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Techno-economic analysis of biomass-powered fixed bed dryer with air dehumidification for paddy drying

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Abstract

This study introduces the innovative use of synthetic zeolite adsorbents in biomass-powered fixed bed dryers for enhanced paddy drying. The novel integration significantly improves moisture removal and energy efficiency, addressing limitations of conventional drying methods. Key findings include an effective moisture diffusivity of 2.24×10^{-8} m²/s and energy efficiency reaching up to 68%. The economic analysis highlights an Internal Rate of Return (IRR) within 2.04 years, confirming the financial viability of this technology. This advanced drying system demonstrates superior performance and sustainability, offering a promising solution for industrial-scale paddy drying.

Keywords: Dehumidification; drying; energy efficiency; paddy

1. Introduction

Rice is the staple food source of Indonesian society to this day. In Indonesia itself, rice is a food ingredient that cannot be replaced with other food ingredients. To produce rice, several process stages are required, starting from harvesting the rice, threshing, drying and milling. Drying is a crucial post-harvest operation that significantly influences the quality and market value of rice [1].

In general, after harvest, rice has a fairly high water content of around 20 - 23% on a wet basis in the dry season and in the rainy season around 24 - 27% on a wet basis [2]. At this level of water content, rice is not safe to store because it is very easily attacked by fungus or easily damaged. To be safely stored for long periods, rice needs to be dried to a moisture content of around 14% on a wet basis [3]. Post-harvest handling must be carried out properly to avoid damage or decrease in the quality which is detrimental to the community [4,5]. This is due to incorrect handling by farmers, one of which is during the drying process, so that the grain shrinks by around 20% of production.

Traditional sun drying methods, while prevalent, are often unreliable due to weather dependency and can result in uneven drying leading to grain damage and loss of nutritional value [6]. As a response, mechanical drying technologies have been developed to offer more controlled and efficient drying processes.Among these technologies, the fixed bed dryer with air dehumidification has gained attention for its potential to achieve faster and more uniform drying compared to traditional methods [7]. By combining a fixed bed dryer's controlled environment with air dehumidification systems, moisture removal from paddy grains can be optimized while minimizing heat exposure, thus preserving the grain's quality attributes such as color, aroma, and texture.

The influencing factor in dehumidifications system is the influence of adsorbents such as zeolite and silica where the adsorbents can make the drying air drier and also provides positive results in the adsorption drying process to speed up and increase energy efficiency. In the drying process where zeolite in this system, the air is heated to a temperature of 30-60ºC and passed through the zeolite, the zeolite will absorb water from this air and then the air is contacted with the grain, so that the air humidity will be kept low and the driving force of the drying process remains high. So the drying process becomes fast, and the energy efficiency of the drying process is predicted to be high.

This study builds upon previous research by addressing critical gaps in drying performance and economic feasibility. Earlier studies have demonstrated the general benefits of fixed-bed dryers with dehumidification but lacked detailed evaluations of adsorbent efficiency and comprehensive economic analysis [7]. Unlike prior works, this study highlights the superior performance of synthetic zeolite, which achieves an energy efficiency improvement over conventional systems that often operate below 40% efficiency [3]. Additionally, the effective moisture diffusivity in other systems such as oven or

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infrared dryers, showcasing the technological advancements in moisture removal and energy conservation [6,8] The inclusion of economic metrics such as Net Present Value (NPV) and Benefit-Cost (B/C) ratio further distinguishes this research by providing actionable insights for large-scale adoption.

The addition of a biomass burning stove and providing air circulation (inlet and outlet) is sufficient to enable the dryer to work optimally with biomass energy. The heat energy from this biomass is delivered by a fan into the drying chamber, resulting in movement of the air flow rate inside the device. Biomass is organic material that is relatively young and comes from plants, animals, products and waste from the cultivation industry (agriculture, plantations, forestry, animal husbandry, fisheries). The main elements of biomass are various chemical substances (molecules) most of which contain carbon atoms (C) [9].

Understanding the economic feasibility and technical performance of this drying technology is crucial for its adoption by rice processing industries [10]. This research aims to conduct a comprehensive techno-economic analysis of the fixed bed dryer with air dehumidification for paddy drying. The study evaluates the system's efficiency in terms of energy efficiency, moisture reduction, and overall cost-effectiveness compared to conventional drying techniques.

2. Materials and Methods

2.1. Paddy samples

Paddy samples for the drying process were harvested in January 2020 from Meteseh District in Semarang, Central Java, Indonesia. The initial moisture content of the paddy samples ranged between 20–24% (wet basis). The initial and further (from the drying process) moisture content of the paddy samples was determined using a G-WON GMK 303RS grain moisture meter (±0.5% accuracy and ±0.1% resolution). For the drying process, three types of adsorbents were used: (1). Silica, A porous material with a particle size of 2–5 mm, sourced from local suppliers in Semarang. (2). Natural Zeolite, Derived from volcanic ash, with a particle size of 3–6 mm, sourced from local suppliers in Semarang. (3) Synthetic Zeolite, A Type 4A molecular sieve (sodium alumina silicate) with 4-angstrom (0.4 nm) pores, spherical particles of 1–3 mm, purchased from Guangdong Xintao, China.

2.2. Drying Process

Drying is done using a biomass-powered fixed bed dryer with air dehumidification (see Fig. 1). The process comprised three main stages:
(1). Dehumidification: Ambient air at 31°C with a relative humidity of 74% was passed through adsorbents (silica, natural zeolite, and synthetic zeolite) to reduce relative humidity to 33%. The weight of the adsorbents used in each trial was maintained at 10 kg for uniformity across experiments. The adsorbents were placed in a designated adsorbent box located at the inlet section of the dryer.
(2). Heating: The dehumidified air was then heated to the desired drying temperature of 40–50°C using biomass fuels (charcoal and rice husks). Approximately 30 kg of biomass fuel was used per drying cycle, ensuring consistent heat supply.
(3). Drying: The hot air, with a flow speed of approximately 12 m/s, was directed over the paddy bed through a perforated tray system. 1000 kg of paddy was loaded onto the drying tray per trial, spread evenly to a bed depth of 10 cm. The drying chamber measured 3.66 m (length) x 2.44 m (width) x 1.20 m (height), ensuring uniform airflow over the paddy. Moisture content was measured hourly using the G-WON GMK 303RS grain moisture meter until the target moisture content of 14% was achieved.

Control experiments were performed under identical conditions but without adsorbents. Comparative drying trials were also conducted using different biomass fuels (charcoal and rice husks) to evaluate their performance.

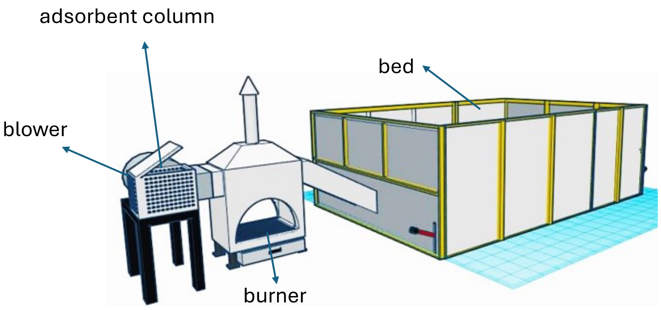

Fig. 1. Schematic of biomass-powered fixed bed dryer with air dehumidification

2.3. Moisture content and effective moisture diffusivity

Approximately 50 grams of paddy grain was withdrawn from the drying chamber during drying at one hour intervals for each drying condition. The moisture content of paddy grain samples was determined using a G-WON GMK 303RS grain moisture meter (Seoul, South Korea). The moisture content determination was carried out two to three times until a constant moisture content value was obtained.

The moisture ratio of paddy was calculated using Equation 1 [5].

$$MR_t = \frac{M_t}{M_0} \quad (1)$$

Where MRt was the moisture ratio, Mt was the moisture cntent at t time, and M0 was the initial moisture content. A mathematical model was used to estimate the effective moisture diffusivity and mass distribution during the drying process

In the calculations of this model, several assumptions were made: the paddy had a certain thickness, the effective moisture diffusivity and water density in the solid were considered constant, the initial moisture content was assumed to be uniform throughout, and the drying air velocity and temperature were uniform throughout the drying section [11].

$$MR_t = \frac{M_t}{M_0} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{L^2}\right) \quad (2)$$

Then, Equation 2 can be simplified to:

$$MR_t = \frac{M_t}{M_0} = \frac{8}{\pi^2} exp\left(-\frac{\pi^2 D_{eff} t}{L^2}\right) \quad (3)$$

2.4. Energy efficiency calculation

Energy efficiency depends significantly on several process characteristics, including the rate of water evaporation from the material, the use of steam as air heating, and the potential to harness heat energy from other processes within the industry. The calculation of energy efficiency (η) can be estimated by dividing the heat required to evaporate water from paddy by the total heat needed to regenerate zeolite and raise air temperature [12].

$$\eta = \frac{M_d(X_{(t=0)} - X_{(t=td)})\lambda}{FC_p(T_1 - T_2)td} \times 100\% \quad (4)$$

Where, M_d was the mass of the dry paddy (kg), $X_{(t=0)}$was the initial moisture content of paddy grain, $X_{(t=t_d)}$ was the moisture content of paddy grain at the end of the drying experiment, and λ was the latent heat of vaporization of water (kJ/kg). The latent heat values were assumed at 2,350 kJ/kg water. F was the mass flow of air (m/s), C_p was the specific heat capacity of air (kJ/kg/°C). Here, C_p of air can be assumed to be constant at 1 kJ/kg/ °C. T_1 and T_2 were the temperature of the inlet and outlet, and t_d was the observed time interval.

2.5. Economic analysis

To evaluate the feasibility of this business with basic capacity of 60 tons per months (2 tons per day) the cost production per kg of product was compared with others. Then the several financial criteria included Net Present Value (NPV), which measures the profitability of an investment by considering the time value of money; the Benefit-Cost Ratio (B/C ratio), which compares the benefits to the costs of a project; and the Internal Rate of Return (IRR), which identifies the rate of growth a project was expected to be generated. These criteria provide a comprehensive understanding of the potential profitability and efficiency of a business, helping to make informed investment decisions [20, 21].

To evaluate the feasibility of this business with basic capacity of 60 tons per months (2 tons per day) the cost production per kg of product was compared with others. The financial feasibility of the drying system was assessed using three key metrics: (1). Net Present Value or NPV, Evaluates profitability by incorporating the time value of money. (2). Benefit-Cost Ratio or B/C ratio, Compares project benefits to costs. (3) Internal Rate of Return or IRR, Calculates the expected growth rate of the project [15,16].

These metrics were calculated based on the following assumptions:

Capital Investment: The total capital investment for the biomass-powered fixed bed dryer, including the dryer unit, biomass burner, adsorbent setup, and installation, was estimated at $14,516.

Operational Costs : The total operational cost, including fuel, labor, and adsorbent regeneration, was estimated at $1,816 per year.

Estimated Maintenance Costs: Regular maintenance, including cleaning, lubrication of moving parts, and minor repairs, was estimated at $155/year.

These criteria provide a comprehensive understanding of the potential profitability and efficiency of a business, helping to make informed investment decisions [13,14].

2.6. Statistical analysis

To assess the effects of adsorbent types and biomass fuels on moisture content reduction, effective moisture diffusivity, and energy efficiency, a Single-Factor Analysis of Variance (ANOVA) was conducted.

3. Results and Discussion

3.1. Drying evaluation of biomass-powered fixed bed dryer with air dehumidification

The type of adsorbent used in paddy drying—whether silica, natural zeolite, or synthetic zeolite—plays a crucial role in determining the efficiency of moisture removal [17]. For various types of adsorbents, the relationship between moisture content reduction and drying time is shown in Fig. 2 and Fig. 3. Fig. 2 showed the moisture reduction in dryer using the rice husk as the fuel, where the Fig. 3 showed the moisture reduction in dryer using the charcoal as the fuel.

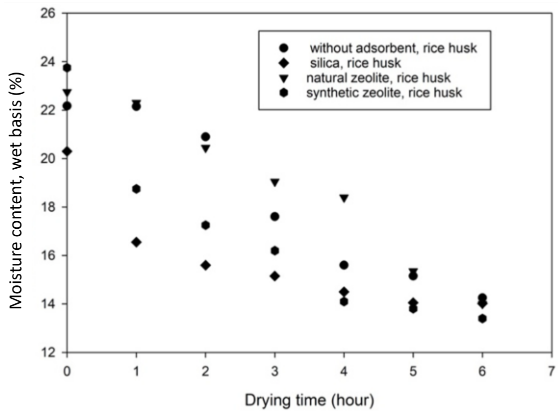

Fig. 2. Moisture content reduction over drying time for various adsorbents used in paddy drying with rice husk biomass fuel

Based on Fig. 2 and 3, it is evident that drying without an adsorbent leaves the paddy with a moisture content above the standard threshold for milling, which is over 14%. This high moisture content can affect the quality and efficiency of the milling process, potentially leading to reduced rice yield and quality [2,23,24]. Additionally, the value of effective misture diffusivity for drying without an adsorbent was also the lowest, about 2.69 × 10-10 m^2/s (see Fig. 4). The ANOVA results for the effect of adsorbents on moisture content reduction when using rice husk biomass fuel (Table 1) indicate a significant difference between groups ($P < 0.05$). This demonstrates that the choice of adsorbent significantly influences the drying process. Among the adsorbents tested, synthetic zeolite exhibited the fastest and most effective moisture reduction, achieving a final moisture content between 11.9–13.4% (wet basis). This is attributed to synthetic zeolite's uniform pore structure and superior thermal stability, enabling more efficient moisture adsorption [20,21]. In comparison, natural zeolite and silica, while effective, showed slightly slower moisture reduction due to differences in pore structure and adsorption properties [22,23].

Table 1. ANOVA for the effect of adsorbents on moisture content reduction in paddy drying with rice husk biomass fuel

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	936.16	4	234.04	31.87	2×10^{-10}	2.69
Within Groups	220.29	30	7.34			
Total	1156.45	34				

Using charcoal as the fuel in the drying process resulted in even lower moisture content compared to rice husk, as shown in Fig. 3. The ANOVA results in Table 2 reveal a significant effect of adsorbents on moisture content reduction (F = 29.08, P < 0.001). Charcoal provided a higher drying air temperature (approximately 43°C) compared to rice husk (35°C), due to its higher calorific value. The higher temperature reduced air humidity, creating a stronger driving force for moisture removal [24,25]. Synthetic zeolite again proved to be the most effective adsorbent, delivering superior performance in terms of moisture reduction and drying speed, making it a preferred choice for industrial applications.

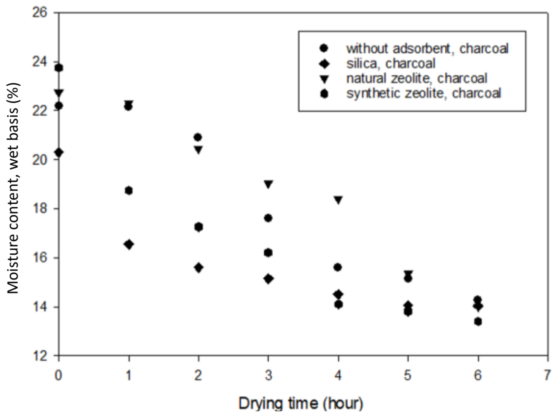

Fig. 3. Moisture content reduction over drying time for various adsorbents used in paddy drying with charcoal biomass fuel

Table 2. ANOVA for the effect of adsorbents on moisture content reduction in paddy drying with charcoal biomass fuel

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1315.13	4	328.78	29.08	6×10^{-10}	2.69
Within Groups	339.13	30	11.30			
Total	1156.45	34				

The effective moisture diffusivity for various adsorbents and fuels is illustrated in Fig. 4. ANOVA results (Table 3) show that the choice of fuel (charcoal or rice husk) does not have a statistically significant effect on effective moisture diffusivity (F = 0.668, P = 0.445). However, charcoal as a fuel resulted in slightly higher diffusivity values across all adsorbents due to its ability to generate higher drying temperatures [24]. The effective moisture diffusivity when using synthetic zeolite and charcoal was the highest, approximately 2.24×10^{-8} m²/s, further supporting the efficiency of synthetic zeolite in accelerating moisture removal [7,21].

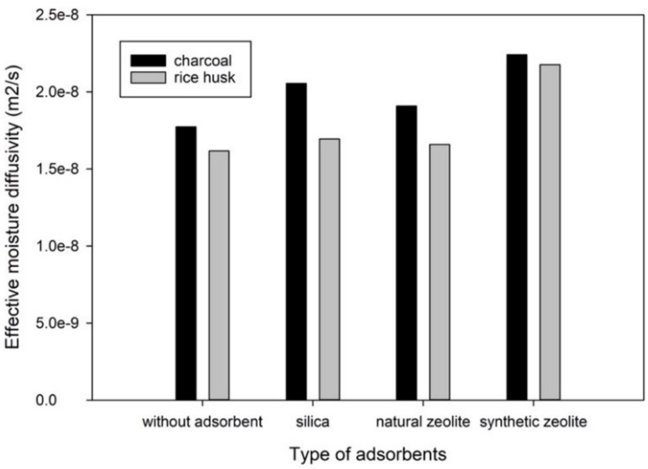

Fig. 4. Effective moisture diffusivity for various adsorbents used in paddy drying with rice husk and charcoal biomass fuel

Table 3. ANOVA for the effect of rice husk and charcoal biomass fuel on effective moisture diffusivity in paddy drying

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7.58×10^{-18}	1	7.58×10^{-18}	6.68×10^{-1}	4.45×10^{-1}	5.99
Within Groups	6.80×10^{-16}	6	1.13×10^{-17}			
Total	7.56×10^{-17}	7				

3.2. Energy efficiency evaluation of biomass-powered fixed bed dryer with air dehumidification

The relationship between drying energy efficiency and adsorbent type is clearly illustrated in Fig. 5, where the use of different adsorbents—silica, natural zeolite, and synthetic zeolite—significantly affects the energy consumption during paddy drying. The drying process without any adsorbent has the lowest energy efficiency, around 24.139%, indicating that a substantial amount of energy is required to reduce the moisture content in the absence of moisture-absorbing materials. In the drying process by dehumidification using synthetic zeolite, the drying temperature is operated at a low or medium temperature and the drying time required is shorter, so the energy requirements for the drying process can be reduced. This is what makes the drying process more efficient [26].

In contrast, the drying process using synthetic zeolite results in the highest energy efficiency, reaching up to 68%. This substantial improvement can be attributed to synthetic zeolite's superior moisture adsorption capabilities, which allow for faster and more effective moisture removal, thereby reducing the overall energy required for drying. The other adsorbents, such as silica and natural zeolite, also enhance energy efficiency compared to drying without adsorbents, but they do not match the performance of synthetic zeolite [27,33]. This demonstrates that selecting the appropriate adsorbent type is crucial for optimizing drying processes, both in terms of moisture removal rate and energy efficiency.

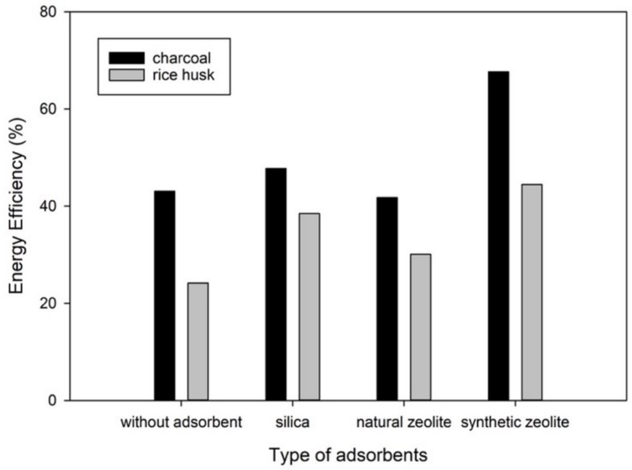

Fig. 5. Energy efficiency for various adsorbents used in paddy drying with rice husk and charcoal biomass fuel

Table 4. ANOVA for the effect of rice husk and charcoal biomass fuel on x energy efficiency in paddy drying

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	498.33	1	498.33	4.44	0.08	5.99
Within Groups	673.01	6	112.17			
Total	1171.35	7				

The ANOVA results for the effect of fuel type (rice husk and charcoal) on energy efficiency (Table 4) indicate that the difference between fuel types is not statistically significant at a P-value = 0.08, which is greater than the commonly used significance level of 0.05. However, it is evident from Fig. 5 that charcoal achieved higher energy efficiency than rice husk across all adsorbent types. Based on Fig. 5, it is evident that the drying process conducted using charcoal as fuel achieved higher energy efficiency than when rice husk was used. This difference in energy efficiency can be attributed to the calorific value of the two fuels. The average calorific value of rice husk is 2,790 calories per gram, which is significantly lower—about half—compared to that of charcoal [24]. This lower calorific value means that rice husk provides less energy per unit mass, leading to less efficient combustion and energy transfer during the drying process [25]. As a result, drying with rice husk requires more fuel to achieve the same amount of moisture removal as charcoal, which has a higher energy output per gram. Therefore, the choice of fuel significantly impacts the energy efficiency of the drying process, with charcoal proving to be the more efficient option due to its higher calorific value.

3.3. Economic analysis of biomass-powered fixed bed dryer with air dehumidification

The cost production of paddy drying with and without air dehumidification was comparable (Table 5). The production cost per kilogram of product for the drying process without adsorbent was \$0.34, while it increased slightly to \$0.38 when using synthetic zeolite. The marginal increase in cost is attributed to the additional expenses associated with synthetic zeolite and its regeneration process. Despite the higher cost, the dehumidification process using synthetic zeolite showed significantly improved financial performance, highlighting its efficiency and profitability.

The business analysis for drying with air dehumidification demonstrated stronger financial performance compared to drying without dehumidification. The Net Present Value (NPV) of the project using synthetic zeolite was \$8,219, significantly higher than \$5,034 achieved without adsorbents, highlighting its substantial profitability potential over the project's lifespan while accounting for the time value of money. Additionally, the Benefit-Cost Ratio (B/C ratio) for the drying process with synthetic zeolite was 1.31, indicating a return of \$1.31 for every dollar invested. This is slightly higher than the 1.27 ratio observed without adsorbents, emphasizing that dehumidification enhances the cost-benefit balance. Furthermore, the Internal Rate of Return (IRR) for drying with synthetic zeolite was reached within 2.04 years, demonstrating a faster return on investment compared to 2.38 years without adsorbents. These results underscore the financial viability and efficiency of incorporating air dehumidification in the drying process.

Table 5. Economic parameters of Biomass-Powered Fixed Bed Dryer

Parameter	Biomass-Powered Fixed Bed Dryer (Charcoal)	
	Without adsorbent	Synthetic zeolite
Cost production (per kg of product)	0.34	0.38
Net Present Value (NPV)	5,034	8,219
Benefit Cost Ratio (B/C ratio)	1.27	1.31
Internal Rate of Return (IRR)	2.38	2.04

To further validate the economic feasibility, a sensitivity analysis was conducted to evaluate the impact of fluctuations in key cost factors, including fuel prices, labor costs, and synthetic zeolite regeneration expenses. The analysis revealed that variations in fuel prices had the most significant effect on overall production costs, underscoring the importance of selecting cost-effective and high-calorific value fuels, such as charcoal, to optimize financial performance. Changes in synthetic zeolite regeneration costs had a moderate impact, highlighting the need for efficient and low-cost regeneration techniques to further improve economic viability. Meanwhile, fluctuations in labor costs had the least influence, reflecting the relatively small contribution of labor expenses to the total operational costs. These findings emphasize the importance of managing critical cost drivers to enhance the overall feasibility of the drying system.

3.4. Enhanced performance in biomass-powered fixed bed dryers with air dehumidification compared to another paddy dryers

A biomass-powered fixed bed dryer, equipped with synthetic zeolite as the air dehumidifier, achieves remarkable effective moisture diffusivity (2.24×10^{-8} m^2/s) and energy efficiency, reaching up to 68%. This effective moisture diffusivity was higher than paddy drying using oven dryer [28] and infrared dryer [29]. While, the efficiency is significantly higher compared to paddy dryer without dehumidification. For instance, paddy dryer without dehumidification often exhibit energy efficiencies below 40% primarily due to their reliance on less advanced dehumidification methods and energy sources [7,8].

The integration of synthetic zeolite in the biomass-powered dryer enhances moisture removal and heat transfer, leading to reduced energy consumption and improved overall performance. This comparison underscores the advanced technological benefits of utilizing synthetic zeolite for enhanced energy efficiency in drying processes, highlighting its potential to revolutionize drying operations in the food industry. In summary, biomass-powered fixed bed dryers with air dehumidification produced paddy with lower moisture content, achieved high energy efficiency, and demonstrated favorable financial outcomes.

4. Conclusion

The biomass-powered fixed bed dryer with air dehumidification demonstrates significant improvements in paddy drying, leveraging synthetic zeolite as an adsorbent to enhance moisture diffusivity (2.24×10^{-8} m^2/s) and energy efficiency (up to 68%), thanks to its superior moisture adsorption properties. Biomass fuel choice is critical, with charcoal providing higher energy efficiency than rice husk due to its greater calorific value. Financial analysis supports the technology's economic viability, with an NPV of $8,219, a B/C ratio of 1.31, and a payback period of 2.04 years, though operational and maintenance costs—such as fuel, labor, and adsorbent regeneration—pose challenges. To maximize scalability and sustainability, future efforts should focus on reducing costs, exploring more affordable adsorbent regeneration methods, and maintaining efficiency at higher capacities, ensuring the technology meets rice processing industry needs while supporting sustainable agriculture.

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