

Original Research Article

Biodrying Performance and Greenhouse Gas Emissions through Hot Air Aeration in Solid Waste Conversion

Badrus Zaman^{1*}, Nurandani Hardyanti¹, Wiharyanto Oktiawan¹, Budi Prasetyo Samadikun¹, Purwono Purwono²

¹ Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang - Indonesia 50275

² Environmental Sciences, Department of Science and Technology, Universitas Islam Negeri Raden Mas Said Surakarta, Jl. Pandawa, Pucangan, Kartasura 57168, Indonesia

* Corresponding Author, e-mail: badruszaman2@gmail.com

Copyright © 2026 by Authors,
Published by Environmental Engineering Department,
Faculty of Engineering, Universitas Diponegoro
This open access article is distributed under a
Creative Commons Attribution 4.0 International License



Abstract

Biodrying can convert solid waste into Refuse Derived Fuel (RDF) as an alternative to fossil fuels. The conversion of solid waste to RDF with a moisture content of 10-30% generally takes 21 days. This study aims to analyze greenhouse gas emissions and biodrying performance by applying hot air aeration to accelerate solid waste conversion into RDF. Laboratory-scale investigation used a bio-drying reactor and a solid waste mixture. Hot air was produced by burning wood charcoal (X₁) and mixture of wood charcoal and sawdust (X₂). The research showed that hot air aeration systems are more efficient and effective at converting solid waste into RDF. Water content of solid waste reduce from 50% to 34.29% after 60 minutes at 47-80°C. N₂O emissions were lower when the hot air source came from burning X₁. CO₂ emissions were lower when the hot air source came from burning X₂. The amount of electrical power required to burn one kg of X₁ and X₂ is 0.0135 and 0.018 kWh, respectively.

Keywords: Biodrying; CO₂ emissions; greenhouse gases; hot air aeration; N₂O emissions; solid waste

1. Introduction

Global environmental governance was changing due to the strong interconnection between humans, ecosystems, and economics. A negative effect of this interconnection is global climate change (Dzebo and Adams, 2023). The phenomenon of climate change has the potential to intensify global warming, leading to severe weather events, including storms, floods, droughts, and increased sea levels (Santos and Lousã, 2022). The combustion of fossil fuels like oil, natural gas, and coal for transportation, energy generation, and various industrial applications can lead to significant global challenges associated with climate change. The combustion process generates emissions of carbon dioxide (CO₂) along with other greenhouse gases (GHG), including methane and nitrogen oxides (Yoro and Daramola, 2020). Indonesia has committed to decrease its dependence on fossil fuels, establishing 2060 as the target year for achieving Net Zero Emissions (LPDP, 2023).

Methane (CH₄) and nitrous oxide (N₂O) gas are significant greenhouse gases emitted from municipal solid waste management (MSW) processes, especially from landfills and biostabilization techniques (Al-Rumaihi et al., 2020; Yasmin et al., 2022). Composting and vermicomposting are widely recognized as sustainable methods for managing organic waste, but they are not without environmental

impact, especially regarding greenhouse gas emissions. Both processes can release large amounts of nitrous oxide, methane, and carbon dioxide, which contribute to global warming. Aeration, C/N ratio, temperature, pH, bulking agent and moisture content significantly affect GHG formation during composting and vermicomposting (Yasmin et al., 2022). GHG emissions from solid waste can occur during collection and transportation due to fossil fuel vehicles such as solid waste trucks emitting CO₂ emissions. When solid waste is processed or disposed in a final landfill, its decomposition can produce methane. Thermal conversion technology is needed in landfills to reduce the impact of climate change (Yaman, 2020). The production of solid waste provides challenges that need to be addressed in order to mitigate its effects on the environment. Consequently, certain solid waste components need to be transformed into RDF to substitute fossil fuels like coal, petroleum, and natural gas in a range of industrial uses, including electricity production and heating (Zaman, Samadikun, et al., 2021).

By adopting biodrying technology, integrated waste treatment facility in Cilacap Regency, Indonesia, enhances waste management efficiency while supporting sustainable energy generation. The implementation of biodrying at the Cilacap, utilizing atmospheric air, requires a duration of 21 days to transform solid waste into RDF. On the other hand, integrated waste treatment facility in Cilacap Regency continues to produce a significant amount of solid waste every day, which leaves a significant portion unsuitable for RDF transformation. Skourides et al. made efforts to improve the biodrying process by using a rotary bio-dryer (RBD) to treat mechanically separated solid waste and organic waste fractions (Skourides, I.; Theophilou, C.; Loizides, M.; Hood, P.; Smith, 2006). The RDB is operated in alternating cooling and heating cycles, using sequential rotating and static intervals and varying air flow rates. The process control strategy aims to maintain the temperature in the bioreactor that is optimal for aerobic biodegradation (range mesophilic to upper thermophilic: 40–55°C). RDB can achieve rapid and homogeneous solid waste drying, reducing MC from 35–40% to 10–15% (w/w) within three days. The challenge of scaling up this research is the small capacity of the rotary bio-dryer; if the number of reactors is increased, it will require very high costs. Optimizing the production of additional fuels from biodegradable municipal waste involves integrating advanced technologies and methodologies to ensure consistent and efficient fuel output. This process not only helps in waste management but also contributes to energy sustainability by replacing some of the fossil fuels.

Biodrying aims to remove water content from solid waste and reduce the volume and biological activity of the solid matrix to obtain a product with low water content and a reasonably large Low Calorific Value (LCV) (González et al., 2019). Biodrying systems in municipal solid waste processing show high energy efficiency and reduce greenhouse gas emissions compared to other systems (Ham and Matsuto, 2021). CO₂, CH₄, and NH₃ emissions are byproducts of biodrying that cause environmental pollution (Xie et al., 2023; Zhao et al., 2023). The biodrying process in processing municipal solid waste can emit greenhouse gases such as CO₂, CH₄, and N₂O (Zaman et al., 2018a). GHG emissions from suspended solids composting processes have been widely reported in recent years due to their potential impact on global warming (Pan et al., 2018). González et al., stated that gas emissions and their environmental impacts have yet to be systematically studied in solid waste biodrying using hot air, and emission factors for specific pollutants are required for environmental impact assessment (González et al., 2019). A shorter heating phase can be achieved by continuous aeration, reducing the overall drying time (Payomthip et al., 2022). Therefore, more information about the performance of solid waste biodrying using hot air must be provided. Biodrying performance is known from the parameters of GHG emissions produced during biodrying, the water content reduction rate, and electrical energy consumption.

This research aims to analyze greenhouse gas emissions and biodrying performance by applying hot air aeration to accelerate solid waste conversion into RDF. Good biodrying performance can accelerate the conversion of solid waste into RDF. In particular, N₂O and CO₂ gas emissions as greenhouse gas emissions are evaluated in depth. In this research, the hot air used came from burning wood charcoal (X₁) and a mixture of wood charcoal + sawdust (X₂).

2. Methods

2.1. Waste sources and sample preparation

Solid waste comes from Rasamala market, Banyumanik, Semarang, Central Java, Indonesia, which was four km from the research location. Solid waste was taken to be tested in the Environmental Laboratory, Faculty of Engineering, Diponegoro University. Solid waste was chopped to a size of two cm using a chopping machine (Zaman, Samadikun, et al., 2021) and then put into the biodrying unit. The fuel uses wood charcoal sold in fuel shops (Ungaran, Indonesia). Sawdust fuel comes from the furniture industry (Semarang, Indonesia).

2.2 Reactor Design

A schematic representation of the biodrying process for solid waste was shown in Figures 11. The biodrying reactor consists of a fuel inlet, a fuel burner furnace, a biodrying reactor equipped with a drying rack, a gas outlet, and samples. The reactor material uses hebel brick, which has non-combustible properties. The combustion furnace has dimensions of 35 x 44.5 cm, the dimensions of the biodrying reactor are 50 x 50 cm, and the thickness of the reactor was 10 cm. A hollow iron plate holds the solid waste sample in the middle of the biodrying reactor.

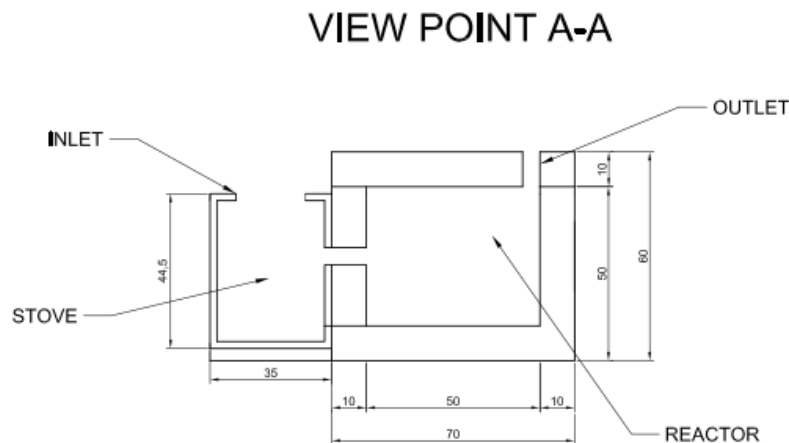


Figure 1. A schematic representation of the biodrying process for solid waste

2.3 Experimental Setup

Solid waste was chopped to 2 cm using a chopping machine (Zaman, Samadikun, et al., 2021) and then put into a biodrying unit equipped with a drying rack. The research used two types of fuel, namely wood charcoal (X₁) and a mixture of wood charcoal + sawdust (X₂). The first variation uses one kg of X₁ as heating fuel. The second variation uses a blend of wood charcoal + sawdust in a ratio of 50:50 (w/w) (X₂). A gas torch assists the initial combustion until the fuel burns. The fan was turned on to supply oxygen from outside so that combustion was more complete and did not produce smoke (Maspion, Indonesia). Hot air will flow to the heat control unit before entering the biodrying and dryer units. This operating process was carried out using a controlling unit. Hot air will heat solid waste to different temperatures. The maximum temperature in the biodrying unit was thermophilic. Temperatures >60°C will kill some microbes, and only thermophilic microbes will survive (Ab Jalil et al., 2016). The biodrying process was stopped when the fuel has burned out.

Solid waste in the biodrying unit was heated until a moisture content of <40% was obtained and a calorific value equivalent to lignite (<7000cal/g) (Zaman, Oktiawan, et al., 2021a). Temperature was monitored using a 1100C mercury thermometer. Water content was measured before and after the

biodrying process. Biodrying products in solid waste with a water content <40 are ready to be used as RDF.

2.4 Sampling Method

Sampling was conducted to determine the performance of the biodrying process using hot air. Good biodrying performance can accelerate the conversion of solid waste into RDF. Biodrying performance was determined based on reduced water content, electrical energy consumption, and greenhouse gas emissions. Solid waste samples were taken before the samples were put into the biodrying reactor. This sample was used to measure water content before treatment. The sampling process was carried out at the end of the biodrying process to determine the final water content. The matrix temperature was measured every 15 minutes until the fuel ran out. The temperature measurement location was at the front of the biodrying unit and the section to determine the heat distribution in the reactor. N₂O and CO₂ emissions were sampled using a 10 mL capacity spin needle and then put into a gas bag. This method refers to previous research conducted by Zaman et al., (Zaman, Oktiawan, et al., 2021b)

2.5 Sample Analysis

Temperature measurements were carried out using a mercury thermometer with a maximum scale of 1100C. Water content was measured using the gravimetric method. Samples were cured in an oven to constant weight (Memert, Germany). Mathematically, water content was calculated using the following equation (Steiner et al., 2022):

$$\text{water content} = \frac{m_{\text{water}}}{m_{\text{solid}} + m_{\text{water}}}$$

Where m water and m solid denote the masses of water and solid, respectively, gas sampling for GHGs was conducted at the maximum temperature for CO₂ and N₂O using a Shimadzu 4A capillary gas chromatograph (Japan), which was equipped with a flame thermionic detector (FTD) and operated at a temperature of 250 degrees Celsius. The limit of detection for N₂O was 39.22 ppb, and for CO₂ was 88.47 ppm.

3. Results and Discussion

3.1 Composition of solid waste

The types and percentages of solid waste used for the biodrying process using hot aeration are shown in Table 1. The types of solid waste used in the research were categorized into three types, namely food waste, organic waste, and plastic, each accounting for 85.32%, 9.68%, and 5.00%. The percentage of food waste is more significant than other types of waste because food waste contains up to 60% water content.

Table 1. Type and percentage of solid waste used for the biodrying process using hot aeration

No	Types of waste	Weight (kg)	%
1	Food waste	2.679	85.32
2	Organic waste	0.304	9.68
3	Plastic	0.157	5.00
Total		3.14	100

3.2 Solid waste temperature profile in the biodrying reactor when hot aeration was supplied

This discussion aims to evaluate the temperature profile of solid waste during the biodrying process using different fuels (X₁ and X₂). Figure2 shows the solid waste temperature profile during the

hot air aeration process using a heat source from X₁ fuel. Temperature measurements were carried out at the front and back of the reactor.

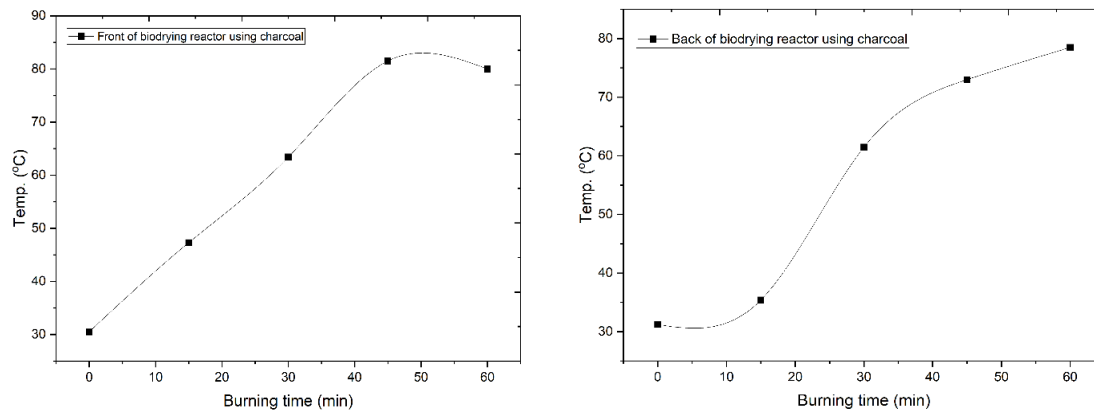


Figure 2. Solid waste temperature profile graph during the hot air aeration process using a heat source originating from X₁ fuel. Temperature measurements were carried out at the front and back of the reactor.

The research showed that X₁ fuel produced higher solid waste temperatures than the X₂ at the front and back of the biodrying reactor. The temperature at the front of the reactor is higher than at the back, ranging from 47.3-80°C. The solid waste temperature at the back is more stable, running between 60-64°C during monitoring at 15 to 60 minutes (Figure 3). X₁ does not burn directly but is assisted by a gas torch heater to start combustion. When the X₁ has been burned, the fan is turned on at a constant speed. The heat from burning charcoal and sawdust is channeled to the biodrying unit containing solid waste. The temperature measurement location is at the front of the reactor (inlet), and the reactor section is the air outlet. Generally, the solid waste temperature profile in the biodrying process is almost similar to the composting process. After reaching the maximum temperature, the temperature is maintained and decreases gradually until it approaches room temperature (González et al., 2019). However, in this research, the solid waste temperature was adjusted so that the solid waste temperature could rise quickly.

X₁ fuel produces temperature profiles at the front and back of the reactor, as shown in Figure 2. The initial temperature of solid waste in the front reactor was 30.5°C; then, the temperature increased to 47.3°C when solid waste was supplied with hot air for 15 minutes. The solid waste temperature rose to 63.4°C when hot air was provided for 30 minutes. The highest solid waste temperature reached 81.5°C when solid waste was supplied with hot air for 45 minutes and tended to stabilize at the 60th minute, namely 80°C. The initial temperature of the solid waste in the rear reactor was 31.2°C; then, the temperature increased to 35.4°C when the solid waste was supplied with hot air for 15 minutes. The solid waste temperature increased to 61.5°C when hot air was provided for 30 minutes and 73°C when hot air was supplied to solid waste for 45 minutes and tended to stabilize at the 60th minute, namely 78.5°C.

Using a mixture of X₂ fuel produces temperature profiles at the front and back of the reactor, as shown in Figure 3. The initial temperature of the solid waste at the front of the reactor was 31°C; then, the temperature increased to 60°C when the solid waste was supplied with hot air for 15 minutes. The solid waste temperature increased to 63°C when hot air was provided for 30 minutes and 62°C when hot air was supplied to solid waste for 45 minutes. It tended to stabilize at the 60th minute, namely 64°C. The initial temperature of solid waste in the rear reactor was 29°C, then the temperature increased to 70°C when solid waste was supplied with hot air for 15 minutes. The solid waste temperature increases to 70°C when hot air is supplied for 30 minutes. The highest solid waste temperature reached 65°C when solid waste was supplied with hot air for 45 minutes and tended to stabilize at the 60th minute, namely 66°C.

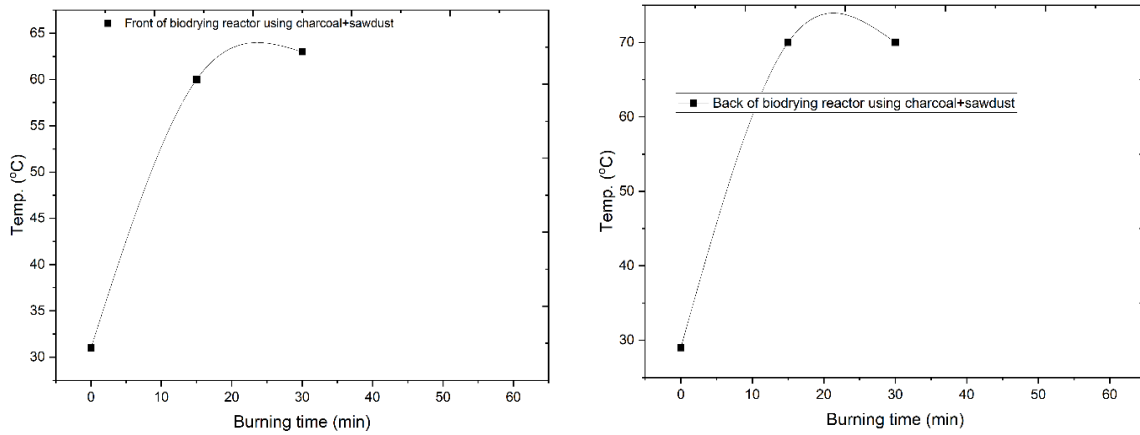
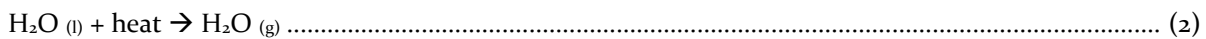
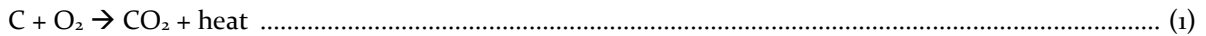


Figure 3. is a solid waste temperature profile graph during the hot air aeration process using a heat source originating from charcoal + sawdust fuel. Temperature measurements were carried out at the front of the reactor and the back of the biodrying reactor.

The increase in temperature in this study was faster than the results of previous research, where the biodrying process used room air at a rate of 2 L/min, 110 hours of aeration succeeded in increasing the maximum temperature to 44°C and reducing the water content to 62.18% (Zaman et al., 2018b).

The sawdust on X2 is more volatile, so more burning occurs at the beginning of the process (Cai et al., 2014). Sawdust acts as a highly reactive material and accelerates the ignition process (Vershina et al., 2017). On the other hand, sawdust contains water (~10–20%), so some of the energy is used to evaporate the water (endothermic process), the effect of which is a lower combustion temperature (Zeng et al., 2017). The wood charcoal combustion reaction produces heat and CO₂, so no energy is wasted to evaporate water or decompose volatile compounds as in the reaction (1). Some of the heat generated from the combustion of wood charcoal + sawdust mixture is used to evaporate the water contained in sawdust such as reaction (2) and produce smoke as wasted energy.



Sawdust offers unique advantages due to its high reactivity and its ability to enhance the combustion process without the need for additional chemical treatments (Berezikov et al., 2021).

Daily temperatures measured during the Wet-RDF biodrying process range between 20–63°C, with peak temperatures occurring during days 2–4 (Bhatsada et al., 2022). Intermittent partial load biodrying with homogenization aeration is more profitable because the reduction in water content is higher, and the operation time is shorter, from 500 to 48 hours (Maia et al., 2023). Hot air aeration causes the water content to evaporate quickly through convection.

3.3 Biodrying performance is based on reducing water content

Biodrying performance refers to the effectiveness of the solid waste biodrying process in achieving desired results and minimizing negative impacts on the environment. The main parameters influencing biodrying performance are aeration, initial water content, final water content, and solid waste temperature. Meanwhile, greenhouse gas emissions assess the negative impacts of solid waste biodrying using hot air aeration.

The research results showed that the wastewater content before the biodrying process was 50.00%, then decreased to 34.29% after the biodrying process was carried out for 60 minutes (31.42% of the initial water content). Biodrying temperatures range between 47–800C. Previous research shows that biodrying municipal solid waste reduces the water content from 73% to 48.3% (33.8% of the initial water content) and increases its calorific value by 157% (Shao et al., 2010). Adding inoculation material to the

solid waste pile processed by biodrying resulted in the highest reduction in water content of 72.7% (from 60.2% to 17.7%). Adding various amounts of inoculating materials through different application methods increased the cellulose degradation rate by 2.3-14.2% (Yuan et al., 2019).

The level of solid waste used as RDF is 25%. Based on the results of this research, it can be seen that the biodrying process using hot air takes more than 60 minutes for a waste amount of 3.14 kg, meaning that one kg of solid waste takes \pm 19.10 minutes with a temperature of 47-800C. The biodrying time needs to be extended so that the water content meets the requirements of RDF. Even though the final results do not yet qualify as RDF, this research significantly reduced the water content of solid waste.

3.4 N₂O gas emissions as a greenhouse gas

The potential for global warming due to N₂O gas is higher than CO₂ gas (265 times higher than CO₂) (IPCC, 2023). Therefore, N₂O gas is significant to study to help choose prevention strategies and minimize its environmental impact. N₂O emissions from the biodrying process can contribute to climate change and must be monitored and minimized.

The hot air source comes from burning X₁ and X₂. Emissions from burning X₁ depend on factors such as burner design, type of wood pellet, and burning conditions (Choiński et al., 2023; Hays et al., 2019; Marcotte et al., 2020). N₂O emissions in the solid waste drying process using hot air are shown in Figure 4. The results showed the average N₂O emissions were lower when the hot air source came from burning X₁ rather than X₂. X₁ fuel produces a maximum N₂O emission of 479.01 ppb at the 60th minute when the MWS temperature is 78.50C, the lowest emission is 110.89 ppb at the 15th minute when the temperature is 35.40C, and the average N₂O emission is 362.71 ppb. X₂ produced maximum N₂O emissions of 395.54 ppb in the 45th minute. The lowest emissions were 388.70 ppb in the 15th minute when the temperature was 700C, and the average N₂O emissions were 392.82 ppb. When analyzed in terms of combustion time, the combustion time of 15 minutes produces the lowest N₂O emissions for X₁ fuel and X₂.

Charcoal tends to produce higher and more stable combustion temperatures compared to charcoal and sawdust mixtures (Ajimotokan et al., 2019). High temperatures can support the decomposition of N₂O into nitrogen (N₂) and oxygen (O₂), thereby reducing N₂O emissions.

N₂O emissions in this study were lower than previous research conducted by (González et al., which shows that the maximum and minimum N₂O emissions measured during the waste sludge biodrying process are 18.75 ppm and 0.37 ppm, respectively, using an air discharge variation of 0.12, 0.36, 0.60; 0.84 and 1.20 Lmin⁻¹ kg⁻¹ mixture (González et al., 2019). Other research states that bio-drying solid waste using 2 L min⁻¹ kg⁻¹ airflow emits 120.82 ppb N₂O gas at 430C on day 2 (Zaman, Oktawan, et al., 2021a). This research used air aeration at room temperature. In the biodrying process, NH₃ emissions and other greenhouse gas production are much lower than in composting because the biodrying process uses aeration and takes less time (Xu et al., 2022). In the biodrying process, the formation of N₂O gas comes from denitrification. NO₃⁻ is converted into N₂O and nitrogen gas, and incomplete nitrification occurs by converting NH₃ to NO₂⁻ (Moënné-Loccoz and Fee, 2010). The temperature of the mesophyll in the biodrying process affects microbial activity in solid waste samples. Denitrifying bacteria play a role in forming N₂O from NO₃⁻ (Thakur and Medhi, 2019). According to Zhang et al., the N₂O emission profile during sludge biodrying can be divided into three stages (Zhang et al., 2017). Denitrification contributed mainly to N₂O emissions in stage I (days 1-5), while N₂O emissions mainly occurred in stage II (days 5-14) due to nitrifier denitrification and NH₂OH accumulation by ammonia-oxidizing bacteria (AOB). This accounted for 51.4% and 58.2% of the total N₂O emissions for stages I and II, respectively. In stage III (days 14-21), nitrifier denitrification is hampered because sludge biodrying is carried out mainly with physical aeration. As a result, N₂O emissions decrease. The amount of N₂O gas emissions produced during biodrying depends on several factors, including the initial moisture content of the organic waste, the C/N ratio (González et al., 2019), the stack temperature, and the oxygen content of the air circulating through the stack.

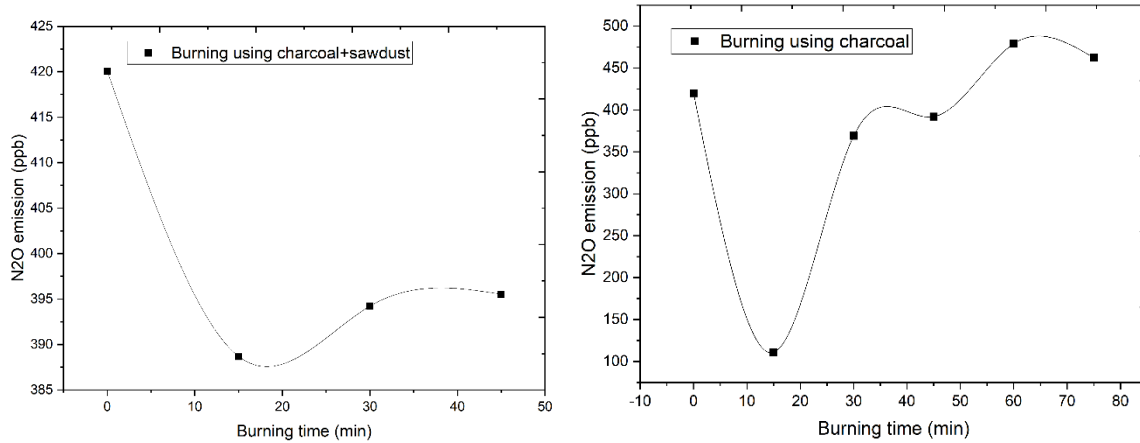


Figure 4. Graph of N₂O emissions from solid waste undergoing hot air aeration process in a biodrying reactor.

3.5 CO₂ gas emissions as a greenhouse gas

CO₂ emissions are a byproduct of the biodrying process, which causes environmental pollution (Xie et al., 2023; Zhao et al., 2023). The composting process produces two forms of CO₂: biogenic CO₂ and non-biogenic CO₂ (Sánchez et al., 2015). Biogenic CO₂ is produced by biological processes such as organic matter degradation or soil respiration, while non-biogenic CO₂ is produced by fossil fuels such as coal.

Figure 5 shows CO₂ emissions from solid waste undergoing the hot air aeration process in the biodrying reactor. The research results show that the average CO₂ emissions are lower when the hot air source comes from burning a mixture of X₂ with a CO₂ concentration of 1,779.57 ppb. Meanwhile, CO₂ emissions average 4,697.65 ppm when the hot air source comes from burning X₁. Wood X₁ fuel produces a maximum CO₂ emission of 10,881.36 ppb in the 15th minute when the solid waste temperature is 35.40C, the lowest emission is 815.02 ppb in the 30th minute when the temperature is 61.50C, and the average CO₂ emission is 4,697.65 ppb. The fuel mixture of wood charcoal + sawdust produces a maximum CO₂ emission of 3,143.81 ppb in the 15th minute. The lowest emissions were 909.01 ppb in the 45th minute when the temperature was 65oC, and the average CO₂ emissions were 1,779.57ppb.

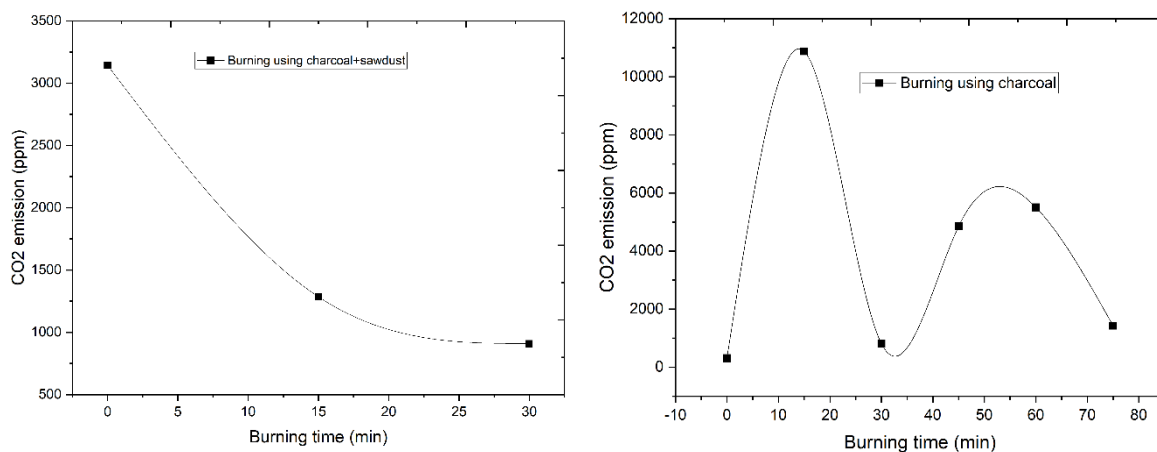


Figure 5. Graph of CO₂ emissions from solid waste being carried out by the hot air aeration process in a biodrying reactor.

Previous research conducted by Xu et al., which focuses on the bidding process of lignocellulosic biomass, states that the decomposition of organic materials during biodrying can release greenhouse gases such as carbon dioxide (CO₂) and methane (CH₄) (Xu et al., 2023). A higher C/N ratio results in

more bacteria associated with greenhouse gas emissions, and excess carbon is released as greenhouse gases (Xu et al., 2023). CO₂ emission levels are valuable indicators of microbial activity and substrate stability in biological processes.

3.6 Electrical energy consumption

Electrical energy consumption in research only comes from the wind fan, which is used to add air to the X₁ burning process, or the charcoal + sawdust mixture. The propeller size is 150mm (6 inches), the overall fan dimensions are 21.5 cm x 16.5 cm x 29 cm, the electrical power is 18 Watts, and the voltage is 220 Volts / 50 Hz (Maspion, Indonesia). The research results show that the amount of electrical energy required to burn one kg of X₁ is 0.018 kWh and requires Rp. 26. The burning time for one kg of X₁ until it is finished is 60 minutes. The amount of electrical power needed to burn one kg of X₂ is 0.018 kWh and requires Rp. 20. The burning time for one kg of X₁ until it is finished is 45 minutes. Details of the electrical energy requirements required for the biodrying process using hot air are shown in Table 2.

Table 2. The electrical energy required for the biodrying process uses hot air.

No	Component	X ₁	X ₂
1	Power, watts	18	18
2	operating time, h	60	45
3	Number of KWH	0.018	0.0135
4	Price per KWH, Rp	1,444.70	1,444.70
5	Amount paid, Rp	26	20

4. Conclusion

This study introduces biodrying with a hot air aeration system for biodrying solid waste. Biodrying performance is determined based on the reduction in water content, electrical energy consumption, and greenhouse gas emissions. The research showed that this system is more efficient and effective than conventional systems. The solid waste water content succeeded in decreasing 31.42% from the initial water content within 60 minutes with a biodrying temperature ranging from 47-800C. Average N₂O emissions were lower when the hot air source came from burning charcoal rather than a mixture of wood charcoal+sawdust. Meanwhile, the average CO₂ emissions were lower when the hot air source burned a mixture of X₂ with a CO₂ concentration of 1,779.57 ppb. The amount of electrical power required to burn one kg of charcoal is 0.018 kWh and requires Rp. 26. The burning time for one kg of charcoal until it is finished is 60 minutes. The amount of electrical power needed to burn one kg of X₂ mixture is 0.018 kWh and requires Rp. 20. The burning time for one kg of charcoal until it is finished is 45 minutes.

The acknowledgments

This project has been funded by the Directorate General of Higher Education, Research, and Technology, Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia with No. 449A-62/UN7.D2/PP/VI/2023.

CRedit Author Statement

Badrus Zaman: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review and editing, and Final approval of the version submitted. **Nurandani Hardyanti:** Supervision and Review. **Wiharyanto Oktawan:** Supervision and Review. **Budi Prasetyo Samadikun:** Methodology, Investigation. **Purwono Purwono:** Review, editing, and Final approval of the version submitted.

Reference

Ab Jalil, N. A., Basri, H., Basri, N. E. A., and Abushammala, M. F. M. 2016. Biodrying of municipal solid

- waste under different ventilation periods. *Environmental Engineering Research*, 21(2), 145–151.
- Ajimotokan, H. A., Ehindero, A. O., Ajao, K. S., Adeleke, A. A., Ikubanni, P. P., and Shuaib-Babata, Y. L. 2019. Combustion characteristics of fuel briquettes made from charcoal particles and sawdust agglomerates. *Scientific African*, 6.
- Al-Rumaihi, A., McKay, G., Mackey, H. R., and Al-Ansari, T. 2020. Environmental impact assessment of food waste management using two composting techniques. *Sustainability (Switzerland)*, 12(4).
- Berezikov, N. I., Gorshkov, A. S., Zenkov, A. V., and Larionov, K. B. 2021. Intensification of ignition and combustion processes of low-reaction solid fuels by liquid hydrocarbons. 2422, 30001.
- Bhatsada, A., Wangyao, K., and Patumsawad, S. 2022. Effect of aeration rate on wet- refuse-derived fuel biodrying process for increasing heating value and water content reduction. *Proceedings of the 2022 International Conference and Utility Exhibition on Energy, Environment and Climate Change, ICUE 2022*, 1–8.
- Cai, P., Zhao, L. J., Wang, K., and Kong, S. T. 2014. Experiment study on mixed combustion of biomass and coal. *Advanced Materials Research*, 978, 3–6.
- Choiński, B., Szatyłowicz, E., Zgłobicka, I., and Joka Ylidiz, M. 2023. A critical investigation of certificated industrial wood pellet combustion: influence of process conditions on CO/CO₂ emission. *Energies*, 16(1), 250.
- Dzebo, A., and Adams, K. M. 2023. Contesting legitimacy in global environmental governance - An exploration of transboundary climate risk management in the Brazilian-German coffee supply-chain. *Earth System Governance*, 15, 100166.
- González, D., Guerra, N., Colón, J., Gabriel, D., Ponsá, S., and Sánchez, A. 2019. Filling in sewage sludge biodrying gaps: Greenhouse gases, volatile organic compounds and odour emissions. *Bioresource Technology*, 291(July), 121857.
- Ham, G. Y., and Matsuto, T. 2021. Comparison of energy recovery system from municipal solid waste in terms of energy balance and life cycle CO₂ emission. *Journal of Material Cycles and Waste Management*, 23(5), 1751–1764.
- Hays, M. D., Kinsey, J., George, I., Preston, W., Singer, C., and Patel, B. 2019. Carbonaceous particulate matter emitted from a pellet-fired biomass boiler. *Atmosphere*, 10(9), 536.
- IPCC. 2023. Climate Change 2023: Synthesis Report. In *Climate Change 2023: Synthesis Report* (Vol. 27, pp. 35–115). IPCC Geneva, Switzerland.
- LPDP. 2023. *RISPRO Invitasi Batch 1 2023: LPDP dan PT. SMI Ajak 15 Universitas Mengikuti Kompetisi Riset Transisi Energi*. <https://lpdp.kemenkeu.go.id/informasi/berita/rispro-invitasi-batch-1-2023-lpdp-dan-pt-smi-ajak-15-universitas-mengikuti-kompetisi-ri-set-transisi-energi>
- Maia, G. D., Horta, A. C. L., and Felizardo, M. P. 2023. From the conventional to the intermittent biodrying of orange solid waste biomass. *Chemical Engineering and Processing - Process Intensification*, 188, 109361.
- Marcotte, S., Castilla, C., Morin, C., Merlet-Machour, N., Carrasco-Cabrera, L., Medaerts, F., Lavanant, H., and Afonso, C. 2020. Particulate inorganic salts and trace element emissions of a domestic boiler fed with five commercial brands of wood pellets. *Environmental Science and Pollution Research*, 27(15), 18221–18231.
- Moënné-Loccoz, P., and Fee, J. A. 2010. Biochemistry: catalyzing NO to N₂O in the nitrogen cycle. *Science*, 330(6011), 1632–1633.
- Pan, J., Cai, H., Zhang, Z., Liu, H., Li, R., Mao, H., Awasthi, M. K., Wang, Q., and Zhai, L. 2018. Comparative evaluation of the use of acidic additives on sewage sludge composting quality improvement, nitrogen conservation, and greenhouse gas reduction. *Bioresource Technology*, 270, 467–475.
- Payomthip, P., Towprayoon, S., Chiemchaisri, C., Patumsawad, S., and Wangyao, K. 2022. Optimization of aeration for accelerating municipal solid waste biodrying. *International Journal of Renewable Energy Development*, 11(3), 878–888.

- Sánchez, A., Artola, A., Font, X., Gea, T., Barrena, R., Gabriel, D., Sánchez-Monedero, M. Á., Roig, A., Cayuela, M. L., and Mondini, C. 2015. Greenhouse gas emissions from organic waste composting. *Environmental Chemistry Letters*, 13(3), 223–238.
- Santos, R. S., and Lousã, E. P. 2022. Give me five: the most important social values for well-being at work. *Administrative Sciences*, 12(3), 101.
- Shao, L. M., Ma, Z. H., Zhang, H., Zhang, D. Q., and He, P. J. 2010. Bio-drying and size sorting of municipal solid waste with high water content for improving energy recovery. *Waste Management*, 30(7), 1165–1170.
- Skourides, I.; Theophilou, C.; Loizides, M.; Hood, P.; Smith, S. R. 2006. Optimisation of advanced technology for production of consistent auxiliary fuels from biodegradable municipal waste for industrial purposes. *Sustainable Waste and Resource Management*, 2B-14.40, 19–21.
- Steiner, M., Katona, T., Fellner, J., and Flores Orozco, A. 2022. Quantitative water content estimation in landfills through joint inversion of seismic refraction and electrical resistivity data considering surface conduction. *Waste Management*, 149(May), 21–32.
- Thakur, I. S., and Medhi, K. 2019. Nitrification and denitrification processes for mitigation of nitrous oxide from waste water treatment plants for biovalorization: Challenges and opportunities. *Bioresource Technology*, 282, 502–513.
- Vershinina, K. Y., Kuznetsov, G. V., and Strizhak, P. A. 2017. Sawdust as ignition intensifier of coal water slurries containing petrochemicals. *Energy*, 140, 69–77.
- Xie, D., Yang, M., Zhang, S., Xu, M., Meng, J., Wu, C., Wang, Q., and Liu, S. 2023. In-situ utilization of nitrogen-rich wastewater discharged from a biotrickling filter as a moisture conditioning agent for composting: Insights into nitrogen transformation behavior and microbial mechanism. *Bioresource Technology*, 369, 128362.
- Xu, M., Sun, H., Yang, M., Chen, E., Wu, C., Gao, M., Sun, X., and Wang, Q. 2023. Effect of biodrying of lignocellulosic biomass on humification and microbial diversity. *Bioresource Technology*, 384(May), 129336.
- Xu, M., Yang, M., Song, N., Xie, D., Meng, J., Gao, M., Wang, Q., and Wu, C. 2022. Biodrying of biogas residue: Maturity and microbial diversity assessment. *Journal of Environmental Chemical Engineering*, 10(6), 108757.
- Yaman, C. 2020. Investigation of greenhouse gas emissions and energy recovery potential from municipal solid waste management practices. *Environmental Development*, 33, 100484.
- Yasmin, N., Jamuda, M., Panda, A. K., Samal, K., and Nayak, J. K. 2022. Emission of greenhouse gases (GHGs) during composting and vermicomposting: Measurement, mitigation, and perspectives. *Energy Nexus*, 7, 100092.
- Yoro, K. O., and Daramola, M. O. 2020. CO₂ emission sources, greenhouse gases, and the global warming effect. In *Advances in Carbon Capture: Methods, Technologies and Applications* (pp. 3–28). Elsevier.
- Yuan, J., Zhang, D., Ma, R., Wang, G., Li, Y., Li, S., Tang, H., Zhang, B., Li, D., and Li, G. 2019. Effects of inoculation amount and application method on the biodrying performance of municipal solid waste and the odor emissions produced. *Waste Management*, 93, 91–99.
- Zaman, B., Oktiawan, W., Hadiwidodo, M., Sutrisno, E., and Purwono. 2018a. Bio-drying technology of solid waste to reduce greenhouse gas. *E3S Web of Conferences*, 73.
- Zaman, B., Oktiawan, W., Hadiwidodo, M., Sutrisno, E., and Purwono, P. 2018b. Desentralisasi pengolahan limbah padat rumah tangga menggunakan teknologi biodrying. *Jurnal Pengelolaan Lingkungan Berkelanjutan (Journal of Environmental Sustainability Management)*, 1(3), 18–24.
- Zaman, B., Oktiawan, W., Hadiwidodo, M., Sutrisno, E., and Purwono, P. 2021a. Calorific and greenhouse gas emission in municipal solid waste treatment using biodrying. *Global Journal of Environmental Science and Management*, 7(1), 33–46.
- Zaman, B., Oktiawan, W., Hadiwidodo, M., Sutrisno, E., and Purwono, P. 2021b. Calorific and

- greenhouse gas emission in municipal solid waste treatment using biodrying. *Global Journal of Environmental Science and Management*, 7(1), 33–46.
- Zaman, B., Samadikun, B. P., Hardyanti, N., and Purwono, P. 2021. Waste to energy: calorific improvement of municipal solid waste through biodrying. *Environmental and Climate Technologies*, 25(1), 176–187.
- Zeng, K., Gauthier, D., Li, R., and Flamant, G. 2017. Combined effects of initial water content and heating parameters on solar pyrolysis of beech wood. *Energy*, 125, 552–561.
- Zhang, J., Wang, Y., Yu, D., Tong, J., Chen, M., Sui, Q., ChuLu, B. H., and Wei, Y. 2017. Who contributes more to N₂O emission during sludge bio-drying with two different aeration strategies, nitrifiers or denitrifiers? *Applied Microbiology and Biotechnology*, 101(8), 3393–3404.
- Zhao, X., Dang, Q., Zhang, C., Yang, T. X., Gong, T., and Xi, B. 2023. Revisiting organic waste-source-dependent molecular-weight governing the characterization within humic acids liking to humic-reducing microorganisms in composting process. *Journal of Hazardous Materials*, 442, 130049.