Terbit *online* pada laman web jurnal :http://jurnaldampak.ft.unand.ac.id/

Dampak: Jurnal Teknik Lingkungan Universitas Andalas

| ISSN (Print) 1829-6084 |ISSN (Online) 2597-5129|

Artikel Penelitian

Quality Improvement of Refuse-Derived Fuel from Landfilled Waste Using Solar Greenhouse Biodrying System

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Diterima: 2 Mei 2024 Diperbaiki : 1 Juni 2024 Disetujui: 1 Juli 2024

ABSTRACT

Final Disposal Sites (landfills) serve as the endpoint in the municipal solid waste management system, functioning as the final destination for our daily waste. Currently, Indonesia is experiencing a waste crisis due to the continuously increasing volume of waste generation, which leads to the rapid overfilling of landfill sites. One of the potential solutions for utilizing landfill waste is the production of Refuse-Derived Fuel (RDF), an alternative fuel derived from solid waste. However, waste that has been buried in landfills generally contains high moisture content, rendering it unsuitable for immediate RDF application. The calorific value of RDF depends greatly on its moisture content, with higher moisture levels resulting in lower energy output. Therefore, a pre-treatment process in the form of drying is necessary to reduce moisture content and optimize the fuel quality of RDF. This study applies the Solar Greenhouse Biodrying (SGB) method as a waste drying technology that combines heat from solar radiation with biological heat generated during aerobic degradation. This method was selected due to its suitability to Indonesia's tropical climate and its potential for large-scale application without requiring high external energy input. The waste material used in this study was obtained from landfill waste excavated at a depth of 3 meters, with an estimated age of approximately 9 years. In this study, a mixture of fresh waste and excavated landfill waste was dried using various composition ratios: 1:0 (control), 1:1, 1:2, 1:3, and 1:4. The results show that the SGB method effectively reduced moisture content by 27–62.2% and increased the calorific value to a range of 7.5–14 MJ/kg. The waste composition ratio significantly influenced moisture reduction, with the most optimal result found at a 1:2 ratio, which provided the best balance between drying efficiency and energy enhancement. These findings indicate that the SGB method is an effective alternative for waste drying prior to further utilization as RDF.

Keyword: landfill mining, solar greenhouse biodrying, refuse-derived fuel, municipal solid waste, moisture content

1. INTRODUCTION

Municipal solid waste (MSW) management in Indonesia continues to face complex challenges, particularly due to the increasing volume of waste and limited processing capacity at final disposal sites. In Jambi City, for instance, the Talang Gulo landfill has been the primary waste disposal facility since 1997. Following the overcapacity of Site1, which received approximately 1,012.2 m³ of waste per day in 2018 (TPA Talang Gulo, 2018), a new landfill cell began operation in early 2021. However, with landfill waste treatment levels remaining below 4% (BPS, 2020), the risk of premature saturation at the new site is substantial.

Among various recovery strategies, the production of Refuse-Derived Fuel (RDF) has emerged as a promising solution for reducing landfill burden while recovering energy from waste.

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RDF offers favorable characteristics such as ease of storage and transportation, relatively high calorific value, and low emissions when used as a secondary fuel (Dutsadee et al., 2015; Nithikul, 2007). Nevertheless, one of the main constraints in RDF production, particularly when derived from landfill-sourced waste, is its high moisture content. Studies have shown that moisture levels in landfill waste can range from 48% to 66% (Quaghebeur et al., 2013), which significantly exceeds the RDF standard of 10%–35% set by the European Commission (2003). Excessive moisture not only lowers the fuel's calorific value but also hinders its combustion efficiency, thereby limiting its applicability in industrial-scale operations.

To address this issue, pre-treatment through drying is necessary. Biodrying has been widely recognized as an effective method that utilizes biological heat from aerobic microbial activity to reduce moisture content (Huilinir & Villegas, 2014; Tom et al., 2016). However, many biodrying systems rely on active aeration and energy input, which may not be sustainable or scalable for large-volume waste processing. In response to this, the current study explores the Solar Greenhouse Biodrying (SGB) method, a passive drying technology that combines solar radiation and biological heat without requiring high external energy input. With Indonesia's tropical climate and an average solar radiation of 3.75 kWh/m²/day (BPSDM, 2021), the SGB method offers a context-appropriate, energy-efficient solution for landfill waste drying.

This study aims to assess the effectiveness of the SGB method in reducing moisture content and improving the calorific value of waste. A mixture of landfill waste and fresh organic waste was processed using five different composition ratios: 1:0 (control), 1:1, 1:2, 1:3, and 1:4. The objective is to determine the most optimal composition that meets RDF standards and supports energy recovery initiatives in developing countries.

2. METHODOLOGY

2.1 Biodrying Sample Preparation

The waste material used in this study was obtained from landfill-mined waste collected during a previous study (Widyarsana & Sevina, 2024), in which excavated waste was retrieved from Site 1 of the Talang Gulo Landfill in Jambi City. The waste material was sourced from a depth of 3 meters and was estimated to be over 9 years old. The excavation and preliminary characterization of the landfill waste, including its moisture content, composition, and physical properties, have been detailed in the aforementioned study and served as the foundation for the current drying experiments. In this study, the excavated waste was further prepared by removing oversized or non-biodegradable items such as stones, metal scraps, and glass. The remaining fraction was manually sorted and homogenized. Fresh waste, dominated by food and vegetable market waste, was collected from local temporary storage sites (TPS) in Jambi City and used as a biological activator due to its high moisture and readily degradable organic content.

Five biodrying piles were prepared with different mixing ratios to evaluate their effect on moisture reduction and energy content. The control pile (pile 1) contained only landfill waste (1:0), while piles 2 to pile 5 consisted of landfill-to-fresh waste ratios of 1:1, 1:2, 1:3, and 1:4, respectively. Each pile weighed approximately 35–40 kg, was thoroughly homogenized, and was then placed inside the solar greenhouse for drying. Adjustment of the composition ratio using the landfill waste composition approach in Jambi City.

2.2 Dryer Configuration

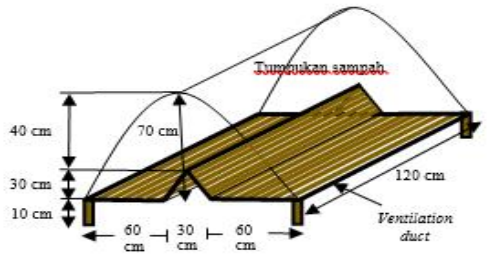


Figure 1. Passive Aerated Pile Configuration *(Source: Widyarsana & Sevina, 2024)*

The drying method employed in this study was a passive aerated pile system, utilizing a simple aeration structure made from long wooden slats and a triangular prism-shaped ventilation duct placed at the center of the pile. The ventilation duct was constructed using flat-cut bamboo. The base of the duct consisted of 17 wooden sticks (each 3 cm wide), arranged with a spacing of 0.5 to 0.7 cm between each, resulting in 16 gaps. Along the sloped sides of the duct, 8 bamboo sticks were used as the supporting

structure. The dimensions of each biodrying pile were 120 cm × 150 cm × 75 cm. A 10 cm elevation was created at the bottom of the pile to accommodate a simple leachate collection tray. This configuration had been previously used in a study by Chaerul and Fakhrunnisa (2020). The use of the ventilation duct facilitated a high level of air recirculation through the waste, allowing air to flow from the top, bottom, and center of the duct.

The greenhouse dryer building used measures 4.35 x 3.5 x 2.2 m. SGB's covering wall is transparent UV plastic. Ventilation is also made to provide air circulation thereby reducing humidity (Ngamket et al., 2021). Greenhouse illustration can be seen in Figure 2.

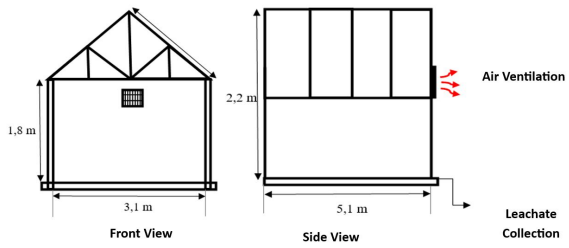


Figure 2. Solar Greenhouse Dryer *(Source: Widyarsana & Sevina, 2024)*

2.3 Analysis Of Sample Characteristics

2.3.1 Initial characterization test

The parameters analyzed to determine the characteristics of the waste used in biodrying is the proximate, ultimate and calorific value. This preliminary test was carried out on mixed waste samples, namely landfill mining waste with fresh waste to determine the initial characteristics of the sample, especially the value of the water content each pile.

2.3.2 Parameter test during the biodrying process

The drying period in this study lasted for 30 days. Throughout the process, key environmental parameters, namely waste temperature and ambient temperature, were observed. Moisture content, which served as the primary parameter in this research, was measured at three-day intervals. Meanwhile, waste temperature was recorded daily using an analog compost thermometer.

2.3.3 Final Product Characteristics Test

At the end of the process, final characteristic tests were carried out in the form of proximate, ultimate (C,H,O,N,S,Cl) tests, and calorific values, then compared with the RDF standard. The sample analysis procedure can be seen in Table 1.

3. ANALYSIS AND DISCUSSION

3.1. Temperature

Temperature is one of the key factors influencing the effectiveness of the biodrying process. According to Slezak et al. (2019), the optimal temperature range for biodrying lies between 50 and 60 °C. Observations from the temperature profiles indicate that greenhouse temperatures generally increased in response to rising ambient air temperatures, due to solar heat being trapped within the SGB structure. This thermal accumulation frequently resulted in internal greenhouse temperatures exceeding 40 °C. The lowest recorded SGB temperature (33.6 °C) occurred on day 15, coinciding with a drop in ambient temperature to 29.1 °C. This condition was caused by the weather factor, where the rain was quite heavy (14.6 mm/hour) from dawn until morning. This weather event temporarily suppressed pile temperatures and slowed the drying process. After this condition occurs, the waste temperature increases again. However, precisely on the 17th day, the temperature of the pile did not increase beyond the SGB greenhouse temperature, although overall it still exceeded the ambient air temperature. In general, the biodrying process in greenhouse-based systems tends to stabilize after 16 days (Mendoza et al., 2019).

Table 1. Sample Analysis Procedure

Parameter	Standard Analysis
Permeability	ASTM D 2434-68
Temperature	SNI 06-6989.23-2005
Moisture content	ASTM D 2216-98
Ash content	ASTM E 830–87
Volatile matter content	ASTM E 897–88
Fixed Carbon	ASTM D 3175
Organic carbon	Black & Walkley
NTK	ASTM E 778-87
Calorific value	ASTM E 711–87
Sieve analysis	ASTM E 828–81

Based on the temperature data on the piles in SGB, it can be seen that the temperature of pile 2 to pile 5 reached 40°C to 57°C in the first week before gradually declining. The highest temperature in the pile dried using the greenhouse dryer system occurred on the first three days (Mendoza et al., 2019), where the temperature exceeded the greenhouse temperature of the greenhouse. The high temperature of the waste at the beginning of the drying process indicates the intensive activity of microorganisms in degrading the substrate so that high heat is formed at the beginning of drying.

The thermophilic phase ends on day 11 which is marked by the temperature of the five piles being below 40°C. On day 12, a single manual turning of the piles was performed to redistribute heat throughout the waste matrix and potentially reactivate microbial activity. However, the temperature chart shows no significant thermal response after turning, suggesting that manual aeration had limited impact on heat generation in this system. The results of temperature measurements on the five piles in the SGB can be seen in Figure 3.

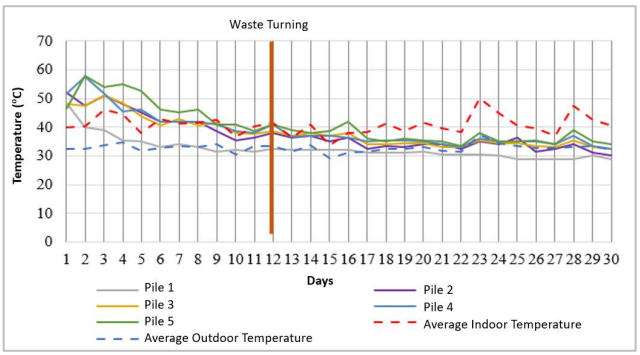


Figure 3. Temperature of SGB

3.2 Proximate Analysis

The proximate tests carried out were moisture, ash, volatile and fixed carbon content.

3.2.1 Ash content

The ash content in all treatment piles showed a decreasing trend by the end of the 30-day drying period. This reduction was observed across all piles, with the most substantial decrease found in pile 1, which dropped by 21.4%. The decline in ash content is attributed to the release of inorganic and mineral-bound fractions during the drying process. The detailed ash content results for each pile are presented in Figure 4.

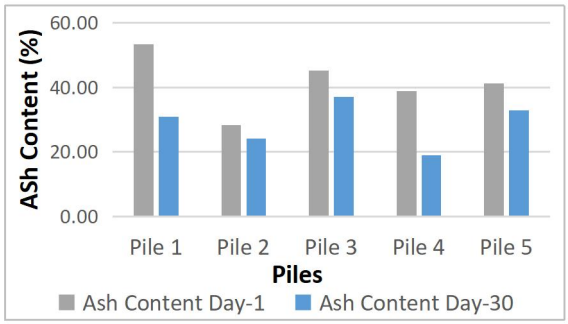


Figure 4. Ash Content in All Pile Variations

3.2.2 Volatile Matter Content

The volatile matter content increased in all piles, with the highest increase recorded in pile 1. On day 1, pile 1 had a volatile content of 46.65%, which increased to 69.07% by day 30 with an overall increase of 22.4%. The increase in volatile matter is likely due to the removal of moisture and the concentration of degradable organic compounds during biodrying. These results are illustrated in Figure 5.

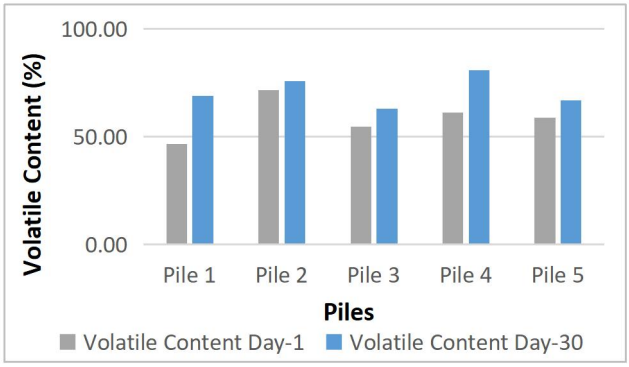


Figure 5. Volatile Matter Content in All Pile Variations

3.2.3 Fixed Carbon

Changes in fixed carbon content varied among the piles. Three piles showed a reduction in fixed carbon, while the others experienced a slight increase. The fixed carbon values is influenced by the value of volatile matter and ash content, and also by the initial composition of the waste in each pile. Pile 1 recorded the lowest fixed carbon value, decreasing from 3.09% to 2.44% by day 30. This pile consisted predominantly of landfill-mined plastic waste combined with a substantial amount of soil fraction adhered to the plastic material. According to Widyarsana & Tambunan (2022), plastic waste excavated from landfills tends to have a higher fixed carbon content due to long-term physiochemical transformation processes and the presence of carbon-rich soil residue attached to its surface.

In the present study, the reduction in fixed carbon observed in pile 1 may be explained by the biodrying process facilitating the detachment and removal of soil

particles from the plastic surfaces. In contrast, other piles containing fresh organic waste, paper, and newer plastic materials exhibited more stable or slightly increased fixed carbon values due to their differing degradation pathways and material compositions. The fixed carbon results for all treatment piles are summarized in Figure 6.

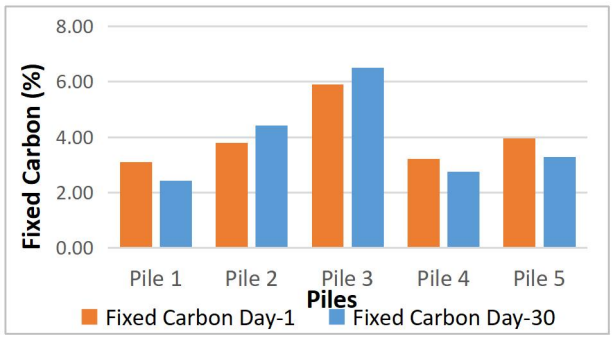


Figure 6. Fixed Carbon Content in All Pile Variations

3.2.4 Moisture Content

The moisture content profile over the 30-day biodrying period exhibited notable fluctuations. A significant reduction in moisture content was observed after day 17. These fluctuations may be influenced by the internal temperature of the piles and the airflow responsible for transporting moisture away from the waste matrix. This is supported by temperature data showing that during the first 17 days, the pile temperatures were consistently higher than the ambient temperature inside the greenhouse, which likely enhanced water evaporation. However, not all evaporated moisture escaped the system; some of it may have condensed on the greenhouse surface or fell back onto the pile, contributing to variations in moisture content. After day 17, both pile and greenhouse temperatures became relatively stable and equalized.

Pile 1 (control) has the lowest moisture content, which may be attributed to its composition, comprising solely of landfill-mined waste (including plastic and coconut fibers), with a predominance of large particle sizes. This structural characteristic increases free air space (FAS) within the pile, thereby facilitating greater airflow and moisture release. In biodrying systems, plastic and paper waste often act as bulking agents, enhancing pile porosity and enabling better oxygen penetration, which in turn promotes microbial activity. The moisture content trend across the drying period for all piles is illustrated in Figure 7.

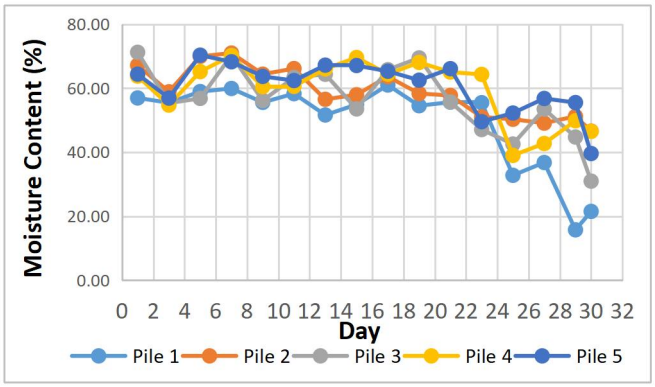


Figure 7. Moisture Content of All Piles

3.3 Ultimate Analysis

The variation in chemical content across the treatment piles is influenced by both microbial degradation activity and the physicochemical conditions within each pile. Factors such as temperature, aeration, and moisture levels directly affect the rate and extent of organic matter breakdown by microorganisms. These processes lead to either the concentration or reduction of specific chemical constituents, depending on the pile composition and biodegradation dynamics. A summary of the chemical characteristics of the biodried waste on day 30 is presented in Table 2.

Table 2. Chemical Characteristics of the Waste on the 30th Day

Samples	C	H	O	N	S	Cl
Pile 1	44,23	6,45	32,05	1,01	0,10	0,47
Pile 2	45,38	6,34	28,51	1,14	0,27	1,24
Pile 3	46,79	9,14	27,25	0,65	0,12	0,17
Pile 4	40,18	5,28	31,29	1,01	0,13	0,61
Pile 5	46,44	5,56	34,06	1,15	0,21	0,57

3.4 Calorific Value

The calorific value of samples from pile 1 to pile 5 ranged from 6.41 to 14.47 MJ.kg. When analyzed in relation to moisture content and waste composition, it was found that samples with lower moisture levels showed higher calorific values. This inverse relationship reflects the fundamental influence of water content on energy yield, as water acts as a thermal sink and reduces combustion efficiency. The results of calorific value measurements obtained on day 30 of the biodrying process are presented in Table 3.

Table 3. The Calorific Value of the Waste on the 30th Day

Samples	Moisture (%)	HHV (MJ/kg)	LHV (MJ/kg)
Pile 1	21,51	18,44	14,47
Pile 2	46,59	16,13	8,61
Pile 3	30,96	19,29	13,32
Pile 4	46,53	18,92	10,11
Pile 5	39,59	14,25	8,60

3.5 Comparison of Product Characteristics with Standards

Comparison of the RDF quality obtained in this study with standards from several countries is presented in Table 4. In general, it can be concluded that RDF products must adhere to established international quality criteria. When compared to the raw landfill waste, characterized in a previous study by Widyarsana & Sevina (2024), all treatment piles in this study show marked improvements in RDF properties, particularly in terms of calorific value and moisture content. However, the other measured values such as ash content and volatile matter remain relatively high, indicating that further optimization may be required to improve RDF quality.

3.6 Statistical Analysis

The influence of waste composition ratio on final moisture content was statistically evaluated using the Kruskal–Wallis test, The results indicated a statistically significant difference ($p < 0.05$) in moisture content across the five treatment piles, suggesting that the variation in mixing ratios between landfill waste and fresh organic waste had a measurable impact on the drying outcome. This finding supports the hypothesis that the addition of fresh waste, containing more readily degradable organic matter—can enhance microbial activity during the biodrying process. Increased microbial metabolism generates biological heat, which, in combination with solar heat, contributes to more effective moisture reduction. Therefore, the ratio of fresh waste addition plays a crucial role in optimizing the biodrying process by influencing internal pile temperature and subsequently, the rate of water evaporation. These results align with the observed temperature profiles and moisture trends recorded during the 30-day drying period.

3.7 Selection of Optimum Variation

Based on the weighting results, pile 1, comprising 100% landfill-mined waste, achieved the highest total score (741). This result indicates that physical drying alone, driven by solar heat in the SGB system, can produce RDF of high calorific value under certain waste compositions. However, among the piles added fresh waste, pile 3, using a landfill-to-fresh waste ratio of 1:2, produced the most optimal RDF characteristics in terms of balanced moisture content and energy potential.

Table 4. Comparison of Product Characteristics with RDF Standards

Parameter	Samples						Standard
	Raw waste	Pile 1	Pile 2	Pile 3	Pile 4	Pile 5	
Calorific value (MJ/kg)	5	14	7,5	12,6	9	7,6	12-16[a]
Moisture content (%)	56,9	21,5	47	31	46,5	40	10-35[a]
Ash content (%)	37,6	28,5	20	30,5	16,3	30	15-20[a]
Volatile matter content (%)	66,2	69	76	63	82	67	50-80[b]
Fixed carbon content (%)	3,7	2,4	4,4	6,5	2,7	3,3	>10[c]
Sulfur (%)	0,11	0,1	0,3	0,1	0,1	0,2	0,1-0,5[c]
Klorin (%)	0,32	0,5	1,2	0,2	0,6	0,6	0,15-1,5[d]

Note: (a) European Commission, (b) Jerman, (c) Inggris, (d) Finland

4. CONCLUSION

Waste drying using the Solar Greenhouse Biodrying (SGB) method successfully reduced the moisture content of landfill-based waste mixtures by 27.05% to 62.25%. The resulting calorific values ranged from 7.5 to 14 MJ/kg. Among the treatment piles, only pile 1 and pile 3 met the minimum calorific value required by the Indonesian RDF standard (SNI). Pile 1, composed entirely of landfill-mined waste (ratio 1:0), yielded the highest calorific value, indicating that physical drying through solar heat alone can produce high-energy RDF under certain waste compositions. Meanwhile, pile 3, which used a landfill-to-fresh waste ratio of 1:2, achieved a balanced performance in

terms of both moisture reduction and calorific value. These findings suggest that while landfill waste can be effectively dried under SGB conditions, the addition of fresh organic waste at a 1:2 ratio also represents an effective strategy for enhancing RDF quality, particularly in the context of municipal solid waste management.

ACKNOWLEDGMENT

The authors are grateful to the LPDP and PPMI ITB for funding support.

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