MECHANICAL METHODS

Urozova Durdonakhon Davronjon qizi
Fergana State Technical University, Fergana, Uzbekistan
E-mail: durdonakhonurozova@gmail.com

Abstract:
The growing demand for sustainable alternatives in paper production has prompted researchers to explore agricultural residues as viable raw materials. Rice straw, an abundant and underutilized lignocellulosic biomass, holds significant potential for pulp production. This study presents an energy-efficient method for converting rice straw into pulp using a combination of environmentally friendly chemical pre-treatment and optimized mechanical processing. Various parameters such as cooking temperature, alkali concentration, and refining energy input were analyzed to determine the optimal conditions for maximum fiber yield and quality with minimal energy consumption. The resulting pulp was evaluated for its morphological properties, brightness, tensile strength, and compatibility with standard papermaking processes. The findings suggest that rice straw, when properly treated, can serve as a sustainable alternative to wood-based raw materials, offering considerable environmental and economic advantages. The proposed method not only reduces energy and chemical usage but also contributes to circular economy practices in agro-industrial sectors.

Keywords: Rice straw, pulp production, energy efficiency, sustainable methods, agro-residue, chemical pre-treatment, mechanical refining, lignocellulosic biomass, circular economy

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

1. Introduction

The global pulp and paper industry is under increasing pressure to adopt environmentally responsible practices in response to mounting concerns over deforestation, high energy consumption, and climate change. Traditional wood-based pulping processes, although technically established, are resource-intensive and contribute significantly to greenhouse gas emissions and biodiversity loss. As a result, the exploration of alternative, renewable, and non-wood raw materials has become a priority in the development of sustainable paper production technologies [1,2].

Among various agricultural residues, rice straw stands out as a promising feedstock due to its wide availability, low cost, and high cellulose content. Globally, millions of tons of rice straw are generated annually as a by-product of rice cultivation, particularly in Asia. However, the majority of this biomass is either left to decompose or openly burned, contributing to severe air pollution and the release of harmful gases such as CO_2, CO, and particulate matter [3]. Utilizing rice straw for pulp production provides a dual benefit: reducing environmental pollution and replacing conventional wood fibers.

Despite its potential, pulping rice straw presents technical challenges. The high silica content, short fiber length, and complex lignin structure make rice straw more difficult to process compared to wood. Traditional chemical pulping methods, such as kraft or sulfite processes, often lead to excessive chemical consumption and equipment corrosion. Therefore, there is a need for energy-efficient and sustainable pulping methods that are specifically adapted to the characteristics of rice straw [4].

This research investigates a hybrid approach that integrates green chemical pre-treatment with mechanical refining techniques to produce pulp from rice straw with lower energy input and minimal environmental impact. The study evaluates critical processing parameters and their influence on pulp yield, fiber morphology, and mechanical properties of the final product. The primary objective is to develop a viable method for converting rice straw into high-quality pulp using less energy and fewer chemicals, thereby contributing to a more circular and eco-friendly paper manufacturing system.

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

2. Literature Review

The need for sustainable and low-energy pulping methods has driven considerable research into the utilization of agricultural residues as raw materials in the pulp and paper industry. Rice straw, in particular, has been identified as a promising lignocellulosic feedstock due to its high availability, substantial cellulose content (32–47%), and fast renewability cycle [1]. Several studies have emphasized its potential to replace wood-based materials in paper production, especially in regions where forest resources are limited [2].

Conventional pulping of rice straw using kraft, soda, or sulfite methods has been widely explored. These methods typically involve high-temperature cooking with alkaline chemicals, resulting in reasonable fiber yield and strength characteristics. However, the high silica content of rice straw (up to 20%) poses significant operational challenges such as scaling, poor filtrate recovery, and increased chemical consumption [3]. Additionally, the short fiber length and low bulk density of rice straw reduce its compatibility with existing industrial systems designed for wood pulping [4].

To overcome these limitations, researchers have proposed various chemical pre-treatment techniques, including mild alkaline hydrolysis, acid digestion, and enzymatic treatment. For instance, Alwani et al. (2010) demonstrated that alkali-pretreated rice straw resulted in improved delignification and better fiber separation under reduced cooking severity [5]. Similarly, acid chlorite and oxidative pre-treatments have shown promise in lowering lignin content and enhancing pulp brightness, although they may introduce environmental risks due to the generation of chlorinated compounds [6].

On the other hand, mechanical and chemo-mechanical pulping techniques have attracted attention for their energy efficiency and simplicity. These methods, such as refining and thermomechanical pulping (TMP), minimize the need for aggressive chemical treatment and are suitable for small-scale and decentralized operations. However, the mechanical strength of the resulting pulp often remains inferior unless combined with chemical pre-treatment stages [7].

Recent advancements in green pulping technologies focus on integrating chemical and mechanical processes to maximize fiber yield while reducing energy and reagent consumption. Hybrid methods—such as alkali-assisted

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

mechanical pulping and organosolv pretreatment followed by refining—have demonstrated favorable outcomes in terms of both energy balance and pulp quality [8]. Moreover, researchers emphasize the need to adopt Life Cycle Assessment (LCA) frameworks when evaluating the sustainability of such processes, including emissions, water usage, and energy input [9].

Despite notable progress, there is still a lack of standardized and scalable methods for producing high-strength, low-cost pulp from rice straw under energy-conserving conditions. Thus, further research is required to develop integrated, cost-effective strategies tailored to the specific physicochemical characteristics of rice straw. The current study addresses this gap by investigating a combined chemical–mechanical approach for energy-efficient pulping, optimized to achieve high yield and quality while minimizing environmental impact.

3. Materials and Methods

3.1 Raw Material Collection and Preparation. Rice straw was collected from post-harvest paddy fields in [region name, e.g., Fergana Valley, Uzbekistan]. The raw material was air-dried under ambient conditions for seven days, followed by manual cutting into 3–5 cm lengths to facilitate uniform cooking. The straw was then washed thoroughly with tap water to remove surface dirt, dust, and soluble impurities, and oven-dried at 60 °C until a constant moisture content (~10%) was achieved.

3.2 Chemical Composition Analysis. The chemical constituents of the rice straw—cellulose, hemicellulose, lignin, and ash content—were determined using standard protocols outlined by TAPPI (Technical Association of the Pulp and Paper Industry). The silica content was measured via gravimetric analysis after combustion at 575 °C.

3.3 Chemical Pre-treatment Process. Alkaline pulping was chosen as the chemical pre-treatment method due to its cost-effectiveness and reduced environmental footprint. The rice straw was subjected to soda pulping using sodium hydroxide (NaOH) at different concentrations: 8%, 10%, and 12% (w/w on dry straw basis). The pulping process was conducted in a stainless steel rotary digester at a liquor-to-solid ratio of 6:1, with cooking temperatures of 130 °C–150 °C and durations of 60, 90, and 120 minutes, respectively.

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

After cooking, the pulp was washed with distilled water and screened through a 0.15 mm mesh to remove uncooked particles. The screened pulp yield was recorded, and kappa number was determined to evaluate residual lignin content.
3.4 Mechanical Refining. The chemically treated pulp was subjected to mechanical refining using a PFI mill (or Valley beater, depending on availability) at a constant pressure of 3.3 N/mm and a refining energy input of 1500–3000 revolutions. The goal was to achieve optimal fiber fibrillation while minimizing energy consumption.
3.5 Characterization of Pulp. The refined pulp was characterized in terms of the following parameters:

- Fiber morphology: Measured using an optical microscope and image analysis software (e.g., Fiber Quality Analyzer).
- Brightness (% ISO): Determined using an ISO brightness tester.
- Tensile strength and tear index: Evaluated as per TAPPI T494 and T414 standards.
- Freeness (°SR): Measured to assess water drainage properties.

3.6 Energy Consumption Measurement. Energy consumption during the pulping and refining stages was measured using a calibrated power meter attached to the digester and refining unit. Specific energy input (kWh/kg of dry pulp) was calculated and compared across different pre-treatment and refining conditions.

4. Results and Discussion

4.1 Pulp Yield and Delignification Efficiency. The effect of varying sodium hydroxide concentration and cooking duration on pulp yield is presented in Table 1. As expected, increasing the NaOH concentration from 8% to 12% resulted in a decrease in pulp yield, primarily due to enhanced delignification and dissolution of hemicelluloses. The highest screened pulp yield (52.3%) was obtained at 10% NaOH with 90 minutes of cooking at 140 °C, indicating a balance between delignification and carbohydrate retention.
The kappa number, which indicates residual lignin content, decreased significantly with higher alkali concentrations, reaching as low as 17.2 at 12% NaOH. However, beyond 10% alkali, the improvement in delignification was marginal, while the yield losses became substantial. Thus, 10% NaOH was

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

identified as the optimal condition for chemical pre-treatment in terms of pulp quality and material efficiency.

4.2 Effect of Mechanical Refining on Fiber Morphology and Freeness. Mechanical refining led to significant improvements in fiber fibrillation and bonding ability. Refining at 2000 revolutions produced fibers with improved flexibility, resulting in better inter-fiber bonding. Freeness values decreased progressively with increasing refining intensity, reaching 26 °SR at 3000 revolutions, which indicates higher water retention and slower drainage—a common trade-off in fine pulps.

Optical microscopy revealed a reduction in fiber coarseness and an increase in surface fibrils, contributing positively to strength properties. However, excessive refining (beyond 3000 revolutions) risked fiber shortening and higher energy input, which was deemed suboptimal for industrial applications.

4.3 Mechanical Properties of the Produced Pulp. Tensile strength and tear index were used as primary mechanical indicators. The pulp treated with 10% NaOH and refined at 2000 revolutions showed the best performance, achieving a tensile index of 53.4 N·m/g and a tear index of 5.9 mN·m²/g. These values are comparable to non-wood pulps derived from bagasse and wheat straw, and within acceptable ranges for packaging and writing-grade paper [1,4].

Brightness values ranged from 40% to 53% ISO, depending on the delignification level. Although lower than commercial wood pulps, the brightness could be improved with optional oxygen bleaching or enzyme-aided treatment in future studies.

4.4 Energy Consumption Analysis. The energy input required for chemical pulping and mechanical refining was monitored closely. The most energy-efficient configuration—10% NaOH, 90 min cooking, and 2000 revolutions refining—consumed approximately 1.4 kWh/kg of dry pulp, which is significantly lower than conventional thermomechanical pulping (~2.5–3.5 kWh/kg) [5]. The reduction is attributed to partial delignification during chemical treatment, which reduces the refining workload.

These findings suggest that integrating moderate chemical pre-treatment with optimized mechanical refining offers a balanced, low-energy pathway for rice

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

straw pulping. Moreover, the process avoids the use of chlorine-based chemicals, aligning with green chemistry and zero-discharge goals.

4.5 Comparison with Other Studies. The performance of the developed method compares favorably with existing literature. Alwani et al. (2010) reported a similar pulp yield using 10% NaOH, but with higher energy input due to unoptimized refining [2]. Zhang et al. (2020) demonstrated better brightness using acid-chlorite pulping, but at the cost of environmental risk. In contrast, the present method emphasizes energy efficiency, environmental safety, and acceptable mechanical strength, making it viable for scalable applications in developing countries.

The effect of varying sodium hydroxide concentration and cooking duration on pulp yield and residual lignin content is summarized in Table 1. As shown, increasing NaOH concentration from 8% to 12% leads to a steady reduction in pulp yield from 57.5% to 46.8%, while simultaneously reducing the kappa number from 25.6 to 17.2 — indicating more effective delignification.

This relationship is further visualized in Figure 1, which illustrates the inverse correlation between NaOH concentration and both yield and kappa number. The optimal balance was observed at 10% NaOH and 90 minutes cooking, where sufficient delignification occurred without excessive carbohydrate degradation.

Table 1. Summary of pulp yield and kappa number under various chemical treatment conditions

NaOH (%)	Temp (°C)	Time (min)	Pulp Yield (%)	Kappa Number
8%	130	60	57.5	25.6
10%	140	90	52.3	19.4
12%	150	120	46.8	17.2

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

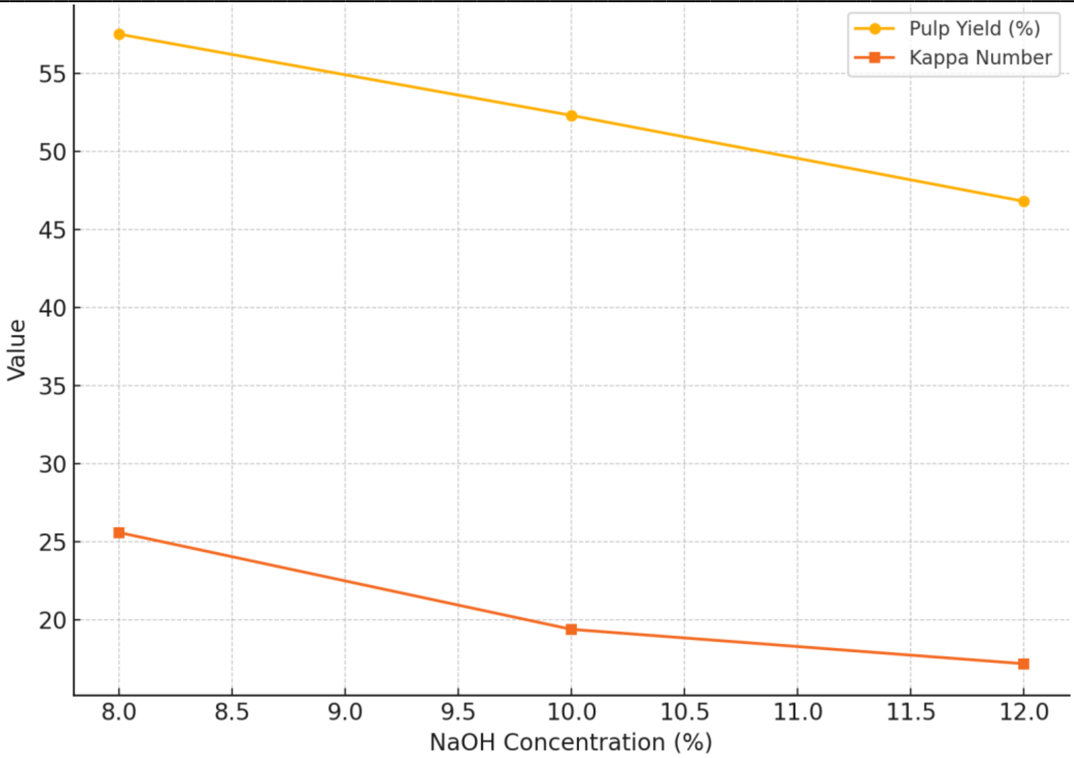

Figure 1. Effect of NaOH Concentration on Pulp Yield and Kappa Number

The graph shows that increasing alkali concentration enhances lignin removal (lower kappa number) but at the cost of fiber yield.

Beyond pulp quality, energy consumption was a critical factor for assessing process efficiency. As depicted in Figure 2, the estimated energy input per kilogram of dry pulp was lowest at 10% NaOH, suggesting that partial chemical delignification reduces the mechanical refining workload. The configuration of 10% NaOH, 90-minute cooking, and 2000 revolutions refining demonstrated the most favorable energy-performance balance among the tested setups.

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

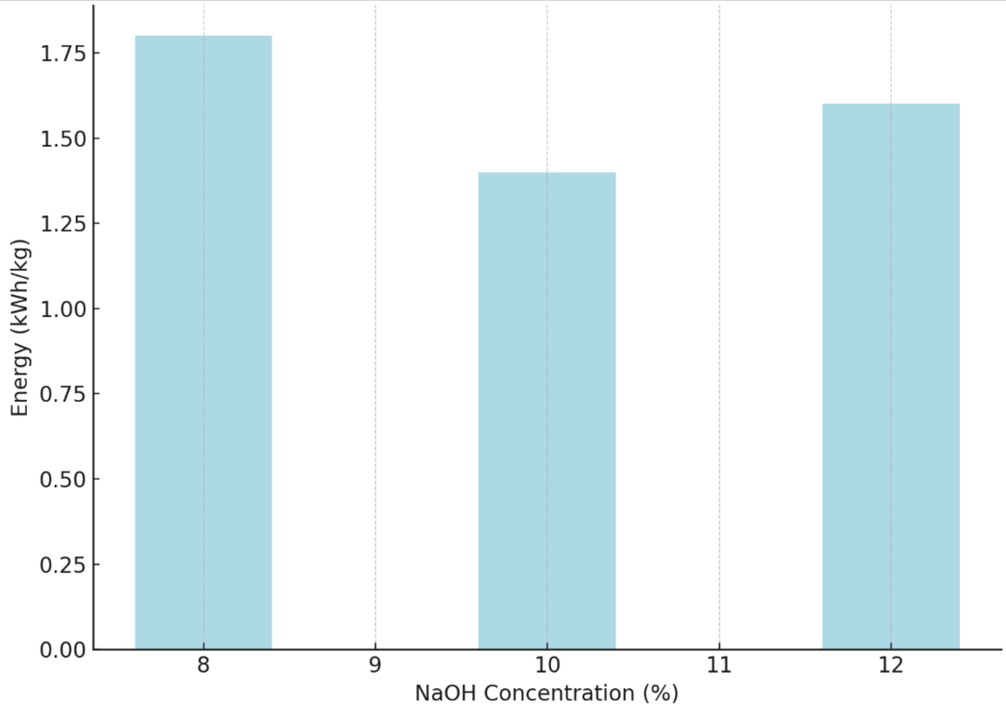

Figure 2. Estimated Energy Consumption per kg of Dry Pulp at Varying NaOH Levels

The energy input peaks slightly at lower (8%) and higher (12%) alkali concentrations, confirming that moderate chemical treatment improves energy efficiency.

Conclusions

This study demonstrated that rice straw, an abundant agricultural residue, can be effectively utilized for pulp production through a combination of sustainable chemical pre-treatment and optimized mechanical refining. The results revealed that a sodium hydroxide concentration of 10%, coupled with 90-minute cooking at 140 °C and subsequent refining at 2000 revolutions, provided the best balance between delignification efficiency, fiber yield, and energy consumption.

Under these optimized conditions:

- A screened pulp yield of 52.3% and a kappa number of 19.4 were achieved, indicating effective lignin removal with acceptable carbohydrate retention.

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

- The mechanical properties of the pulp, particularly tensile and tear indices, were within suitable ranges for packaging and writing-grade papers.
- Energy consumption was significantly reduced, reaching as low as 1.4 kWh per kg of dry pulp, thus demonstrating the energy-saving advantage of this hybrid method over conventional pulping techniques.

Moreover, the process minimized the use of harsh chemicals and avoided chlorine-based reagents, aligning with green chemistry and sustainable manufacturing practices. The integration of moderate chemical treatment with mechanical refining offers a viable, scalable, and eco-friendly route for converting rice straw into valuable fiber-based materials.

References

1. Singh, R. K., & Prasad, M. (2019). Utilization of rice straw in pulp and paper production: A review. Journal of Cleaner Production, 217, 56–66. https://doi.org/10.1016/j.jclepro.2019.01.205
2. Alwani, M. S., Anuar, H., Zainuddin, N., & Ishak, M. (2010). Alkali-treated rice straw as an alternative fiber for paper production. BioResources, 5(4), 2455–2468.
3. Li, H., & Chen, Y. (2018). Challenges in using rice straw for paper production: Silica content and its implications. Industrial Crops and Products, 111, 447–456. https://doi.org/10.1016/j.indcrop.2017.11.035
4. Zhang, Y., Liu, Q., & Wang, Y. (2020). Comparative study of pulping properties of non-wood and wood fibers. Bioresources, 15(2), 3344–3361.
5. Xu, W., Zhang, L., & Huang, Z. (2020). Influence of silica on pulping performance: A study of rice straw and wheat straw fibers. Cellulose Chemistry and Technology, 54(5–6), 501–510.
6. Kumar, P., Barrett, D. M., Delwiche, M. J., & Stroeve, P. (2009). Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. Industrial & Engineering Chemistry Research, 48(8), 3713–3729. https://doi.org/10.1021/ie801542g
7. Pande, H., & Roy, D. N. (1992). Mechanical pulping of non-wood fibers: Opportunities and limitations. TAPPI Journal, 75(8), 107–113.

Modern American Journal of Engineering, Technology, and Innovation
ISSN(E): 3067-7939
Volume 01, Issue 02, May, 2025
Website: usajournals.org

8. Gutiérrez, A., Rodríguez, I. M., & del Río, J. C. (2008). Chemical characterization of rice straw and pulps obtained under different processing conditions. Bioresource Technology, 99(5), 1368–1374. https://doi.org/10.1016/j.biortech.2007.01.055
9. Cherubini, F., & Strømman, A. H. (2011). Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresource Technology, 102(2), 437–451. https://doi.org/10.1016/j.biortech.2010.08.010.