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EMISSION PROFILES AND TOXICITY ASSESSMENT OF SAWDUST-WASTE PAPER BRIQUETTES FOR CLEAN HOUSEHOLD ENERGY

Kwadwo Boakye Boadu[1]*, Emmanuella Anthonia Yaa Benewaa Antwi[1], Bernard De-Graft Sackey[1], Rogerson Anokye[1], Michael Ansong[2]

[1]Department of Wood Science and Technology, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

[2]Department of Silviculture and Forest Management, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

***Corresponding author: kbboadu.canr@knust.edu.gh**

ABSTRACT

The study examined the emission characteristics and toxicity index of biomass briquettes produced from sawdust and waste paper, an area that remains relatively underexplored in briquette research. Five different sawdust–paper blends were prepared and analysed for carbon monoxide (CO), carbon dioxide (CO_2), particulate matter ($PM_{2.5}$), and an overall toxicity index. These properties were examined under simulated household cooking conditions using standardized experimental procedures. The results indicated that increasing the proportion of waste paper in the briquettes consistently reduced CO, CO_2, and $PM_{2.5}$ emissions. Accordingly, the 100% waste paper formulation exhibited the cleanest combustion profile. In contrast, briquettes with higher sawdust content emitted significantly greater levels of CO, CO_2, and $PM_{2.5}$. Importantly, all briquette samples emitted CO and CO_2 concentrations below internationally accepted indoor safety thresholds. Only the 100% waste paper briquettes and the 30/70 sawdust-paper blends met the U.S. EPA 24-hour $PM_{2.5}$ limit of 35 µg/m^3. These findings are consistent with previous studies on biomass combustion and provide empirical support for substituting conventional wood-residue biomass with paper-based waste. The study provides important insights into optimiszing clean-burning biomass fuels in alignment with the Sustainable Development Goals (SDGs), particularly those related to clean energy, public health, responsible production, and climate action. Overall, the findings demonstrate that paper-dominant briquettes offer a practical pathway for reducing indoor air pollution while advancing circular waste management.

Keywords: Biomass briquettes, emission characteristics, indoor air pollution, sustainable energy, waste paper.

INTRODUCTION

As the search for sustainable energy resources becomes increasingly significant across the globe, the use of energy from forest and agricultural wastes has increased. Biomass briquettes have come to be viewed as viable alternatives to fuelwood and traditional fossil fuels in the family of biofuels. The problem is particularly significant in developing nations where deforestation, inefficient management of waste, and air pollution are still common. Briquetting may be described as the act of pressing/densification of low-density organic waste/biomass materials (charcoal fines, sawdust, agricultural wastes, paper) into high-density fuel briquettes (Kaliyan and Morey, 2009; Rousset *et al*., 2011). Briquetting is commonly viewed as an inexpensive and technologically simple method of producing clean cooking energy in developing nations (Sotannde *et al*., 2010). For example, in economies like Kenya and Ghana where charcoal and fuelwood take major positions in the household energy mix, briquettes may serve as a sustainable alternative that would reduce deforestation and provide employment through waste valorisation.

Sawdust is a byproduct of wood processing. This and waste paper are two of the most common types of waste available, but underused. These products have considerable bioenergy potential. Previous researchers (e.g., Kong *et al*., 2012; Odusote *et al*., 2016) have explored the production of briquettes using a mixture of these two materials due to their complementary characteristics. While the fibrous nature of the waste paper enhances binding, the sawdust helps in enhancing the energy content and the density of the fuel mixture. Even though there has been considerable progress in improving the physical and mechanical properties (including calorific value, density, and longevity) of briquettes made from waste paper and sawdust (Lela *et al*., 2016), not much has been done regarding the environmental aspects of the process, including emission of gases during burning.

Biomass combustion causes CO, CO_2, $PM_{2.5}$, and volatile organic compounds (VOCs) to be emitted (Boadu *et al*., 2022). Among all these pollutants, CO and $PM_{2.5}$ pose considerable health and environmental risks (WHO, 2014; EPA, 2024). According to Im *et al*. (2023), $PM_{2.5}$ and CO, especially, have been identified as important sources of indoor air pollution and cause more than 3 million premature deaths each year. The majority of these fatalities happen in low-income families that use solid fuel extensively (Im *et al*., 2023; Gordon *et al*., 2014). The pollutants worsen the symptoms of diseases related to the respiratory and cardiovascular systems. According to Laiman *et al*. (2022), they become especially dangerous in places with poor ventilation since they can build up to harmful levels there.

The absence of comparative data for the different ratios of sawdust and waste paper briquettes restricts our knowledge of how to formulate a safer composition for domestic applications. In accordance with the information provided by Keita *et al*. (2018), there is a major research gap with respect to the characterisation of emissions for the different briquette compositions, especially within the West African settings. The current research was conducted in order to fill the aforementioned gap and provide an emission profile for the briquettes prepared from the different ratios of sawdust and waste paper. Namely, the amount of CO, CO_2, and $PM_{2.5}$ was determined, and a toxicity index was estimated in order to evaluate the possible health risks. The uniqueness of the research lies in the focus on emission analysis with the aim of providing a safe and health-oriented briquette composition. The study's findings contribute to the broader discourse on clean household energy and offer insights that are relevant to environmental health, sustainable waste management, and policy.

MATERIALS AND METHODS (METHODOLOGY)

Raw Material Collection and Processing

The waste paper was sourced from printing and publishing shops at the Asafo printing enclave in Kumasi [Latitude: 6.687284386795921, Longitude: -1.6117233037948608], the capital of the Ashanti region of Ghana. Asafo is considered the hub of package printing businesses in the city with a host of small-, medium-, and large-scale printing firms, book binding shops, stationery shops, and graphic design companies (Okyere, 2017). Substantial amounts of waste are generated by the package printing industry, which can be used as valuable resources for briquette production. The waste paper was kept in a dry condition at room temperature for further processing.

The sawdust was collected from the Sokoban Wood Village (637.2640N, 00136.2790W), which is a timber processing enclave in Kumasi (Antwi-Boasiako *et al*., 2018; Boadu *et al*., 2018). According to the literature, over 100 to 150 mt of sawdust are produced at the Sokoban Wood Village daily (Millennium Cities Initiative, 2013). This volume of sawdust is dumped or burnt as waste with serious environmental challenges (Antwi-Boasiako *et al*., 2018). The collected sawdust comprised material from several wood species. It was initially sieved using a 2 mm mesh screen at the wood workshop of the Department of Wood Science and Technology of the Kwame Nkrumah University of Science and Technology, Kumasi. This was done to remove the larger wood particles, wood bark, and other foreign materials. This was needed to ensure a uniform particle size distribution, which is suitable for briquette production. Uniformity in size enhances the packing density, bonding efficiency, and consistency in the combustion of the final briquettes. The sawdust was dried in the sun for 48 hours after sieving to reduce its moisture content (MC) to below 12% based on the recommended MC for briquette manufacturing (Grover and Mishra, 1996; Kaliyan and Morey, 2009). The dried sawdust was then stored in sealed polyethylene bags to prevent reabsorption of moisture from the environment until it was ready for use. The sawdust was not chemically pretreated or mixed with any additives since the study sought to evaluate emissions from unmodified and commonly available biomass residues.

The waste paper was manually shredded and soaked in water for 3 hours to enable the fibres to soften (Tangsathit and Sanongraj, 2012). This was followed by mechanical pulping to produce a homogeneous slurry.

Pulping and Briquette Formation

The binding agent used in the briquette production was cassava starch. The binder was prepared by dissolving 200g of starch in water and boiling until a viscous gel was formed, following the standard procedures earlier described by Mitchual *et al*. (2013). Five briquette formulations were prepared by varying the ratio of pulp to sawdust as follows:

A – 100 % paper pulp

B – 70 % paper pulp, and 30% sawdust

C – 50 % paper pulp, and 50% sawdust

D – 30% paper pulp, and 70% sawdust

E – 100% sawdust

These ratios were selected based on similar formulations used in previous studies by Odusote and Fodeke (2016) and Adeyanju (2021). The authors investigated other properties of briquettes composed of varying proportions of waste paper and sawdust.

Each 500g blend of sawdust and waste paper was mixed with 20% w/w cassava starch (Aransiola *et al*., 2019) and manually compressed at 4 MPa (Brunerová *et al*., 2024; Morales-Máximo *et al*., 2025) using a metallic screw press at room temperature.

Where clumping of the sawdust was observed, it was lightly mixed by hand before it was blended with pulp and binder. The briquettes (Figure 1) were left to set for 48 hours at the Faculty of Renewable Natural Resources Chemistry laboratory located at the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. They were then air-dried for three days to achieve optimal moisture reduction (Odusote *et al*., 2016). Each formulation was replicated three times.

Figure 1: Briquettes formulated from waste paper and sawdust

Determination of the Emission Properties of the Briquette

The briquettes were combusted in a traditional charcoal stove, which was placed inside a specially designed chimney box to mimic typical household cooking conditions at the Cookstove Testing and Expertise Laboratory (C-Lab), which is located at the Technology Consultancy Centre (TCC) at KNUST. The emissions were measured using the Aprovecho Laboratory's Emissions Measurement System (LEMS) (Aprovecho Research Centre, USA). It has an exhaust hood with ductwork, a data acquisition system, and sensors for measuring the concentration of carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter ($PM_{2.5}$) emitted during combustion (Obeng *et al*., 2021). The sensors were positioned at the chimney outlet to capture the real-time concentrations of these gases during combustion. The LEMS software recorded and exported data to Microsoft Excel for preliminary processing.

Calculation of the Toxicity Index of Briquettes

A toxicity index, which indicates the potential health risk associated with emissions and can serve as an indicator of combustion cleanliness in terms of pollutant release, was calculated for each briquette type (Dula *et al*., 2024). The index was calculated as the quotient of the concentration of CO to the concentration of CO_2 in the exhaust gases (Robinson *et al*., 2010; Anca-Couce *et al*., 2017; Dula *et al*., 2024):

$$\text{Toxicity Index (TI)} = \frac{CO}{CO_2} \times 100$$

Data analysis

The data collected on the emission parameters (i.e., CO, CO_2, $PM_{2.5}$) and the derived toxicity index were analysed using IBM SPSS Statistics (version 25). The Completely Randomiszed Design (CRD) with five treatments (briquette formulations A to E) and three replications for each treatment was the experimental design used. Before performing the parametric statistical analysis, the assumptions that are fundamental to the use of one-way Analysis of Variance (ANOVA) were tested. The Normality of residuals was assessed using the Shapiro-Wilk test for each emission variable, and the visual inspection of Q-Q plots was also performed to confirm the distribution shape. The homogeneity of variances was assessed using Levene's test, with a p-value greater than 0.05 taken as evidence that the variance across groups was not significantly different. To ensure the independence of the observations, all the briquette formulations were independently prepared and randomly assigned with the emissions measured under consistent and controlled combustion conditions. Once these assumptions were verified, a one-way ANOVA was conducted to determine any statistically significant differences in the emission levels among the different briquette formulations. The level of significance was set at $\alpha = 0.05$. Where the ANOVA results were significant, post hoc pairwise comparisons were done using Tukey's Honestly Significant Difference (HSD) test to detect which formulations differed. Descriptive statistics, including means and standard errors, were calculated for all the measured parameters, and the results were presented in scatter plots.

RESULTS

Emission Characteristics of Briquette Formulations

Carbon monoxide

There was a significant difference ($F_{4,10}$ = 15.65, p = 0.00) in the carbon monoxide concentrations from the different briquette samples. The 70% sawdust and 30% paper briquettes released the highest CO concentration (12.4 ± 0.1 ppm), while the 100% paper briquettes had the lowest (6.9 ± 0.3 ppm) (Figure 2). The 100% sawdust briquette produced 11.8 ± 0.1 ppm of CO, which was substantially higher than the emissions recorded for paper-dominant formulations.

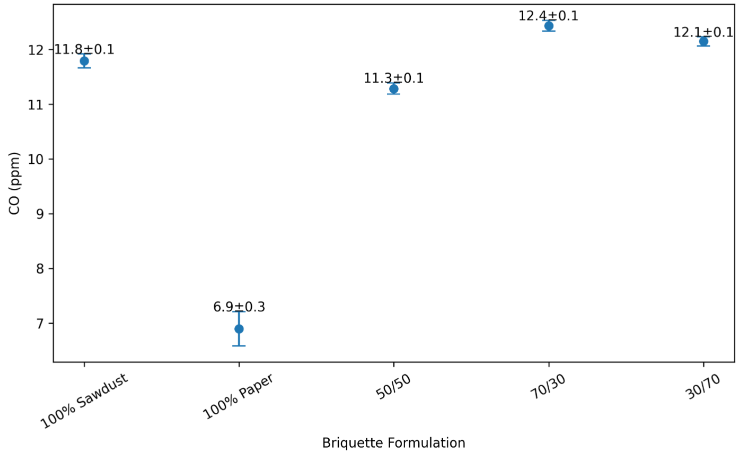

Figure 2: Concentration of Carbon monoxide (with standard errors) emitted from briquettes from different mix ratios of sawdust and waste paper

Carbon Dioxide (CO_2)

The carbon dioxide concentrations from the different briquette samples were significantly different ($F_{4,10}$ = 1146.48, p = 0.00). The 70/30 sawdust-paper blend briquettes produced the most CO_2 (2328.4 ± 4 ppm), followed by the 100% sawdust (2158 ± 15 ppm) (Figure 3). The 100% paper briquettes produced the lowest CO_2 emissions (1089.0 ± 27 ppm).

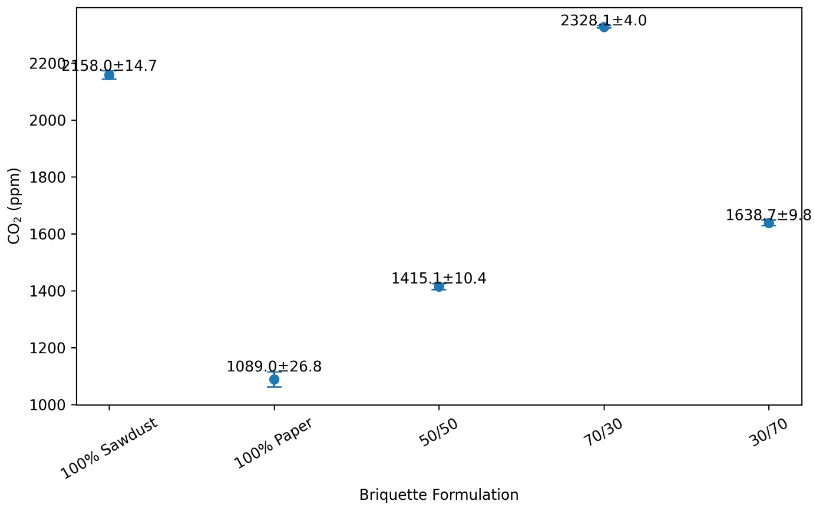

Figure 3: Concentration of Carbon dioxide (with standard errors) emitted from briquettes from different mix ratios of sawdust and waste paper

Particulate Matter

The particulate matter emissions also differed significantly among the different briquette samples ($F_{4,10}$ = 54788.68, p = 0.000). The 50/50 sawdust-paper blend briquettes generated the most $PM_{2.5}$ (63.6 ± 0.1 µg/m^3), while the 100% paper briquettes had the lowest (14.6 ± 0.0 µg/m^3) (Figure 4). The 70/30 sawdust-waste paper blend emitted higher $PM_{2.5}$ than the 30/70 sawdust-paper blend briquettes.

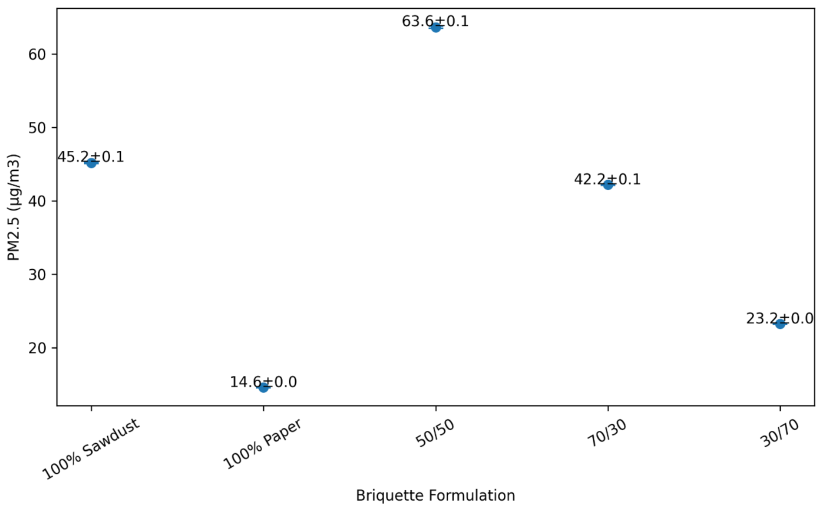

Figure 4: Concentration of particulate matter (with standard errors) emitted from briquettes from different mix ratios of sawdust and waste paper and toxicity index

Toxicity index

The results indicated a significant effect of briquette composition on the toxicity index at the 0.05 significance level ($F_{4,\,10}$ = 149.06, p = 0.001). The briquettes composed of 50% sawdust and 50% paper had the highest average toxicity index (0.79 ± 0.01), while those with 70% sawdust and 30% paper had the lowest (0.53 ± 0.0) (Figure 5).

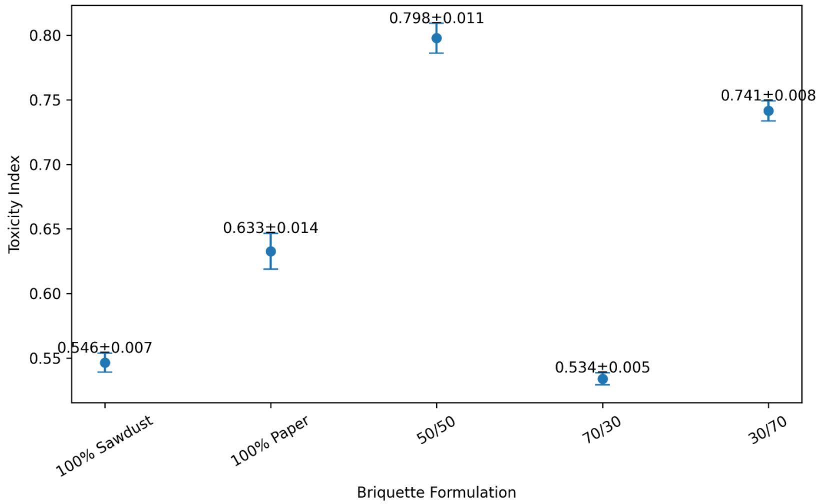

Figure 5: Toxicity index (with standard errors) of emissions from briquettes from different mix ratios of sawdust and waste paper

DISCUSSION

Emission Characteristics of Briquette Formulations

Carbon Monoxide (CO) Emissions

Carbon monoxide (CO) is a poisonous, colourless, and odourless gas, which is formed primarily from the incomplete combustion of fuels that contain carbon under low oxygen conditions (Wiinikka and Gebart, 2005; Lai *et al*., 2024). The study showed CO emissions ranging from 6.9 ± 0.3 ppm to 12.4 ± 0.1 ppm, with sawdust-dominant briquettes having greater CO emissions as compared to paper-dominant ones. This aligns with Imeh *et al*. (2017), who reported that loose biomass fuels containing high quantities of lignin, such as sawdust, are more prone to incomplete combustion, hence higher CO emissions. The lower CO emissions from waste paper briquettes may be attributed partly to differences in the chemical and physical characteristics of waste paper and sawdust. Waste paper consists predominantly of processed cellulosic fibres and generally contains less lignin than untreated woody biomass, which may favour more efficient oxidative degradation during combustion (Xu *et al*., 2021). In contrast, sawdust retains characteristics of the original wood, including lignin, extractives and moisture associated with the wood structure. These constituents may influence devolatilisation and combustion behaviour, and residual moisture can absorb heat during evaporation. These temporarily lower the combustion temperature and thereby create conditions that favour incomplete oxidation and CO formation. The presence of wood extractives may also contribute additional volatile compounds during thermal decomposition, potentially affecting the completeness of combustion. Unlike sawdust, waste paper has undergone pulping and other processing that substantially modifies the original fibre structure and removes or alters some wood constituents.

These differences between the relatively processed fibres of waste paper and the less-modified wood fibres in sawdust may therefore partly explain the lower CO emissions observed from the paper-rich briquettes. In addition, the fibrous characteristics of paper may promote more uniform combustion. Budzyń and Tora (2016) similarly demonstrated the potential of paper-industry residues as biomass fuels.

Generally, the emissions determined in this study fall within the range of 5–15 ppm for residential indoor air quality standards and well below the occupational limit of 50 ppm set by OSHA (Kupczewska-Dobecka and Czerczak, 2004). This indicates that all tested briquette formulations are appropriate for indoor use when ventilation is provided.

Carbon Dioxide (CO_2) Emissions

CO_2 is a principal product of complete combustion and a major greenhouse gas. During this study, the sawdust-rich briquettes produced the most CO_2 emissions of up to 2328 ± 4.0 CO_2 ppm, while the waste paper briquettes produced the least amount of emissions at 1089 ± 26.8 CO_2 ppm. This aligns with Glalah *et al*. (2024)'s observation that sawdust briquettes tend to emit more CO_2 because of their structure and how quickly they burn. Wardoyo *et al*. (2011) reported higher CO_2 emissions from denser woody biomass due to prolonged combustion and more extensive carbon oxidation. The increase in CO_2 for sawdust-dominant briquettes may reflect a more complete combustion process, particularly in oxygen-rich pockets of the burning mass. The waste paper briquettes, by contrast, emitted lower levels of CO_2, which can be linked to their lower fixed carbon and higher volatile matter content (Demirbas, 2004). Their structure facilitates a quicker combustion with reduced carbon retention.

Although the higher CO_2 levels produced by sawdust-rich samples demonstrate a relatively complete combustion, it also signals a higher carbon output. This could have implications for greenhouse gas emissions (Akinyemi and Olaiya, 2018). Thus, the higher CO_2 concentrations indicate a greater heating value of the fuel. However, the potential negative environmental impacts in the form of indoor air quality should receive more consideration. Nevertheless, all the types of briquettes tested emitted CO_2 well below OSHA's occupational exposure limit of 5000 ppm (Kupczewska-Dobecka and Czerczak, 2004). This confirms their appropriateness for enclosed environments.

Particulate Matter ($PM_{2.5}$)

One of the most harmful pollutants emitted by burning solid fuels is $PM_{2.5}$. It can cause major health issues by deeply penetrating the respiratory system (Han and Zhuang, 2020). In this study, sawdust-rich briquettes had the highest $PM_{2.5}$ emissions, while paper-based briquettes had the lowest. This pattern is consistent with research by Itoh *et al*. (2020), which demonstrated that ash content and volatile matter of the feedstock directly influence particulate formation. Similarly, ash-forming minerals and extractives are more abundant in sawdust. These elements considerably raise particulate emissions when combustion is suboptimal (Nussbaumer, 2003). In contrast, waste paper briquettes have a uniform texture and smaller particle size because of the paper-making process. These qualities probably enable more reliable combustion, which lowers the production of particulates (Sheng and Azevedo, 2005). Only the 100% paper briquettes and the 30/70 sawdust-waste paper blends met the US EPA's 24-hour average limit of 35 µg/m³ (EPA, 2024). The implications for public health, especially in biomass-dependent regions, are profound. These findings demonstrate how cleaner paper-based briquettes may reduce indoor air pollution and the health hazards associated with it.

Toxicity Index

Toxicity index is an aggregate inhalation exposure risk metric for briquette combustion. For the current study, briquettes with higher paper content all had lower toxicity indexes, thereby confirming their suitability for safer indoor use. The highest calculated toxicity index was found in a 50:50 sawdust-paper mixture. This suggests that multi-component mixtures can contaminate combustion uniformity and air-fuel distribution. This finding is in line with those of Al-qazzaz *et al*. (2024). The authors found that unbalanced feedstock ratios produce unstable flame temperatures and a high amount of pollutants. Although the 50:50 sawdust-waste paper mixture appears to be an equal blend of sawdust and waste paper, the difference in their combustion characteristics tends to make them burn in an unbalanced manner. This imbalance likely leads to higher emissions. Generally, the findings show that sawdust briquettes possess a less desirable emission pattern. Waste paper, as an available urban waste stream, has cleaner burning and is compatible with circular waste management principles.

Implications of Findings for Sustainable Development Goals (SDGs)

This study has implications that are relevant to several Sustainable Development Goals (SDGs). First, the remarkable reduction in particulate matter and carbon monoxide emissions from waste paper-based briquettes has a direct influence on SDG 3 (Good Health and Well-being). It mitigates household air pollution as well as the resultant health risks of respiratory and cardiovascular diseases. Cleaner fuels reduce the health impact for vulnerable groups, such as children and women in poor settings who are typically most exposed to indoor smoke. Guided under the umbrella of SDG 7 (Affordable and Clean Energy), the study supports the utilisation of low-cost and locally found materials like waste paper to produce sustainable energy. This not only reduces the dependency on traditional wood fuels but also promotes energy justice among off-grid populations. The recycling of waste also aligns well with SDG 12, which is titled Responsible Consumption and Production, by conserving resources and preventing municipal paper waste from entering landfills. Lastly, the reduction in carbon dioxide emissions, although modest, helps contribute to SDG 13 (Climate Action) by lowering the overall carbon footprint associated with home energy use, especially when cleaner-burning briquettes substitute more carbon-rich fuels such as firewood and charcoal.

Policy Implications and Recommendations

From an environmental management perspective, the study confirms the viability of waste-to-energy pathways through paper and sawdust. This pathway is supportive of climate goals and urban refuse containment. The research also encourages a shift from considering only the calorific value or compressive strength to an emissions-based evaluation of domestic fuels. The findings of this study also have policy implications at key levels in energy access, public health, industrialization, employment, and the environment. To begin with, there is a need to have national standards defining acceptable emission levels for biofuels in homes. These standards must include limits for CO, $PM_{2.5}$, and CO_2 emissions, which will enable certification of clean-burning briquettes as well as influence consumer choices. Such information can be used by governments and regulators to develop labelling schemes through which consumers can get informed about the health and environmental record of biomass fuels.

Secondly, enterprises that manufacture briquettes from recycled or agro-industrial waste should be given policy support in terms of subsidies or tax incentives. This will not only strengthen circular economy strategies but will also enhance access to clean energy in underdeveloped regions. Furthermore, incorporating emissions-tested briquettes into development partner or multilateral bank-funded public clean cooking programmes can proliferate adoption while maintaining safety. Such programmes should also facilitate the production of enhanced cookstoves with the capability to maximise combustion efficiency for different types of briquettes. Finally, capacity-building initiatives such as training small-scale producers, technical assistance in quality control, and micro-financing for equipment to make briquettes are critical. These will enable decentralised briquette production, encourage the establishment of employment opportunities, and enable communities to own their energy systems. Policymakers should therefore consider briquette production not just as an energy issue but a multi-dimensional opportunity cutting across health, waste management, economic development, and climate resilience.

Limitations of the Work and Future Research Directions

While this study provides valuable insights into the emission characteristics and toxicity index of briquettes produced from varying proportions of sawdust and waste paper, certain limitations should be acknowledged. First, the study focused primarily on emission-related parameters (CO, CO_2, $PM_{2.5}$) and a derived toxicity index, without evaluating key fuel performance indicators such as calorific value, burning rate, ignition time, and thermal efficiency. These parameters are essential for a comprehensive assessment of briquette quality and user acceptability. Furthermore, the study was limited to a single binder type (cassava starch) and a fixed binder proportion, which may influence both combustion behaviour and emissions. Future research should therefore explore the calorific values of the different sawdust–waste paper blends to better understand the energy potential of each formulation. This will also help to establish a balance between emission performance and fuel efficiency. Overall, addressing these areas in future work will contribute to the development of more efficient, cleaner, and sustainable biomass fuel alternatives.

CONCLUSION

This study presents an assessment of briquette emission behaviour and toxicity index across different sawdust-waste paper proportions. The findings provide empirical evidence that the chosen raw material significantly influences biomass briquette combustion emissions. Waste paper-dominant briquettes consistently released lower levels of carbon monoxide, carbon dioxide, and particulate matter than sawdust-dominant briquettes. Incorporating a toxicity index provides an integrated metric for evaluating health-related emission risks. These results confirm the public health and environmental advantages of using waste paper briquettes. They suggest a pathway to cleaner indigenous energy sources for low-income settings. The CO and CO_2 emissions of all briquette compositions were within internationally accepted indoor air quality limits, confirming their safety for indoor use. For particulate matter emissions, only the 100% paper briquettes and 30/70 sawdust-paper blends met the US EPA 24-hour average recommendation of 35 µg/m³. Equal proportions of paper and sawdust, however, were more variable and emitted higher levels, indicating that feed ratios would need to be optimised carefully. The broader applications of this study extend to sustainable waste management, clean cooking fuel technology, economic development, and climate change mitigation policy.

By converting urban waste to energy and assigning value to it, the study supports the circular economy and addresses some of the most important energy access challenges. Combining emission testing with fuel assessment in future studies would offer a pragmatic tool for policymaking, especially in countries seeking to transition toward cleaner domestic energy alternatives. Long-term performance, burn kinetics, and the scalability of paper-based briquettes across various stove technologies and user settings need to be investigated in future research.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest exists.

AUTHOR CONTRIBUTIONS

Conceptualisation: KBB and EAYBA; Data curation: KBB and EAYBA; Formal analysis: KBB and SBD; Investigation: KBB and EAYBA; Methodology: KBB, EAYBA, SBD, MA, RA; Supervision: KBB, MA, RA; Writing – original draft: KBB, EAYBA and SBD; Writing – review & editing: KBB, SBD, MA, RA

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