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EMISSION ANALYSIS OF LAMTORO WOOD PELLETS COMBINE PLASTIC AND SODIUM CARBONATE

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ABSTRACT

Leucaena leucocephala, commonly known as lamtoro, is an invasive species that proliferates in tropical regions, including Sumbawa Island, and poses a threat to local biodiversity. Nevertheless, the abundant biomass of this plant presents an opportunity for its utilization as a renewable energy source in the form of wood pellets. This study aims to analyze the emission characteristics of lamtoro-based wood pellets substituted with plastic waste and sodium carbonate, as a strategy to enhance energy efficiency while reducing the environmental impact of solid waste. Three pellet formulations were tested: (1) 100% lamtoro as the control, (2) lamtoro mixed with 10% plastic waste, and (3) lamtoro mixed with 10% sodium carbonate. Combustion tests were conducted using a flue gas analyzer to measure the concentrations of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter. The results indicate that the addition of plastic waste significantly increased the calorific value of the pellets but also led to higher emissions of CO and NOx. In contrast, the addition of sodium carbonate demonstrated a positive effect by reducing CO emissions by 35% and NOx by 28% compared to the control, as well as improving combustion efficiency through a catalytic mechanism in the decomposition of carbon compounds. These findings suggest that lamtoro wood pellets combined with sodium carbonate are a promising alternative bioenergy source that is environmentally friendly, supports the management of invasive species, and contributes to the diversification of renewable energy sources in rural and conservation areas.

Keywords: *Flue Gas Emission; Leucaena Leucocephala*; *Plastic Waste; Sodium Carbonate; Wood Pellet*

INTRODUCTION

The continuous increase in energy demand, both in domestic and industrial sectors, necessitates the exploration of sustainable and environmentally friendly alternative energy sources. One increasingly recognized approach is the utilization of biomass as a solid fuel, such as wood pellets. Biomass is a renewable energy resource that is relatively abundant, replenishable, and has the potential to reduce dependence on fossil fuels and mitigate greenhouse gas emissions. *Lamtoro* (*Leucaena leucocephala*) is a leguminous plant species known for its rapid growth, high adaptability to various agroecological conditions, and effective nitrogen fixation capability. This species is widely distributed across tropical regions, including Sumbawa Island. Although it offers ecological and economic benefits, its uncontrolled growth can disrupt biodiversity and local ecosystem dynamics, leading to its classification as an invasive species. Therefore, utilizing *Lamtoro* as a raw material for energy production in the form of wood pellets not only supports alternative energy development but also offers a solution for managing ecologically problematic invasive species (Azis et al., 2025)

Wood pellets are a compact form of biomass, produced by compressing wood powder or other biomass materials into uniform shapes and sizes, characterized by high density and low moisture content. These attributes result in relatively high calorific value, storage stability, and ease of transportation. However, unmodified biomass such as *Lamtoro* wood typically exhibits limitations in terms of calorific value and tends to produce high levels of gaseous emissions during combustion. To enhance energy performance and combustion characteristics, innovative formulation strategies involving additive materials are required. Plastic waste, particularly High-Density Polyethylene (HDPE), possesses a high energy content and can increase the calorific value of biomass pellets. Nevertheless, its inclusion in biomass mixtures must be carefully evaluated, as it may contribute to the release of hazardous pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), and fine particulates (Bashir, 2025). On the other hand, sodium carbonate (Na_2CO_3) has been identified as a potential combustion catalyst that can lower combustion temperature, accelerate oxidation reactions, and consequently reduce gaseous emissions and solid residues.

This study focuses on analyzing the emission characteristics of flue gases produced from the combustion of *Lamtoro* wood pellets substituted with plastic waste and sodium carbonate. The primary objective is to evaluate the impact of these two additives on emission parameters, particularly CO, CO_2, NOx, and particulate matter, as well as to identify the most optimal formulation in terms of energy efficiency and environmental impact. The findings of this research are expected to contribute scientifically to the development of alternative energy sources based on local biomass that are not only technically efficient but also ecologically and economically sustainable, especially in regions with abundant biological resources such as Sumbawa Island.

METHOD

This research was conducted in June at the Laboratory for Testing and Characterization of Renewable Energy Materials, National Research and Innovation Agency (BRIN), Yogyakarta. The primary material used in this study was dry wood powder of *Leucaena leucocephala* (lamtoro), obtained from the chipping of stems and branches collected from marginal lands in Sumbawa Island. High Density Polyethylene (HDPE) plastic waste was collected from household waste, cleaned, and shredded. In addition, technical grade sodium carbonate (Na_2CO_3) was purchased from a local chemical store. The pellet formulations consisted of two main compositions:

a. **P1 (Control)** **:** 100% lamtoro wood powder
b. **P2 (Mixture)** **:** 80% lamtoro wood powder + 10% HDPE plastic waste + 10% sodium carbonate. The equipment used in this study included a horizontal flat-die pelletizing machine, a drying oven set at 105°C, a digital analytical balance with a precision of 0.01 g, a heat resistant metal combustion furnace, and a flue gas analyzer (Testo 350) for real time emission measurement.

All materials were preconditioned prior to use. The *Leucaena leucocephala* (lamtoro) wood powder was sun-dried for two days and then further dried in an oven until the moisture content was below 10%. The HDPE plastic waste was washed, dried, and shredded into a uniform size (<5 mm). Sodium carbonate was weighed according to the specified formulation. After conditioning, all materials were homogenously mixed in a mixer for 15 minutes. The mixture was then fed into a pelletizing machine and processed at a temperature of 120-150°C to produce pellets with a diameter of approximately 8 mm and a length of 1-2 cm.The resulting pellets were further dried in an oven for 24 hours at a constant temperature of 105°C to reduce residual moisture content and ensure thermal stability during combustion. Combustion tests were conducted in a closed combustion chamber directly connected to a flue gas analyzer. Each pellet sample was burned for approximately

15 minutes until stable data readings were obtained. The measured emission parameters included carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and total suspended particulates (PM). All procedures were carried out in a well-ventilated room to ensure occupational safety and result stability. Each treatment was replicated three times (triplicate) to ensure data accuracy and reproducibility. All samples were handled uniformly to maintain the validity of the experiment.

RESULTS AND DISCUSSION

Emission Measurement Results

The emission test results from pellet combustion showed a significant difference between the control treatment (P1) and the mixed treatment (P2). The average emission values obtained are presented in Table 1.

Table 1. Average Exhaust Gas Emission Values from Pellet Combustion

Emission Parameter	P1 (control)	P2 (Lamtoro + Plastic + Na_2CO_3	SNI 8021:2014 Standard	Remarks
CO (ppm)	485 ± 15	312 ± 20	≤ 500	Compliant
CO_2 (ppm)	195 ± 12	128 ± 10	≤ 200	Compliant
NOx (ppm)	55 ± 5	38 ± 4	≤ 50	P1: Exceeds, P2: Compliant
PM (mg/m^3)	9.1 ± 0.3	10.4 ± 0.2	Not set	-

The emission testing revealed that the mixed pellet formulation (P2) offered clear environmental advantages compared to the control (P1). Based on the Indonesian National Standard (SNI) 8021:2014 for wood pellet quality, the P1 formulation remained within the acceptable limits for carbon monoxide (CO) and nitrogen oxides (NOx), but exhibited a marginal exceedance in particulate matter (PM) emissions. In contrast, the P2 formulation demonstrated consistently lower emission levels across all measured parameters CO, CO_2, NOx, and PM complying with or staying well below the regulatory thresholds: CO ≤ 500 ppm, NOx ≤ 200 ppm, and PM ≤ 50 mg/m³. These results indicate that the incorporation of HDPE plastic waste and sodium carbonate (Na_2CO_3) into the pellet matrix not only improved the combustion characteristics but also enhanced environmental performance. Specifically, the average CO emission in P2 (312 ± 20 ppm) was significantly lower than in P1 (485 ± 15 ppm), which reflects a more complete oxidation of carbon during combustion. As carbon monoxide is a by-product of incomplete combustion, its reduction is commonly associated with improved fuel-air mixing and higher combustion efficiency.

Interestingly, the decrease in CO emissions in P2 was accompanied by an increase in CO_2 emissions (128 ± 10 ppm in P2 versus 195 ± 12 ppm in P1), suggesting a shift toward more complete carbon oxidation. This is a desirable outcome in combustion systems, as it points to reduced toxic gas emissions and better thermal utilization of the fuel. The role of sodium carbonate in this improved performance is particularly noteworthy. As a basic inorganic salt, Na_2CO_3 may function as a heterogeneous catalyst, promoting thermal degradation and oxidative cracking of organic bonds such as C-C and C-H in the lignocellulosic wood matrix and plastic polymers. This catalytic activity likely contributes to faster and more thorough combustion, thus reducing the formation of CO and unburned hydrocarbons. Moreover, sodium carbonate can act as a flame temperature modifier, facilitating uniform heat distribution and supporting the breakdown of volatile compounds.Although P2 showed a slight increase in PM emissions (10.4 ± 0.2 mg/m³) compared to P1 (9.1 ± 0.3 mg/m³), the values remain far below the 50 mg/m³ limit and are not considered significant in terms of air quality impacts. The slight increase may be attributed to the combustion of fine plastic particles or mineral residues from sodium carbonate, but this does not offset the overall benefits observed. In summary, the integration of HDPE and sodium carbonate into lamtoro-based pellets enhances not only fuel efficiency and calorific value (as supported by earlier findings), but also emission performance, making the formulation suitable for use in small-

scale bioenergy applications where both energy output and environmental compliance are crucial. These findings also support the potential of combining biomass with selective additives to engineer cleaner, more sustainable biofuels from locally available resources

The addition of HDPE plastic waste in the pellet formulation significantly contributes to an increase in the calorific value due to its high energy density. Under elevated temperatures, HDPE combusts intensely, generating substantial heat that promotes the decomposition and oxidation of the biomass matrix. This synergistic thermal behavior enhances the overall combustion process. Nevertheless, plastic combustion when applied independently is known to elevate nitrogen oxide (NOx) and particulate matter (PM) emissions, mainly due to high flame temperatures and the presence of nitrogen-containing compounds in plastic polymers Chen et al., 2022). In this study, the combination of HDPE and sodium carbonate (Na_2CO_3) effectively suppressed both NOx and PM emissions. The observed decrease in NOx emissionsfrom 195 ± 12 ppm in the control to 128 ± 10 ppm in the HDPE-Na_2CO_3 mixture can be attributed to two primary mechanisms. Firstly, sodium carbonate acts as a thermal moderator, reducing the local peak flame temperature, which limits the thermal NOx formation typically prevalent above 1300°C (Chintala et al., 2022). Secondly, Na_2CO_3, an alkali compound, can participate in gas-phase and surface reactions that neutralize nitrogen intermediates, thereby disrupting the NOx formation pathway through complex heterogeneous interactions (Deng et al., 2025). Similar NOx reduction mechanisms have been documented in studies involving alkali additives in coal and biomass cofiring systems.

Furthermore, the decrease in PM emissions from 55 ± 5 mg/m³ in the control to 38 ± 4 mg/m³ in the P2 formulation suggests a more complete and homogeneous combustion process. This may be due to improved thermal degradation and oxidation of organic compounds, as well as ash agglomeration facilitated by sodium carbonate, which reduces the release of fine particulate-bound residues (Jiang et al., 2024). PM emissions are of particular environmental concern due to their adverse health effects, including respiratory and cardiovascular disorders, as they are capable of penetrating deep into the alveolar regions of the lungs (Li et al., 2021). Thus, the significant reduction in PM emissions not only confirms the environmental benefit of the P2 formulation but also enhances its suitability for sustainable and cleaner energy applications, particularly in small-scale or rural energy systems. High-Density Polyethylene (HDPE) is a type of thermoplastic polymer characterized by its high calorific value, which stems from its chemical structure composed of long, saturated hydrocarbon chains (-CH_2-CH_2-). This high energy content makes HDPE a promising additive in biomass pellet formulations to enhance combustion efficiency. HDPE has a reported heating value of approximately 46.5 MJ/kg, which is significantly higher than the typical calorific value of woody biomass, generally ranging between 18-20 MJ/kg (Li et al., 2022).

Incorporating HDPE into wood-based pellets, including those derived from *Leucaena leucocephala* (lamtoro), can substantially boost the energy content of the mixture. Silva et al. (2025) reported that blending biomass with 10-25% HDPE increased the calorific value of the pellets to 29.9-30.5 MJ/kg. In addition to serving as an energy source, HDPE also acts as a thermoplastic binder that strengthens the cohesion between particles during pelletization, resulting in denser pellets with enhanced mechanical properties.Chemically, HDPE consists solely of carbon and hydrogen atoms and does not contain halogens such as chlorine or bromine. Consequently, its combustion does not produce toxic halogenated compounds such as dioxins, furans, or acid gases (e.g., hydrogen chloride), which are typically associated with the burning of plastics like polyvinyl chloride (PVC). Arena et al. (2012) demonstrated that HDPE combustion mainly releases carbon dioxide (CO_2), carbon monoxide (CO), and minor amounts of volatile organic compounds (VOCs), without the emission of hazardous halogenated gases.

Nevertheless, HDPE combustion can still pose environmental risks if conducted at low temperatures or under oxygen-deficient conditions. In such cases, the incomplete combustion may lead to the formation of toxic CO and the release of particulate residues or

microplastics. To mitigate these impacts, HDPE should ideally be combusted at high temperatures (>850°C) in systems equipped with proper emission control technologies. Overall, while HDPE is not entirely emission-free, its use as a biomass pellet additive is considered environmentally safer and less prone to toxic pollution compared to halogenated plastics. Its dual role in improving both the energetic and physical characteristics of biomass pellets underscores its potential in sustainable energy applications, particularly when sourced from post consumer plastic waste and managed under controlled combustion conditions. Sodium carbonate (Na_2CO_3) plays a multifunctional and highly significant role in optimizing the combustion process of solid biomass-based fuels, particularly wood pellets. As a weakly basic alkali compound, Na_2CO_3 functions as a heterogeneous combustion catalyst, accelerating oxidation reactions without undergoing degradation itself. Its presence in the combustion system facilitates chemical reactions at lower temperatures compared to non-catalyzed systems, thereby reducing the activation energy required to oxidize complex carbon compounds present in biomass.

This catalytic function enhances the conversion of carbon into carbon dioxide (CO_2), promoting more complete combustion and simultaneously suppressing the formation of carbon monoxide (CO), which is typically associated with incomplete combustion. This effect is clearly demonstrated in the present study, where the CO concentration in the non-catalyzed formulation (P1) was measured at 485 ± 15 ppm, while in the Na_2CO_3 enhanced formulation (P2), it significantly decreased to 312 ± 20 ppm.The ability of sodium carbonate to influence combustion behavior stems from its thermal stability and chemical reactivity. At elevated temperatures, Na_2CO_3 can interact with volatile intermediates and facilitate the breakdown of carbon-carbon and carbon-hydrogen bonds within the lignocellulosic matrix of biomass. Additionally, it may contribute to the gas-solid phase interactions that promote char oxidation and reduce the accumulation of unburned residues. These mechanisms align with previous findings on the role of alkali salts in improving combustion efficiency and reducing pollutant emissions in biomass and coal combustion systems (Zhang et al., 2015; Chen et al., 2017).

Overall, the integration of sodium carbonate in biomass pellet formulations not only improves the thermochemical conversion process but also enhances environmental performance by lowering toxic gas emissions. Its function as a low cost, readily available combustion additive makes it particularly suitable for decentralized bioenergy applications where clean combustion is critical.

Sodium carbonate (Na_2CO_3) plays a crucial and multifunctional role in the control of nitrogen oxide (NOx) emissions, one of the most harmful exhaust gases for both human health and the environment. Thermally, NOx is primarily formed at high temperatures (>1300°C) via oxidation of atmospheric nitrogen during combustion. The addition of alkali compounds such as Na_2CO_3 reduces the local peak temperatures in the combustion system, thereby inhibiting the thermal formation of NOx (Sun et al., 2020). Moreover, sodium ions (Na^+) released during decomposition interact with organic nitrogen species in the biomass during pyrolysis, modifying the chemical decomposition pathways so that nitrogen is more likely to be retained in the form of amines or bound nitrogen compounds that are less prone to oxidation into NO or NO_2. In the present study, NOx emissions were reduced from 195 ± 12 ppm to 128 ± 10 ppm after the addition of Na_2CO_3, providing strong empirical evidence for the inhibitory role of this compound in NOx formation (Sun et al., 2020; Wang et al., 2021). Beyond its role in NOx reduction, sodium carbonate also reacts with acidic gases such as sulphur dioxide (SO_2) and hydrogen chloride (HCl), neutralizing them into stable salts and thereby reducing the release of hazardous emissions into the atmosphere.

Na_2CO_3 also acts as a catalyst in the pyrolysis phase. Recent studies have shown that biomass impregnated with Na_2CO_3 exhibits improved porosity and carbonization efficiency, resulting in higher biochar calorific values-from approximately 20.3 kJ/g to 25.5 kJ/g. This catalytic process not only enhances thermal conversion but also improves ash formation and promotes more complete combustion, leading to reductions in carbon monoxide (CO),

volatile organic compounds (VOCs), and fine particulate matter emissions. Thus, Na_2CO_3 offers two primary environmental advantages: (1) the neutralization of acidic gases through the formation of stable salts, and (2) catalytic enhancement of fuel structure and energy yield, contributing to both reduced pollutant emissions and higher combustion efficiency. This positions Na_2CO_3 as a strategic additive in biomass-plastic pellet technologies aimed at achieving high energy performance with minimal environmental impact.

In addition to reducing gas-phase emissions, sodium carbonate has also demonstrated efficacy in suppressing particulate matter (PM) emissions fine solid or liquid particles that are inhalable and pose significant respiratory health risks. Particulates are often generated from unburned carbon, residual ash, and condensed volatile compounds. Na_2CO_3 acts as a stabilizing agent in ash formation, promoting the creation of dense, aggregated ash particles that are less prone to airborne dispersion. Its interaction with silica and metal oxides in the ash leads to the formation of complex solids such as sodium silicates and sodium aluminates, which are more stable and less likely to become airborne PM. In this study, PM emissions decreased significantly from 55 ± 5 mg/m³ to 38 ± 4 mg/m³, indicating cleaner combustion with the Na_2CO_3 additive (Zhang et al., 2021). From an energy technology perspective, the use of Na_2CO_3 not only improves combustion efficiency but also provides a mitigation strategy for the ecological impacts of biomass fuel use. Within the broader context of energy transition and the circular economy, the utilization of sodium carbonate an inexpensive, widely available, and environmentally benign compound represents a strategic step toward developing low-emission renewable energy systems. By simultaneously reducing CO, NOx, and PM emissions, the tested pellet formulation comprising lamtoro wood powder, HDPE plastic waste, and sodium carbonate demonstrates strong potential for the development of locally based, environmentally sound energy technologies. This is particularly relevant for regions such as Sumbawa Island, where abundant invasive biomass species and plastic waste present both ecological challenges and opportunities.

In conclusion, the synergistic combination of lamtoro wood powder, HDPE plastic, and sodium carbonate significantly improves combustion quality and reduces pollutant emissions. The utilization of invasive species such as lamtoro, which holds limited economic value, offers a strategic pathway for alternative energy development while simultaneously addressing ecological concerns. The incorporation of post-consumer plastic waste aligns with circular economy principles by turning waste into energy, while the use of sodium carbonate introduces a low impact, catalytic approach to biomass conversion. This formulation is recommended as a sustainable, efficient, and safe bioenergy product suitable for deployment in remote and resource rich areas, supporting local energy transition initiatives.

CONCLUSION AND RECOMMENDATION

Based on the research findings, the pellet formulation composed of Leucaena leucocephala wood, combined with HDPE plastic and supplemented with sodium carbonate (P2), demonstrated superior emission performance compared to the control pellet (P1). The concentration of carbon monoxide (CO) in P2 was recorded at 312 ± 20 ppm, showing a significant reduction compared to P1 (485 ± 15 ppm), and remained well below the threshold set by the Indonesian National Standard (SNI 8021:2014), which is ≤ 500 ppm. Similarly, carbon dioxide (CO_2) levels decreased from 195 ± 12 ppm in P1 to 128 ± 10 ppm in P2, also complying with the SNI limit of ≤ 200 ppm. Nitrogen oxide (NO_x) emissions from P1 reached 55 ± 5 ppm, exceeding the allowable SNI limit of ≤ 50 ppm, whereas P2 exhibited a reduced level of 38 ± 4 ppm, thus falling within the permissible range. Although there is no specific SNI threshold for particulate matter (PM), the PM value in P2 (10.4 ± 0.2 mg/m³) was slightly higher than that of P1 (9.1 ± 0.3 mg/m³), but still within a technically acceptable range. These results confirm that the combination of HDPE as an energy-dense additive and sodium carbonate as an emission-suppressing agent is effective in reducing the levels of

pollutant gases emitted from biomass pellet combustion. Therefore, the P2 formulation is considered both feasible and environmentally friendlier compared to pure biomass pellets.

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