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Review

Local Microorganism-Based Biomass Biodrying in Biopellet Production: Integration of Microbiology, Process Engineering, and Fuel Quality Aspects

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ABSTRACT. Lignocellulosic biomass derived from organic waste has significant potential as a renewable energy source; however, its high moisture content remains a major constraint in its conversion into solid fuel. Biodrying is a biological drying method that utilizes microbial aerobic oxidation reactions to generate heat (bioheat), thereby accelerating moisture evaporation without substantial external energy input. This review article evaluates the integration of microbiological mechanisms and process engineering within the Technology for Waste Processing at Source (TWPS) system using Local Microorganisms (LMO). Based on a systematic synthesis of the literature, biodrying has been shown to reduce moisture content to below 20% (as low as 5% when specific LMO inoculants are applied) while increasing the calorific value to approximately 3,500 kcal/kg, meeting the requirements of SNI 8966:2021. The key findings indicate that carbohydrate degradation is the primary contributor to bioheat generation, whereas the use of LMOs derived from locally available waste materials offers greater economic efficiency compared with commercial inoculants. These transformations strengthen the valorization of tropical biomass and support the implementation of a sustainable circular economy framework.

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INTRODUCTION

The increasing need for fossil fuels, driven by population growth and industrialization, has caused a global energy crisis. In addition to limited reserves, the use of fossil fuels also has significant environmental impacts, especially through greenhouse gas (GHG) emissions and air pollution. The burning of fossil fuels releases GHG, especially Carbon Dioxide (CO_2), Methane (CH_4), and Nitrogen Oxide (N_2O). Increasing awareness of these environmental impacts is driving the search for more sustainable alternative energy sources. One promising solution is the use of biomass waste as solid biofuel, which not only has the potential to replace fossil fuels partially but also reduces the volume of organic waste that pollutes the environment and lowers greenhouse gas emissions. Organic waste that is allowed to decompose anaerobically produces methane gas that has about 25 times greater warming potential than carbon dioxide (Calvin *et al.*, 2023). Therefore, treating biomass waste to produce alternative fuels can provide dual benefits: waste reduction and climate change mitigation.

Indonesia, as an agrarian country and tropical archipelago, has a huge biomass potential, especially from the agriculture, plantation, and forestry sectors. Unfortunately, most of this biomass is still considered waste and has not been utilized optimally. Indonesia has the potential to produce 146.7 million tons of biomass per year, equivalent to around 470 GJ/year. Biomass utilization in 2023 has reached 0.6 million tons, still below the target of 2.2 million tons (Abdullah *et al.*, 2025). This condition indicates a gap between the potential of biomass resources and their implementation as an alternative energy source.

The use of biomass waste as solid fuel derived from agricultural waste, municipal waste, and pests such as areca nut bark, leaves and twigs, rice straw, bagasse, and water hyacinth has many advantages. The advantages of using biomass waste include reducing solid waste, reducing dependence on fossil fuels, reducing greenhouse gas emissions and air pollution, providing added value to society, and supporting a circular economy and sustainable waste management. However, technical challenges such as high water content and low calorific values are obstacles to large-scale implementation. Therefore, this study aims to examine the potential of biomass waste as a solid fuel, evaluate its thermal characteristics, and develop efficient and environmentally friendly treatment methods. One of the waste-processing methods is Waste Management Technology at the Source (TWPS), which was popularized by the start-up company Comestoarra Bentarra Noesantarra (comestoarra.com). This method utilizes organic and biomass waste to produce biofuel in the form of biomass pellets that can be used as an alternative to coal. The processes in the TWPS method are chopping, the use of bioactivators in biodrying, and compaction with pelletization (Brunner *et al.*, 2021). Bioactivators are solutions containing various microorganisms that can accelerate the decomposition of organic matter and improve the quality of the final product.

Several studies have developed bioactivators, such as EM4, also known as AR124 (Brunner *et al.*, 2021). Bioactivators can be replaced with local microorganisms (LMO). LMO is obtained through the fermentation of natural materials, such as fruits, vegetables, animals, or organic waste rich in decomposers, and its development potential is enormous, tailored to Indonesia's local characteristics.

Research by Dewilda *et al.* (2023) shows that the use of LMO has the potential to enhance the effectiveness of biodrying organic waste, especially twigs and leaves, within the framework of TWPS. The study highlights the use of LMO derived from bagasse and cob fish waste as an alternative bioactivator that accelerates the biological drying process while improving the quality of the final product, biomass pellets. Compared with commercial bioactivators, LMO shows competitive performance in reducing moisture content to below 20% and producing pellets with quality parameters that meet the SNI 8966:2021 standards. The quality of the pellets produced is indicated by low moisture content (7.67 – 11.33%), an adequate calorific value (±3,512 kcal/kg), and a fixed carbon content that supports solid-fuel characteristics. In addition, the presence of dominant microorganisms such as *Candida sp.* and *Bacillus sp.* accelerates the decomposition of organic matter during biodrying. These findings indicate that the use of local resources as bioactivators not only improves process efficiency but also increases the added value of biomass waste in the context of the circular economy and renewable energy.

The study by Dewilda *et al.* (2025) advances the development of TWPS by using water hyacinth (*Eichhornia crassipes*) as a raw material for biomass pellets, with the addition of rice husks. Conceptually, water hyacinth has a high cellulose content (±60%), making it a potential source of renewable energy, but its calorific value is

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relatively low (around 3,300 kcal/kg). Therefore, combining it with higher-energy biomass, such as rice husks (±4,177 kcal/kg), is a strategy to improve fuel quality. The results showed that increasing the proportion of rice husks significantly improved pellet quality, with a 1:3 ratio yielding a calorific value of up to ±16.92 MJ/kg (≈4,041 kcal/kg), an increase of about 31.5% compared to pellets without additives. These findings confirm that optimizing the composition of raw materials is important for improving the energy performance of TWPS-based biodrying products.

Previous studies have also shown that the use of bioactivators, including local microorganisms (LMO), is able to accelerate the reduction of moisture content to below 20%, increase process stability, and produce biomass pellets that meet the SNI 8966:2021 quality standards (Dewilda *et al.*, 2025). However, existing TWPS studies still predominantly focus on the physicochemical characteristics and quality of the final product, while microbiological aspects—especially the dynamics of microorganism communities during the biodrying phase—have not been explored in depth. Globally, biodrying has been applied to various types of organic waste such as sludge, kitchen waste, biogas residues, and lignocellulose biomass with a focus on aeration optimization, *bulking agent use*, microbial inoculation, as well as improving the quality of the final product (Wu *et al.*, 2018; Xu *et al.*, 2022; Yang *et al.*, 2024). However, most of the research was conducted on centralized systems that required active aeration or additional energy, thereby incurring relatively high operational and waste transportation costs. This approach differs from the TWPS concept, which relies on passive aeration via hollow-reactor design (e.g., air-slit bamboo), thereby making it more energy-efficient and suitable for treatment at the source.

The research gap and the novelty of research on biodrying so far tend to focus on the physicochemical evaluation of the final product in energy-intensive centralized processing systems. There is a gap in the literature on mapping the synergy between microbial molecular activity and decentralized process design. The novelty of this article lies in a comprehensive synthesis that integrates the dynamics of the metabolic pathways of microorganism communities with decentralized-scale process engineering (TWPS) using LMO. This article fills this gap by examining how local waste-based adaptive bioactivators can modulate biochemical transformations to produce high-quality solid fuels.

Although various review articles have discussed biodrying from the perspective of process optimization and moisture reduction, studies that integrate microbiological mechanisms, lignocellulose transformation, and their impact on biopellet energy quality remain limited. In addition, the use of LMO in biodrying systems within TWPS has not been discussed comprehensively. Therefore, this article offers a new perspective on the synthesis of relationships among microorganism communities, bioheat formation, biomass chemical transformation, and the improvement of biopellet energy quality in tropical biomass. This approach is expected to broaden understanding of biodrying not only as a drying process but also as a biomass valorization strategy to support the circular economy and the sustainable energy transition. The main objective of this review is to formulate an efficient, adaptive, and sustainable biodrying model by synthesizing biochemical data with the latest operational parameters to support local resource-based energy independence.

This literature review was prepared using a systematic literature review approach. The search was conducted in reputable databases, including Scopus, ScienceDirect, and Google Scholar, with a publication period of 2016 – 2025. Parameter Synthesis: The keywords used in the search were biodrying, bioheat, biomass, biopellets, lignocellulose, and calorific value. The selection criteria for the selected articles included a biodrying pilot study, the use of local bioactivators, microbiological metabolic pathway analysis, and the standardization of solid fuel quality (SNI 8966:2021). A total of 50 relevant articles were synthesized to evaluate the relationship between operational parameters and the quality of biopellet products.

The data extracted from each article included the characteristics of biomass raw materials (moisture content, lignocellulose composition, particle size), biodrying parameters (temperature, aeration, retention time, and drying efficiency indicators), microbiological aspects (type and dominance of microorganism communities), as well as energy quality parameters such as calorific value, ash content, fixed carbon, and volatile substances. The data were then compared and interpreted to explain the relationships among microorganism activity, biomass transformation, water content reduction, and improvements in biopellet energy quality. These data are expected to provide a more comprehensive understanding of the interaction between microbiology and process engineering in supporting the development of efficient, adaptive, and sustainable biodrying technologies. The synthesis of biomass biodrying research and the role of microorganisms in biopellet quality is presented in Table 1. The main synthesis: microorganisms accelerate the formation of bioheat; aeration and porosity determine efficiency; lignocellulose

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transformation increases the calorific value; LMO integration has the potential to be a low-cost approach to biopellet production.

Table 1. Synthesis of biomass biodrying research and the role of microorganisms on biopellet quality.

Types of Biomass	Biodrying Approach	Factors Studied	Key Results	Implications for Biopellets	References
Mixed organic waste	Biodrying aerobic	Reactor matrix height	Higher reactor improves heat retention and drying efficiency	Decreased moisture content and increased energy density	(Tom *et al*., 2016)
Sewage sludge	Biodrying + bulking agent	Aeration and porosity	Bulking agent improves airflow and evaporation	The product is more stable and easy to compact	(Liu *et al*., 2018a)
Brewery residue	Energy biodrying	Types of bulking agents	The composition of microbes affects the drying performance	Fixed carbon increase	(Wolny-Koładka *et al*., 2021)
Kitchen waste	Metagenomic analysis	Microbial enzyme activity	Cellulase and amylase correlate with bioheat	Improving the quality of biomass energy	(Cai *et al*., 2022)
Kitchen waste	Biodrying Biological	Bioheat production	Degradation of carbohydrates as the main source of heat	Moisture decreases and HHV increases	(Xin *et al*., 2022)
Biogas residue	Inoculation of thermophilic bacteria	Microbial communities	Final moisture content reaches about 9 – 10%	Products are more suitable as fuel	(Xu *et al*., 2022)
Sewage sludge	Back-mixing biodrying	Re-inoculation	Accelerating the thermophilic phase	Reduced processing time	(Yu *et al*., 2023)
Leaves and twigs	LMO + TOSS	Local bioactivators	Moisture <20% faster to achieve	Biopellets meet quality standards	(Dewilda *et al*., 2023)
Leaf-twig biomass	LMO snail mas–pineapple peel	Local microbial activity	Volume reduction and increased moisture content	Increased calorific value	(Goembira *et al*., 2024)
Sewage sludge	Biodrying + biochar + $MgCl_2$	C–N emissions and transformations	GHG emissions are reduced, and efficiency is increased	More environmentally friendly products	(Zhang *et al*., 2024)

BIODRYING

Biodrying is a biological drying process that utilizes the biological heat (bioheat) generated by aerobic microorganisms as they degrade organic matter, thereby reducing the material's moisture through evaporation, with or without additional external energy. The principle is similar to the composting process, but it is controlled to more strongly emphasize the drying phase (evaporation) and the formation of low-moisture products suitable for solid fuels or pellet feedstocks (Xin *et al*., 2022). Conceptually, biodrying is a process of mass exchange (water evaporation) that is "driven" by biologically released energy. A simple calculation compares the available bioheat (energy released by organic degradation) with the evaporation energy, indicating that, under a wide range of conditions, the internal bioheat is sufficient to support drying without external heat input. Efficiency is highly dependent on heat loss to the environment, airflow (convection), and stack structure (Xin *et al*., 2022).

Phases of the Biodrying Process

In general, biodrying goes through three phases that can be identified thermally and microbiologically (Xin *et al*., 2022). The transition between these phases is influenced by the availability of substrates, stack structure (porosity), and oxygen supply (aeration).

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Mesophilic Phase

In this phase, temperature increases due to environmental conditions and the activity of mesophilic microbes. In this phase, there is also a degradation of biodegradable materials (e.g., simple sugars and some proteins), and it is characterized by relatively low water evaporation.

Thermophilic Phase

In this phase, the temperature reaches 45 – 50 °C, during which thermophilic microorganisms become dominant. In this phase, bioheat production is very strong, so the rate of water evaporation increases dramatically. Pilot studies show that carbohydrates (amylum/cellulose) contribute significantly to the bioheat source during the thermophilic phase.

Cooling and Stabilization Phases

In this phase, the easily decomposed material thins out and the temperature drops. The degradation process slows down, and the product reaches a higher level of maturity/stability.

Mechanism of Bioheat Formation and the Role of Biochemical Components

The microbiological-energy relationship model refers to the biological-energy relationship model (Figure 1). This mechanism is initiated by microbial communities (bacteria, fungi, and actinomycetes) that secrete extracellular hydrolytic enzymes such as amylase, cellulase, protease, and ligninase. This enzymatic activity accelerates the degradation of organic matter (carbohydrates, proteins, lipids, and lignin). The main metabolic pathway in bioheat production is the oxidation of carbohydrates (amylum and cellulose) via glycolysis and the citric acid (TCA) cycle, which releases energy more rapidly than the degradation of complex lignin. Biochemically, this process leads to changes in the structure of lignocellulose through cellulose depolymerization and lignin modification. This chemical transformation is crucial: the decrease in the fractions of hemicellulose and volatile matter was followed by an increase in the fraction of fixed carbon, which directly contributed to the increase in the Higher Heating Value (HHV) of biopellet products (Velis *et al.*, 2009; Wu *et al.*, 2018; Xu *et al.*, 2022; Dewilda *et al.*, 2023; The *et al.*, 2024).

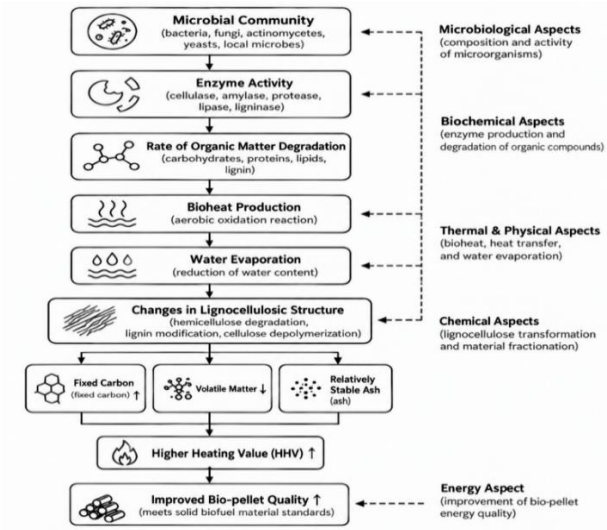


Figure 1. The relationship between microbiological-chemical transformation and energy quality in the biomass biodrying process.

Bioheat arises from aerobic metabolic reactions (oxidation of organic compounds) that release energy. Carbohydrates, especially amylum and the degradable part of cellulose, often account for the largest portion of the degraded mass in the biodrying of kitchen waste and also make a major contribution to bioheat. Carbohydrates can account for the majority of the total bioheat in biodrying kitchen waste (Xin *et al*., 2022).

Lipids and proteins degrade faster in the early stages of heating, but their relative energy contribution to total bioheat is usually smaller than that of carbohydrates in several pilot studies (Cai *et al*., 2022). The biodrying process is carried out using bulking agents such as sawdust and rice husks to improve aeration and accelerate moisture reduction. The biodrying reactor is operated aerobically for 10 – 20 days, with daily monitoring of

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temperature, humidity, and sample weight. The main parameters analyzed include moisture content, calorific value, carbon and nitrogen content, and C/N ratio.

During the biodrying process, the temperature can increase to 60 – 70 °C due to the intensive activity of thermophilic microorganisms in the initial phase, followed by a decrease in moisture content from more than 60% to about 20 – 30%. The calorific value of the material increases to 3,000 – 4,500 kcal/kg, meeting the criteria for alternative solid fuels (SRF). The addition of bulking agents has been shown to speed up drying, improve air circulation, and reduce odor emissions during biodrying. In addition, the final C/N ratio indicates a good level of stability of the material for utilization as a solid fuel. The activity of hydrolytic enzymes (amylase, cellulase, lipase, protease) is directly correlated with the rate of degradation and heat production; metagenomic analysis and enzyme activity have been used to attribute microbial community function to the energetic output of biodrying (Cai *et al*., 2022).

The microbial communities in biodrying are dynamic. Early mesophilic communities (a variety of bacteria and fungi) are replaced by thermophilic communities as temperatures rise. Genera that are often reported to be involved include *Bacillus*, *Ureibacillus*, *Aeribacillus*, and the Actinobacteria group. In addition, Proteobacteria and some fungi play roles in the early or late stages of humic formation. Inoculation of thermophilic microbes or thermophilic bacterial agents (TBA/MA) can accelerate the initiation of the thermophilic phase and increase the rate of moisture reduction (Cai *et al.*, 2022).

Microbiological Mechanisms, Metabolic Pathways, and Molecular Approaches to Biodrying

The effectiveness of biodrying is influenced by the activities of the microorganism community that utilizes organic compounds as a source of energy through aerobic metabolism. During the process, biomass transformation generally begins with the hydrolysis stage, in which complex polymers such as cellulose, hemicellulose, and some lignin fractions are broken down into simpler molecules by extracellular enzymes. The enzymes involved include cellulase, hemicellulase, amylase, protease, and ligninase, produced by bacteria and fungi. The products of hydrolysis then enter the oxidative metabolic pathway via glycolysis and the citric acid cycle (TCA cycle), which produce ATP, carbon dioxide, water, and biological heat (bioheat). The heat generated during aerobic respiration is the main driver of water evaporation in biodrying and contributes to the decrease in biomass water content.

Several studies have shown that the degradation of carbohydrate fractions makes the greatest contribution to bioheat generation, whereas lignin degradation occurs more slowly due to its complex aromatic structure. These dynamics lead to changes in lignocellulose composition that increase the fixed carbon fraction and the calorific value of biopellets. In recent years, molecular approaches have begun to be used to understand the mechanism of biodrying better. Techniques such as 16S rRNA gene analysis, ITS sequencing for fungi, metagenomics, and microbial function analysis allow the identification of changes in community structure and metabolic potential during the process. These approaches help to explain the relationship between microorganism activity, biomass chemical transformation, and biodrying performance more comprehensively. However, the application of molecular approaches to biodrying systems based on waste management technology at source (TWPS) and the use of local microorganisms (LMO) remain relatively limited, presenting opportunities for future research and development.

Operational Parameters That Affect Operating Performance

Aeration (Airflow Rate)

Provides oxygen for microbial respiration and transports water vapor; over-aeration can cool the stack (reducing thermophilic degradation efficiency), while under-aeration can lead to anaerobic conditions and odors. Aeration optimization is important to maintain a balance between heat production and steam transport (Cai *et al.*, 2022). Proper regulation of aeration patterns can improve drying process performance and microbiological stability (Wu *et al.*, 2018).

Depth/Height of Pile and Porosity

The depth/height of the pile affects the air distribution and temperature gradient. A higher pile allows for heat accumulation and drying efficiency. The results show that increasing the reactor height can improve drying efficiency, as evidenced by reduced weight and higher waste moisture content in the higher reactors (Tom *et al.*, 2016).

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C/N Ratio

The C/N ratio affects the biodrying process of lignocellulosic biomass, consisting of wood dust and biogas residues, for conversion into organic fertilizer. By setting the C/N ratio to 20, 30, and 40, this study evaluated the effects of these ratios on drying time, compost quality, and microbial community diversity during biodrying. The results showed that a C/N ratio of 20 was most effective at accelerating moisture-content reduction, increasing humate content, and increasing microbial diversity, especially bacteria in the phylum Firmicutes. In addition, this process can produce a mature biofertilizer within 8 days, meeting good quality indicators. This study provides insight into the molecular and microbiological mechanisms underlying biodrying and offers guidance to optimize the lignocellulosic waste treatment process efficiently and in an environmentally friendly manner.The composition of the substrate and the C/N ratio affect the availability of energy to microbes and the formation of the final humic; a very low or very high C/N ratio interferes with microbial performance (Xu *et al*., 2023).

Bulking Agent

The addition of lignocellulosic bulking agents derived from either wood residues or agricultural waste is crucial for optimizing the biodrying of high-moisture organic waste (Liu *et al*., 2018b; Zhao *et al*., 2011). Physically, these agents increase the Free Air Space (FAS) and porosity, prevent substrate compaction, and ensure uniform airflow distribution within the reactor (Velis *et al*., 2009; Wolny-Koładka *et al*., 2021). Beyond supporting the physical structure, the degradation of volatile solids from these bulking agents accounts for 82 – 86% of the total biological heat (bioheat) generated within the system (Liu *et al*., 2018c; Zhao *et al*., 2011). Optimal aeration promotes the proliferation of thermophilic bacteria (such as those from the phyla Firmicutes, Actinobacteria, and Proteobacteria) and stimulates the activity of hydrolase enzymes (Liu *et al*., 2018c; Yang *et al*., 2024). This synergy between bioheat release and microbial metabolism accelerates water evaporation, enhances humus stability, and increases the Lower Heating Value (LHV) of the final Refuse-Derived Fuel (RDF) product (Ma *et al*., 2020; Yuan *et al*., 2019).

Microorganisms in the Biodrying Process

Microorganisms play a central role in the biodrying process, as their metabolic activity generates biological heat (bioheat) that evaporates moisture from the material. In aerobic processes, microorganisms decompose easily degradable organic matter (carbohydrates, proteins, lipids) into CO_2, H_2O, and heat (Xin *et al.*, 2022). This activity raises the pile's internal temperature to the thermophilic phase (>45 °C), thereby enabling rapid evaporation and stabilization of the material (Cai *et al.*, 2022).

In Indonesia, this concept is applied by using LMO as bioactivators. LMO is derived from natural materials from fruit waste and from animal waste. The use of LMO has been shown to accelerate drying and increase the calorific value of biopellets produced by biodrying. Research by Goembira *et al.* (2024) examined the use of LMO derived from golden snails and pineapple peels, as well as rice washing water, as alternative bioactivators in the biodrying of leaf and twig waste using TWPS method. This study compares the performance of LMO with that of the commercial bioactivator AR124, which Comestoarra has used in the biodrying process to produce Refuse-Derived Fuel (RDF). Research shows that both bioactivators can accelerate the biodrying process, as evidenced by a decrease in moisture content from 21% to 13 – 14% on day 5, compared with 15.3% without bioactivators. The biodrying process also indicates stability at neutral pH (6 – 7) and mesophilic temperature (30 – 34 °C), indicating optimal microbial activity. The variation in the use of MOL provides the highest reduction in waste volume (3.2 cm), followed by AR124 (2.8 cm), indicating the influence of microbial populations on the effectiveness of decomposition. Microbiological identification shows that AR124 contains Bacillus sp., while MOL contains *Candida sp.,* both of which contribute to accelerating organic decomposition and heat production. In terms of pellet quality, both bioactivators meet SNI 8966:2021, with moisture content, volatile matter, ash, fixed carbon, and heat-equivalent parameters that are close to the RDF standards for classes 1 – 2. Biopellets with AR124 show the highest calorific value (3,523 kcal/kg), while LMO produces the lowest moisture content (5%). Economic analysis shows that MOL production is much cheaper than AR124 because it uses local waste (pineapple peels, golden snails, and rice-washing water) and generates no additional waste. Overall, the study concludes that MOL made from golden snails–pineapple peels has the potential to be a cheap, effective, and environmentally friendly bioactivator alternative in biodrying of leaf and twig waste based on TWPS.

Research conducted by Dewilda *et al.* (2023) evaluated the use of LMO derived from bagasse and tuna fish waste as bioactivators in the biodrying process of leaf and twig waste using the Waste Management Technology at Source (TWPS) approach. This study compared the performance of LMO with the commercial bioactivator AR124 and a control without the activator to assess the effect on the acceleration of biodrying and the quality of the biomass pellets produced. The study showed that the addition of LMO and AR124 accelerated the reduction of the material's moisture content to below 20% on day 2, faster than the control, which required up to 4 days. The

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microbial activity of LMO and AR124 contributes to increased initial decomposition, as indicated by a shift from acidic to neutral pH, and to temperature stability within the mesophilic range (27 – 30 °C). The control variation failed to achieve optimal conditions due to the limitations of natural microorganisms in breaking down organic matter. In terms of pellet quality, all variations met the SNI 8966:2021 quality standard, with moisture content parameters of 7.67 – 11.33%, volatile matter 65 – 69.33%, ash 13 – 13.67%, and fixed carbon 5.67 – 14%. The LMO variation produced the lowest moisture and ash contents, while AR124 produced the highest calorific value, reaching 3521.17 kcal/kg, close to the quality of SNI class 2 pellets. Both bioactivators outperformed the controls, which had lower moisture content and heat values due to a less efficient biodrying process. This study confirms that local waste-based LMO has potential as a low-cost, readily available, and effective bioactivator to improve biodrying efficiency in the TWPS system. The identification of microorganisms indicates the presence of *Candida sp.* and *Bacillus sp*., which are known to play active roles in organic decomposition and in local temperature increases during the aeration process. These findings are reinforced by comparisons with previous studies that report similar ranges of pellet parameters, thereby supporting the consistency and replicability of the biodrying process for producing biopellets from high-water biomass.

Microbial Community Succession

The biodrying process consists of three phases of microbial activity: mesophilic, thermophilic, and cooling. In the initial phase, mesophilic communities such as *Pseudomonas* and *Bacillus subtilis* dominate the degradation of volatile materials (saccharides and amino acids). The next thermophilic phase is dominated by thermophilic bacteria such as *Ureibacillus*, *Geobacillus*, and *Thermus*, which produce significant heat (Xu *et al.*, 2022; Yu *et al.*, 2023). The main role of microorganisms in biodrying is related to the production of hydrolytic enzymes (amylase, cellulase, lipase, and protease). These enzymes break down complex macromolecules into simple compounds that are easier to oxidize (Cai *et al.*, 2022). The oxidation process generates internal heat that triggers water evaporation (Xin *et al.*, 2022). Molecularly, the thermophilic microbial community produces bioheat through the degradation of carbohydrates (lignocellulose, starch, and hemicellulose), which are the dominant energy sources (Xin *et al.*, 2022).

Several approaches to speed up biodrying involve thermophilic microbial inoculation or *back-mixing* of mature materials. Back-mixing inoculation accelerates the rise in temperature and shortens the drying time (Yu *et al.*, 2023). The performance of microbes is strongly influenced by aeration, initial humidity, C/N ratio, and type of bulking agent. Optimal aeration ensures the availability of oxygen and the transport of water vapor. The research by Zhang *et al.* (2024) and Liu *et al.* (2018c) shows that over-aeration can lower the temperature of the pile due to cooling, while too low aeration leads to anaerobic conditions. The microbial community determines the calorific value and stability of the biodrying product. According to Wolny-Koładka *et al.* (2021), the organic degradation conducted by microbes leads to an increase in the relative carbon fraction in dry residues, which increases the calorific value of solid fuels. To provide a more comprehensive picture of the effect of biodrying on solid fuel quality, several research findings were compared using biopellet quality parameters. The selected parameters included moisture content, fixed carbon, volatile matter, ash content, calorific value, and conformity with quality standards. This comparison was used to identify patterns of change in biomass energy characteristics due to the biodrying process and to evaluate the effectiveness of various bioactivation approaches and process configurations. LMO is a bioactivator produced through the fermentation of local waste (banana hump, pineapple peel, or golden snail). The key microorganisms identified in effective LMO are *Candida sp.* and *Bacillus sp.* The advantage of LMO lies in its ability to adapt to heterogeneous substrates and produce enzymes that accelerate early decomposition. A comparison of the performance of the bioactivator AR124 and LMO is shown in Table 2. The data synthesis shows that LMO is not only technically competitive, capable of achieving a moisture content of up to 5%, lower than AR124, but also economically superior to a decentralized TWPS system.

Table 2. Comparison of the performance of commercial bioactivators vs LMO.

Parameters	AR124 (Commercial)	LMO (Local - Snail/Pineapple)
Main Microbial Content	*Bacillus sp.*	*Candida sp.* and *Bacillus sp.*
Efficiency of Reducing Moisture Content	13 – 14% (day 5)	**5 – 11%** (day 5)
Pellet Heat Value	±3,523 kcal/kg	±3,512 kcal/kg
Production Costs	Height (Manufacturer)	**Very Low** (Waste)

Source: compiled from a synthesis of research results and does not represent an experimental comparison.

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OPERATIONAL FACTORS THAT AFFECT THE EFFICIENCY OF THE BIODRYING PROCESS

The efficiency of the biodrying process is determined not only by the activity of microorganisms but also by operational factors that influence the interactions among biology, thermodynamics, and system engineering. Parameters such as aeration, temperature, initial humidity, C/N ratio, type of bulking agent, particle size, and reactor design will determine the extent to which the biological heat (bioheat) generated by microorganisms can be utilized to lower the moisture content of the material (Tom *et al.*, 2016; Xin *et al.*, 2022). In general, biodrying efficiency is measured through two main indicators: (1) the rate of reduction in moisture content and (2) the increase in the calorific value of the material after the process. Optimal adjustment of operational conditions can accelerate evaporation, maintain stable aerobic conditions, and reduce convective heat loss (Table 3).

Table 3. Optimum parameters affecting biodrying based on various studies.

Parameters	Optimum Range	Effects on Biodrying	References
Initial moisture content	50 – 70%	Determining microbial activity, bioheat formation, and evaporation	(Velis *et al.*, 2009; Wu *et al.*, 2018)
C/N Ratio	20 – 35	Controls the growth of microorganisms and the rate of biodegradation	(Tom *et al.*, 2016; Xu *et al.*, 2022)
Temperature	45 – 65 °C	Increases biological activity and evaporation rate	(Velis *et al.*, 2009; Yang *et al.*, 2024)
Aeration	Stable aerobic condition	Maintain oxygen supply and water vapor release	(Adani, 2002; Wu *et al.*, 2018)
Particle size	10 – 50 mm	Optimizes heat and mass transfer	(Tom *et al.*, 2016)
Porosity	Medium–high	Improves air distribution and maintains aerobic conditions	(Velis *et al.*, 2009; Yang *et al.*, 2024)
Bulking agent	Adapted to biomass character	Maintains structure and improves aeration	(Colomer-Mendoza *et al.*, 2012; Xu *et al.*, 2022)
Biodrying time	7 – 21 days	Determining the final moisture content and stability of the product	(Wu *et al.*, 2018)
Microorganisms	Aerobic / MOL consortium	Accelerates biodegradation and bioheat formation	(Brunner *et al.*, 2021; Dewilda *et al.*, 2023)

Influence of Aeration and Oxygenation

Aeration is the most critical parameter in biodrying. Airflow is dual, i.e., it provides oxygen for microbial respiration and transports moisture from the material. Unbalanced aeration leads to process inefficiencies: low aeration triggers anaerobic conditions that produce odors and methane, while high aeration lowers the pile temperature through evaporative cooling (Liu *et al.*, 2018c; Zhang *et al.*, 2024). Liu *et al.* (2018) reported that increasing aeration from 0.15 to 0.30 m^3/kg of dry matter increased the drying rate by 40%, but a rate of 0.45 m^3/kg actually lowered the peak temperature by 10 °C. A similar study by Zhang *et al.* (2024) found that the optimal aeration rate maintained the thermophilic phase for the first 4 – 6 days, thereby increasing water evaporation efficiency by up to 75%.

Carbon to Nitrogen Ratio (C/N)

The carbon-to-nitrogen (C/N) ratio affects the availability of nutrients for microorganisms. A ratio too low (<15) leads to excess nitrogen and ammonia formation, while a ratio too high (>40) limits enzymatic activity due to nitrogen deficiency (Liu *et al.*, 2018c). In the biodrying process, the ideal C/N ratio ranges from 20 – 30 to maintain a balance between microbial growth rate and substrate degradation (Yu *et al.*, 2023). Regulating the initial C/N ratio to 20:1 accelerates the decomposition of organic matter, extends the thermophilic phase, and promotes moisture reduction to below 30% within 8 days while enhancing humification and microbial diversity." (Xu *et al.*, 2023; Kristanto and Hanany, 2017). In addition to the C/N ratio, the composition of raw materials also has an effect. Wastes with high carbohydrate content (such as vegetable and fruit residues) tend to produce *higher bioheat* than fatty or protein waste (Xin *et al.*, 2022).

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Initial Moisture and Particle Size

Initial humidity affects microbial activity and oxygen diffusion. The optimal initial humidity range is 55 – 65% (Tom *et al.*, 2016). When the initial humidity is too high (>70%), the pore space is reduced, and oxygen diffusion is inhibited; conversely, low humidity (<45%) leads to microbial dormancy (Cai *et al.*, 2022).

Effects of *Bulking Agent* and Porosity

Bulking agents function to maintain porosity, absorb moisture, and provide structure for air circulation. Common materials used include wood powder, rice husks, straw, and sawdust. Research by Xin *et al.* (2022) shows that adding a 20 – 30% wood bulking agent can improve evaporation rates without reducing biological activity. On the other hand, it was found that the type of bulking agent determines the composition of the dominant microbes: wood increases the dominance of *Bacillus thermophilus*, while straw favors *Actinobacteria* more (Wolny-Koładka *et al.*, 2021).

Temperature and Thermal Dynamics

The acquisition and maintenance of thermophilic temperatures (≥45 – 50 °C) indicate biodrying success; peak temperatures are reached when microbial bioheat production exceeds convective heat loss and radiation. Inoculation or modification of substrates that increase the degradation rate can accelerate the attainment of peak temperatures and extend the thermophilic phase, thereby aiding pathogen inactivation and improving product stability. Temperature is the result of the synergy between microbial activity and convective heat loss. A peak temperature of 50 – 60 °C indicates an active thermophilic phase (Tom *et al.*, 2016). Microbial inoculation accelerates the achievement of peak temperatures and maintains thermophilic conditions for longer (Yu *et al.*, 2023). However, the pile's design (height, width) and environmental conditions also determine heat loss, so it should be combined with aeration and insulation controls when necessary.

The Influence of Additives and Technology Integration

Several recent studies have explored the use of additives to improve biodrying efficiency. The combination of *biochar* and $MgCl_2$ increases maximum temperature, prolongs the thermophilic phase, and lowers greenhouse gas emissions (CO_2 and N_2O) (Zhang *et al.*, 2024). Operational factors have an equally important role as microorganisms in determining biodrying efficiency. The combination of optimal aeration, a balanced C/N ratio, controlled humidity, and the use of local bulking agents enables the process to proceed effectively without requiring large external energy inputs. The integration of additive innovations, such as biochar, and the reinforcement of local microbial inoculants are the latest research trends that promise to improve efficiency and reduce carbon emissions in waste treatment at the source (TWPS).

Reactor Design, Process Scale, and Operational Control

Biodrying performance at the pilot/industrial scale is influenced by the reactor design (batch pile, tunnel, rotary), aeration mechanism (passive vs. forced), and monitoring capability (temperature, humidity, CO_2). Numerical models and pilot-scale experiments show that reactors with controlled airflow and real-time sensors can achieve higher drying efficiency and shorter runtime than simple passive systems (Tom *et al.*, 2016).

INTEGRATION OF TECHNOLOGY AND INNOVATION IN BIODRYING

The acceleration of biodrying adoption at a practical scale depends not only on an understanding of microbiology and the optimization of basic operations, but also on integrating technologies and innovation methods that increase drying rates, reduce greenhouse gas emissions, and improve final product quality. Some of the innovative approaches that are currently receiving research attention are thermophilic bacterial agents (TBA), back-mixing techniques (re-inoculation/redistribution of mature materials), biodrying matching with photocatalytic processes (photocatalysis) for EPS degradation and microbial matrices, and the incorporation of biodrying with an accelerated composting stage known as biodrying-enhanced composting (BEC). Studies of each approach show that the combination of biological and engineering often provides synergistic benefits to product efficiency and quality.

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Inoculation of Thermophilic Bacterial Agents (TBA)

Inoculation with TBA aims to introduce microbial communities that quickly utilize biodegradable substrates and effectively produce *bioheat*, thereby accelerating the transition to the thermophilic phase and increasing the rate of moisture reduction. Recent research on biodrying of kitchen waste shows that TBA inoculation significantly increases the dewatering rate compared to controls and alters the microbial community succession pattern and dominant metabolic pathways during the process (e.g., increased hydrolytic enzyme activity and substrate oxidation rate). TBA implementation is particularly effective on very high-humidity substrates (e.g., biogas residues) where the original microbiota does not generate sufficient bioheat. These results confirm the potential of TBA as a biological strategy to shorten the biodrying process under limited operational conditions (Yang *et al.*, 2024).

Back-Mixing - Mechanisms and Operational Benefits

The back-mixing technique (moving some of the ripe/thermophilic material back to the wet part of the pile) serves as an in situ inoculation method that spreads functional communities to areas that need accelerated heating. Experimental studies on sludge biodrying have shown that back-mixing accelerates temperature rise, shortens processing time, and modulates microbial succession, so that thermophilic communities become dominant more quickly; this effect can resemble or complement the effects of commercial inoculants, but with lower operational costs if the operating design is simple. Mechanistically, back-mixing increases the number of thermophilic active cells per unit volume and improves thermal heterogeneity as well as micro-local substrate composition (Yu *et al.*, 2023).

Photocatalysis Integrated with Biodrying — Principles and Empirical Evidence

The integration of photocatalysis (e.g., the use of TiO_2 or biochar-TiO_2-based catalysts) with biodrying is explored for several purposes: (1) damaging the extracellular matrix (EPS) that binds water and inhibits dewatering; (2) reducing resistant organic compounds that slow degradation; and (3) suppressing pathogens or antibiotic resistance genes on specific substrates. Studies on sludge suggest that pre- or simultaneous photocatalytic treatment can lower EPS content, thereby increasing the rate of water release and improving dewatering during biodrying. This suggests a promising hybrid (physical-chemical + biological) technological pathway for materials with high EPS. However, the cost, catalyst safety (nanoparticle-related risks), and energy integration require further evaluation before large-scale adoption (Cai *et al*., 2023).

Biodrying-Enhanced Composting **(BEC) — Concept and Application**

BEC is an approach in which biodrying is used not only as a pre-drying step but also to accelerate compost maturity. By combining biodrying to rapidly reduce moisture content with optimized microbiological stages of composting (e.g., inoculation of mature compost, residual moisture regulation), some studies have achieved the maturity level of composting in much less time than traditional composting. The BEC model is particularly useful for managing food waste and organic residues that require rapid sanitation and final agronomic value. BEC has also been reported to reduce antibiotic resistance genes in some studies, owing to its extended thermophilic phase. This approach is promising for regions that require value-added product finishes (fertilizers/soil amendments) in addition to solid fuels (Xin *et al.*, 2023).

Combination Strategy: Inoculation + Back-Mixing + Additives (Biochar / $MgCl_2$)

Some studies suggest that the combination of strategies provides synergistic effects: for example, TBA inoculation accelerates bioheat production; *back-mixing* disperses the community efficiently; while additives such as *biochar* or mineral salts ($MgCl_2$) improve retention of pore structures, improve moisture absorption, and reduce GHG emissions during biodrying. Recent research on sludge suggests that this combination of additives and biological strategies can lower CH_4/N_2O emissions while maintaining thermophilic temperatures for longer, thereby improving dewatering and final product quality. However, dose optimization, application sequence, and cost-benefit analysis are required for this combined approach to be operationally viable (Zhang *et al.*, 2024).

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Advantages, Limitations, and Practical Adoption Aspects

The advantages of technology integration include process acceleration, potential for HHV improvement of the final product, emission reduction, and flexibility on different substrate types. Key limitations include capital requirements (catalysts, inoculants), process control needs (sensors/monitoring), potential nanoparticle risks associated with photocatalysis, and the need for field-scale studies to validate long-term efficiencies. In implementation contexts in developing countries, cost-effective approaches such as back-mixing and the use of LMO tend to be more feasible than capital-intensive photocatalytic technologies. Testing seasonal influences on waste composition and local economic models is a mandatory step prior to implementation at operational scale (Yu *et al.*, 2023). The latest innovations in biodrying include the use of Thermophilic Bacterial Agents (TBA) and back-mixing techniques to accelerate the thermophilic phase. Photocatalysis integration (TiO_2) is also being studied to degrade the water-binding Extracellular Polymeric Substances (EPS) matrix. The most practical innovation is Biodrying-Enhanced Composting (BEC), which can reduce the compost maturation time from 30 – 50 days to just 9 days, with a germination index >90%.

LOCAL MICROORGANISMS (LMO)

LMO solution is a fermented product based on available resources from both plants and animals. LMO is used as a starter or decomposer, containing micro- and macronutrients and bacteria that have the potential to transform organic matter in the soil, stimulate plant growth, and control pests and diseases. Plant materials that can be used as MOL include banana humps, papayas, coconut water, bamboo shoots, and vegetable waste. Animal materials include cow rumen, snails, fish bones, and livestock waste.

Microorganisms, in their activities, require nitrogen and carbon as sources of energy and nutrients for metabolic processes, and these compounds also stimulate the growth and proliferation of hydrocarbon-degrading microorganisms. The activity of microorganisms, such as bacteria, can shorten hydrocarbon chains, making them more readily degraded into CO_2 and H_2O (Zahro and Fitrihidajati, 2023). The bacteria commonly found in LMO are Rhizobium sp., Azospirillum sp., Bacillus sp., and phosphate-solubilizing bacteria (Trubus, 2012). The characteristics of LMO are that they smell sour, like fermentation; are white to cloudy yellow in color; have a temperature range of 22 – 55 °C; and have a pH of 4 – 9.

CLASSIFICATION OF BIOMASS WASTE

Biomass waste is solid organic material derived from human and natural biological activities that is no longer used for its primary function. This waste includes agricultural residues (straw, rice husks, corn cobs), forestry waste (twigs, leaves, wood powder), plantation waste, aquatic weeds, and organic fractions of urban waste. Based on its characteristics, biomass is generally composed of lignocellulose components consisting of cellulose, hemicellulose, and lignin, with different proportions depending on the type of raw material (Basera *et al.*, 2024).

From an environmental management perspective, biomass waste is often treated as a burden because it is high in volume, easily degradable, and can cause greenhouse gas emissions if left to decompose anaerobically. However, from an energy perspective, biomass waste is a renewable energy source that stores chemical energy captured through photosynthesis, making it a potential alternative fuel (Begum *et al.*, 2024).

The Potential of Biomass Waste as a Bioenergy Source

Bioenergy is energy produced from biomass through thermochemical, biochemical, or physical conversion processes. Biomass, including agricultural, plantation, and organic waste, can be converted into heat, electricity, and biofuels through processes such as pyrolysis, gasification, anaerobic digestion, and fermentation, thereby serving as an important renewable energy source in sustainable energy systems.

The use of biomass waste as a bioenergy source offers the advantages of its abundant availability, renewable nature, contribution to circular economy principles, and reduced dependence on fossil fuels. The energy stored in biomass is reflected through the *calorific value,* which is influenced by water content, chemical composition, and ash content; processing such as drying, densification, or pelletization can improve the energy density and quality of solid fuels (Begum *et al.*, 2024).

Challenges of Biomass Waste Utilization

Despite its great potential, the utilization of biomass waste as fuel faces various technical and operational challenges. The main challenge is the high initial moisture content, which can lower the effective calorific value

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and increase energy consumption during combustion. In addition, the physical and chemical heterogeneity of biomass complicates handling, transportation, and energy conversion. Without preliminary treatment, biomass is also susceptible to uncontrolled biological degradation, producing odors, energy loss, and greenhouse gas emissions. Therefore, a treatment technology capable of efficiently, economically, and easily improving the physical and energy quality of biomass at the source level is needed.

Biomass Waste Processing into Solid Fuel

One widely developed approach is the conversion of biomass waste into solid fuels such as biopellets or RDF. This process generally involves the stages of size reduction, drying, and compaction. Biopellets have the advantages of uniform size, high density, low moisture content, and ease of handling and storage.

However, conventional drying methods often require substantial energy inputs, thereby reducing the environmental benefits of bioenergy. Therefore, biological process-based approaches, such as biodrying, are an attractive alternative because they use heat generated by microorganisms to reduce the moisture content of biomass naturally and are relatively energy-efficient.

Relevance of Biomass Waste in Treatment Systems at Source

In modern waste management, source-level biomass treatment is becoming increasingly important. Decentralized treatment allows for reduced waste volume, lower transportation costs, and more efficient use of local resources. Biomass waste treated directly at the source can be converted immediately into a valuable product, such as solid fuel, without going through a lengthy management chain. This approach is particularly relevant to the concept of TWPS, which integrates biomass waste treatment, bioenergy utilization, and emission control in a single system. Thus, biomass waste is no longer seen as a residue to be disposed of, but rather as an energy resource that can be managed sustainably through a combination of technology and biological approaches.

Biomass is generally defined as dry matter from organic materials, or as material remaining after moisture is removed from a plant or other organic material (Alpian *et al*., 2023). Biomass is an environmentally friendly fuel that can substitute for fossil fuels, reduce global warming, and has low production costs. Biomass is the 4th primary energy source that is widely available in several developing countries. Biomass energy sources are renewable and can provide a sustainable energy supply. Biomass can be processed into fuel such as briquettes or pellets. The advantages of using biomass include its renewability, environmental friendliness, and reduced emissions of greenhouse gases and acidic gases. Biomass also has disadvantages, namely high moisture content, non-uniform shape and size, low density, and susceptibility to destructive microbes (Alpian *et al*., 2023; Ali *et al*. 2024).

The quality of biomass for energy is determined by the content of its chemical components, namely cellulose, hemicellulose, lignin, extractive substances, and ash. Cellulose and hemicellulose levels influence calorific values and the formation of vaporizers due to high oxygen fractions, whereas lignin and extraction levels have a positive effect on calorific value. Biomass with high lignin content has potential as an energy material because lignin increases calorific value. Volatile levels reduce calorific values, whereas bound carbon levels increase them. The proximate properties of biomass are influenced by the levels of the chemical components of biomass. Cellulose and hemicellulose are polyhydroxy carbohydrates with high oxygen content, resulting in high fly ash yields during combustion. High levels of flying matter lead to low levels of bound carbon, resulting in a low calorific value. Lignin is phenolic, has low oxygen content, and has a high carbon content, so it contributes significantly to the bound carbon content and calorific value of biomass. The higher the lignin content of the raw material, the higher the biopellet's calorific value. The lignin content of natural materials contributes more to the calorific value than cellulose; lignin can also be used as a source of natural adhesives (Alpian *et al*., 2023; Bantacut *et al*., 2015).

Indonesia, as an agricultural country with a tropical climate, has a fairly large area and abundant biomass. The quality of biomass as a solid fuel can be improved by converting it into a denser form with uniform particle mass, making it easier to handle, transport, and store (Alpian *et al*., 2023; Bantacut *et al*., 2015). The advantage of using biomass as an energy source is that the combustion gases are fewer and can be reabsorbed by plants, reducing the carbon dioxide released into the atmosphere. Biomass has a high moisture content, so the calorific value is low. This weakness can be overcome by making biomass pellets. Biopellets are a renewable fuel derived from biomass. Biopellets can be used as boiler fuel for industrial and heating applications. The use of biopellets in Indonesia remains limited, even though biopellet resources are abundant, including waste from plantations, agriculture, timber, and other industries. Biopellets have uniformity in size, shape, moisture, density, and energy

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content. The stages of biopellet manufacturing are the drying, milling, printing, and cooling processes (Qadry *et al*., 2023; Alpian *et al*., 2023; Fantozzi and Buratti, 2010).

ECONOMIC PERSPECTIVES AND INDUSTRY-SCALE CHALLENGES

The economic feasibility analysis of the TWPS-LMO system benefits from very low capital costs. The use of bamboo reactors with air gaps (passive aeration) minimizes the need for blower electricity. In addition, using local waste as raw materials for LMO eliminates dependence on expensive commercial inoculants. The large-scale implementation of the transition to industrial scale faces the challenge of raw material heterogeneity, which affects the consistency of pellet quality. A reactor design that optimizes heat accumulation and the integration of real-time sensors (temperature/humidity) for automatic aeration control is needed to prevent dead zones in large stacks.

CONCLUSION

Biodrying is a biological drying process based on aerobic oxidation reactions that improves the quality of lignocellulosic biomass as a solid fuel by producing bioheat and chemically transforming organic fractions. This process not only significantly reduces the moisture content but also alters the chemical composition of biomass, including partial degradation of hemicellulose and volatile fractions, an increase in the fixed carbon fraction, and an improvement in the C/N ratio. Operational factors such as aeration, particle size, porosity, microorganism inoculation, and the addition of bulking agents have been shown to affect drying kinetics, temperature dynamics, and the system's thermal efficiency. The mesophilic and thermophilic phases play important roles in determining biodegradation reaction rates and material stabilization. The integration of proper process-condition control enables optimization of heat and mass transfer, thereby minimizing energy loss due to excessive evaporation. In the context of biopellet production, biodrying serves as a pretreatment stage that improves energy density, storage stability, and compliance with renewable solid fuel quality standards. With an approach that integrates microbiology, process engineering, and chemical characterization, biodrying shows great potential as an efficient and sustainable technology for the valorization of tropical biomass. In the future, further in-depth research is needed into the mechanism of lignocellulose structural transformation, based on chemical and thermal analyses (e.g., FTIR, TGA, and DSC), bioheat kinetics modeling, and reactor design optimization, to improve energy efficiency and the consistency of product quality. This approach will strengthen biodrying's position as a strategic solution for developing biomass-based renewable energy.

CONFLICT OF INTEREST

There are no conflicts of interest in this article.

AUTHOR'S CONTRIBUTION

ZUL: Conceptualization, Methodology; YMD: Data Analysis, Writing – Original Draft; RAS: Supervision; PUT: Supervision; FGA: Writing – Review and Editing.

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DECLARATION OF GENERATIVE AI

During the preparation of this work, the author used ChatGPT to assist in developing the outline and structure of the literature review. Additionally, the author used NotebookLM to assist in summarizing scientific articles relevant to the topic. After using these tools, the author reviewed, verified, and edited the content as needed, and takes full responsibility for the content and integrity of the published article.

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