Scientific Reports
https://doi.org/10.1038/s41598-026-37608-6
Article in Press

Feasibility of cow-dung groundnut-shell composite as a decentralized renewable fuel for clean cooking

Received: 7 September 2025
Accepted: 23 January 2026
Published online: 02 February 2026

Cite this article as: Gautam S., Asirvatham L.G., Rakshith B.L. *et al.* Feasibility of cow-dung groundnut-shell composite as a decentralized renewable fuel for clean cooking. *Sci Rep* (2026). https://doi.org/10.1038/s41598-026-37608-6

Sneha Gautam, Lazarus Godson Asirvatham, Bairi Levi Rakshith & Chang-Hoi Ho

Feasibility of cow-dung groundnut-shell composite as a decentralized renewable fuel for clean cooking

Sneha Gautam[a], Lazarus Godson Asirvatham[b,c], Bairi Levi Rakshith[b,c], and Chang-Hoi Ho[d]

[a]Division of Civil Engineering, Karunya Institute of Technology and Sciences, Coimbatore 641114, Tamil Nadu, India

[b]Division of Mechanical Engineering, Karunya Institute of Technology and Sciences, Coimbatore 641114, Tamil Nadu, India

[c]Centre for Research in Material Science and Thermal Management, Karunya Institute of Technology and Sciences, Coimbatore 641114, Tamil Nadu, India

[d]Department of Climate and Energy Systems Engineering, Ewha Womans University, Seoul 03760, Republic of Korea

Corresponding Author: Sneha Gautam (snehagautam@karunya.edu) and Chang-Hoi Ho (hoch@ewha.ac.kr).

Abstract

Conventional biomass fuels (e.g., untreated firewood and raw cow dung cakes) continue to be the predominant household energy source in rural areas, but this can lead to serious indoor air pollution and associated health consequences. This study presents a cost effective, scalable, and environmentally friendly energy source derived from a mixture of locally available cow dung and groundnut shell powder. Fuel cakes are made in the form of a disc so that they could be used directly in already existing rural cookstoves, making them user-friendly and requiring minimal change in cooking habits. Four different composition ratios C1 (100% cow dung), C2 (75% cow dung + 25% groundnut shell), C3 (50% cow dung + 50% groundnut shell), and C4 (25% cow dung + 75% groundnut shell) are experimented. It is noted that the C4 ratio results in a 29.6% higher calorific value (19,700 ± 370 kJ kg^{-1}) compared to pure cow dung with significant emission reduction up to 43% of particulate matter ≤ 2.5 μm in diameter, 29% of carbon dioxide, and 53% formaldehyde. The present study contributes directly to Sustainable Development Goal (SDG) 7 (affordable and clean energy) and SDG 13 (climate action), providing a realistic solution to reduce pollution, improve indoor air quality, and promote energy equity in disadvantaged populations.

Keywords: Air quality; Bio-composite fuel; Emission analysis; Cow dung; Groundnut shell; Renewable energy; Sustainable development

Nomenclature

Symbol / Term	**Description**	**Unit**
ΔT	Temperature rise during combustion	K
BC	Black carbon	–
C1	100% cow dung composition	–
C2	75% cow dung + 25% groundnut shell powder	–
C3	50% cow dung + 50% groundnut shell powder	–
C4	25% cow dung + 75% groundnut shell powder	–
C_b	Heat capacity of bomb	MJ K^{-1}
C_g	Concentration of gas	ppmv
CO	Concentration of carbon monoxide	ppmv
CO_2	Concentration of carbon dioxide	ppmv
$C_{PM2.5}$	Concentration of $PM_{2.5}$	µg m^{-3}
C_w	Heat capacity of water in calorimeter	kJ K^{-1}
FWER	Family-wise error rate (Tukey test)	–
GCV	Gross calorific value	kJ kg^{-1}
HCHO	Formaldehyde concentration	µg m^{-3}
$M_{PM2.5}$	Mass of $PM_{2.5}$ collected	µg
m_s	Mass of fuel sample	kg
PM	Particulate matter	–
$PM_{2.5}$	Particulate matter ≤ 2.5 µm in diameter	µg m^{-3}
Q_c	Correction for heat loss	kJ
SDG	Sustainable Development Goals	–
V_a	Volume of air sampled	L
V_g	Volume of gas emitted	mL

1. Introduction

Black carbon (BC), a major component of atmospheric particulate matter (PM), consists of fine carbon particles generated through incomplete combustion of fossil fuels and biomass. As a potent climate-forcing agent and air pollutant, BC exerts significant impacts on both atmospheric warming and public health [1]. According to the Climate and Clean Air Coalition (2020), household energy use is the dominant source of total emissions (48.1%), followed by transport (24.5%), open burning (16.2%), industry (7.3%), and fossil fuel production (3.9%) [2]. Further disaggregation of household emissions, biomass cookstoves were reported as the primary contributor (66%), followed by biomass heating stoves (12.6%), coal stoves (9.7%), and other residential combustion sources (11.7%) [2].

Nearly one-third of the global population still continues to rely on traditional biomass sources for heating and cooking, such as firewood, agricultural waste, and animal dung [3]. The trend is especially common in the developing world, including China, India, Bangladesh, Pakistan, Nigeria, Kenya, Brazil, and Indonesia [3,4]. In these countries, due to the lack of clean and modern energy technologies, and in the absence of alternatives, households are compelled to use low-efficiency stoves or open fires in poorly ventilated kitchens [6]. Consequently, indoor air can become heavily polluted with harmful substances. According to the United States Environmental Protection Agency, combustion of solid fuel is the cause of about 3.2 million premature deaths annually particularly among women and children [7]. For instance, in India, over 41% of the households are still using solid biomass fuels, which are estimated to yield about 340 million tons of carbon dioxide (CO_2) emissions every year [8]. This dependency is unequally likely to affect the rural and tribal communities especially women and children who are subjected to chronic exposure to higher doses of PM $\leq$ 2.5 μm in diameter ($PM_{2.5}$), carbon monoxide (CO), and polycyclic aromatic hydrocarbons (PAHs). More than 95% of all air pollution-related deaths are now linked to household air pollution [9]. This trend directly challenges the targets outlined in Sustainable Development Goal (SDG) 3.9, which aims to significantly reduce deaths and illnesses from air, water, and soil pollution [10].

The ongoing global health and environmental crisis highlights the pressing need for a sustainable energy transition, with particular urgency in developing countries [11]. The conventional use of biomass fuel is ineffective, disastrous to our environment and leads to household air pollution, deforestation, and global warming. This highlights the urgent need for innovative solutions that can reduce reliance on traditional biomass while addressing environmental and public health concerns. Decentralized waste-to-energy systems particularly those utilizing anaerobic digestion and solid bio-composite fuel technologies can be seen as viable path forward. Such systems will make use of vast local sources of materials like agricultural residues and animal waste to generate more efficient and cleaner solid fuel with the support of the notions of a circular economy. These systems support circular economy principles while improving indoor air quality, especially through the utilization of locally available agricultural residues and animal waste [10,11].

It is anticipated that the amount of cattle manure collected is more than double from 572.11 million tons in 2020 to 1,176.7 million tons in 2030. These substantial waste quantities represent significant potential for decentralized waste-to-energy solutions [14]. The development of these systems therefore directly supports the SDG 7 as it would be used to bring more clean, affordable, and modern energy to rural households [15]. These systems also contribute to achieving SDG 3.9 by reducing reliance on traditional biomass burning, a major source of indoor air pollution that causes millions of premature deaths annually. Moreover, the ability of such systems to convert agricultural waste into useful energy sources leads to the achievement of SDG 13, i.e., reduction of greenhouse gas emissions and climate action [16].

The combination of these interventions provides a viable and scalable pathway to achieving several sustainability objectives, particularly in regions most vulnerable to energy crises. Anwar et al.[17] reported optimal performance with 30% cow dung blends (3,768 kcal kg^{-1}), while Lubwama et al.[18] achieved 21.75 MJ kg^{-1} using rice husk biochar with fruit waste binders. Wulandari et al.[19] developed ramie-based bio-briquettes reaching 6,455 kcal kg^{-1}, and Ali et al.[20] obtained 17.01 MJ kg^{-1} from sawdust-bagasse-straw hybrids. Kujawiak et al.[21] found sewage sludge with wood additives yielded 15−16 MJ kg^{-1} with reduced ash content. Salifu et al. [22] produced shea kernel/groundnut shell briquettes with exceptional energy density (26.15 MJ kg^{-1}). Other works include potato stalk briquettes (15.76 MJ kg^{-1}) [23], sunflower husk-coal composites (24.675 MJ kg^{-1}) [24], and coal-pomegranate blends (6.728 MJ kg^{-1}) [25]. He et al. [26] further identified cotton byproducts as promising feedstocks (17−19 MJ kg^{-1}). Groundnut shells are an abundant agricultural by-product generated during large-scale peanut processing in southern India. They contain high proportions of cellulose (30–35%), hemicellulose (20–25%), and lignin (25–30%), which contribute to their high calorific value of 18–20 MJ kg^{-1} [27]. Due to their low ash and moisture content, groundnut shells have been previously utilized for briquette and pellet production, demonstrating efficient combustion and reduced particulate emissions [22]. These characteristics make them a suitable complementary biomass for blending with cow dung to enhance fuel quality and thermal efficiency. Previous studies [21,28–30] have explored blending cow dung with various agricultural residues to improve combustion properties. However, among these, groundnut shell stands out due to its high lignocellulosic content, low ash concentration, and clean-burning characteristics, making it a promising complementary biomass for enhancing both the calorific value and emission profile of cow dung-based fuels. This forms the central motivation for the present study.

The efforts to improve the performance of solid biomass fuel have long been concentrated on enhancing the calorific value and combustion level. Most of these efforts have, however, been insufficient to tackle the environmental and health effects of biomass combustion, especially the emission of $PM_{2.5}$, CO, and volatile organic compounds. The above pollutants significantly promote air pollution indoors and particularly in the case of poorly ventilated kitchens in the rural settings of many developing world countries [31]. This has made it increasingly important need to develop the efficient bio-composite fuels with greater energy yield and capable of greatly reducing the emissions released during fuel burning.

Although several studies [28–30] have examined the production of biogas or pellet from cow dung and other residues, research on solid bio-composite fuels designed for direct use in cookers remains limited. In particular, limited attention has been given to optimizing blends of cow dung and groundnut shell that balance higher calorific value with lower emissions. This study addresses this lack of research by developing and experimentally validating various solid fuel compositions aimed at improving combustion performance and emission characteristics in rural household energy applications.

The combination leverages cow dung's natural binding properties and lignocellulosic content of groundnut shells, potentially providing a higher calorific value and reduced emissions of $PM_{2.5}$ and gaseous pollutants such as CO_2 and formaldehyde (HCHO) critical factors for improving indoor air quality in rural households. By systematically varying the composition ratios, this study identifies the optimal blend that maximizes energy efficiency while minimizing environmental impact. The resulting composite fuel is designed as a decentralized, low-cost, and user-friendly energy solution for rural communities. The present study focuses on rural communities in and around Coimbatore District, Tamil Nadu, India, where cow dung and groundnut shells are readily available and commonly used as traditional household energy sources. To validate these objectives, comprehensive thermal and environmental characterizations were conducted, including calorific value measurements, emissions analysis. This research advances the development of scalable, clean biofuels, supporting energy access, public health, and climate change mitigation in rural areas of developing countries.

2. Material and Methods

2.1 Sample size and experimental design

In this study, 120 bio-composite fuel samples were systematically prepared and equally divided into four composition groups (30 specimens each) with varying cow dung to groundnut shell powder ratios: 100:0 (i.e., pure cow dung), 75:25, 50:50, and 25:75. This experimental design enables a comprehensive comparative analysis of energy performance and emission characteristics across a controlled range of formulations.

2.2 Collection and preparation of raw materials

The cow dung used in this study was collected fresh from local cattle sheds to ensure purity. Samples were obtained within minutes of excretion following strict protocols to prevent soil contamination or inclusion of foreign matter. The dung was spread in thin layers and sun-dried for 2−3 days, as shown in Figure 1. To achieve uniform moisture content, the partially dried dung underwent controlled dehydration before being stored in airtight containers to maintain consistency. After sun drying, the cow dung was crumbled and ground, then sieved to ≤ 500 μm; the groundnut shells were mechanically ground and sieved to ≤ 500 μm before blending. Groundnut shells were sourced from nearby agricultural processing units.

Groundnut shells were sun-dried for 48 hours to remove moisture, then ground using a rotary blade grinder and sieved to ≤ 500 μm for uniform particle size. The powdered form ensured homogeneous mixing with cow dung, improved moldability, and increased combustion surface area, thereby enhancing thermal efficiency.

Cow dung and groundnut shells were selected as composite materials because they are widely available in rural Tamil Nadu, India, and their complementary physical and chemical properties. Cow dung offers a natural binding ability, a uniform consistency, and an ease of shaping, which make it ideal for forming solid fuel cakes. The combination of these two biomasses leverages the binding nature of cow dung and the energy-rich characteristics of groundnut shells to produce a dense, efficient, and low-emission bio-composite fuel.

2.3 Sample formation and composition ratios

The bio-composite fuel cakes were fabricated using standardized cylindrical molds (4 cm diameter □ 1.6 cm height) to ensure dimensional consistency. Each cake was prepared with a target mass of 7.0 □ 0.1 g to maintain uniformity across the experimental set. Four distinct compositional variants were manufactured to systematically investigate the influence of cow dung-to-groundnut shell powder ratios on combustion performance characteristics. The formulations were C1: 100% cow dung (control group), C2: 75% cow dung + 25% groundnut shell powder, C3: 50% cow dung + 50% groundnut shell powder, and C4: 25% cow dung + 75% groundnut shell powder. All component proportions were measured using a high-precision analytical balance (□0.1 g) to ensure accurate formulation of each composition. Deionized water was added incrementally to achieve optimal rheological properties (i.e., malleability and cohesiveness) for the molding process.

ARTICLE IN PRESS

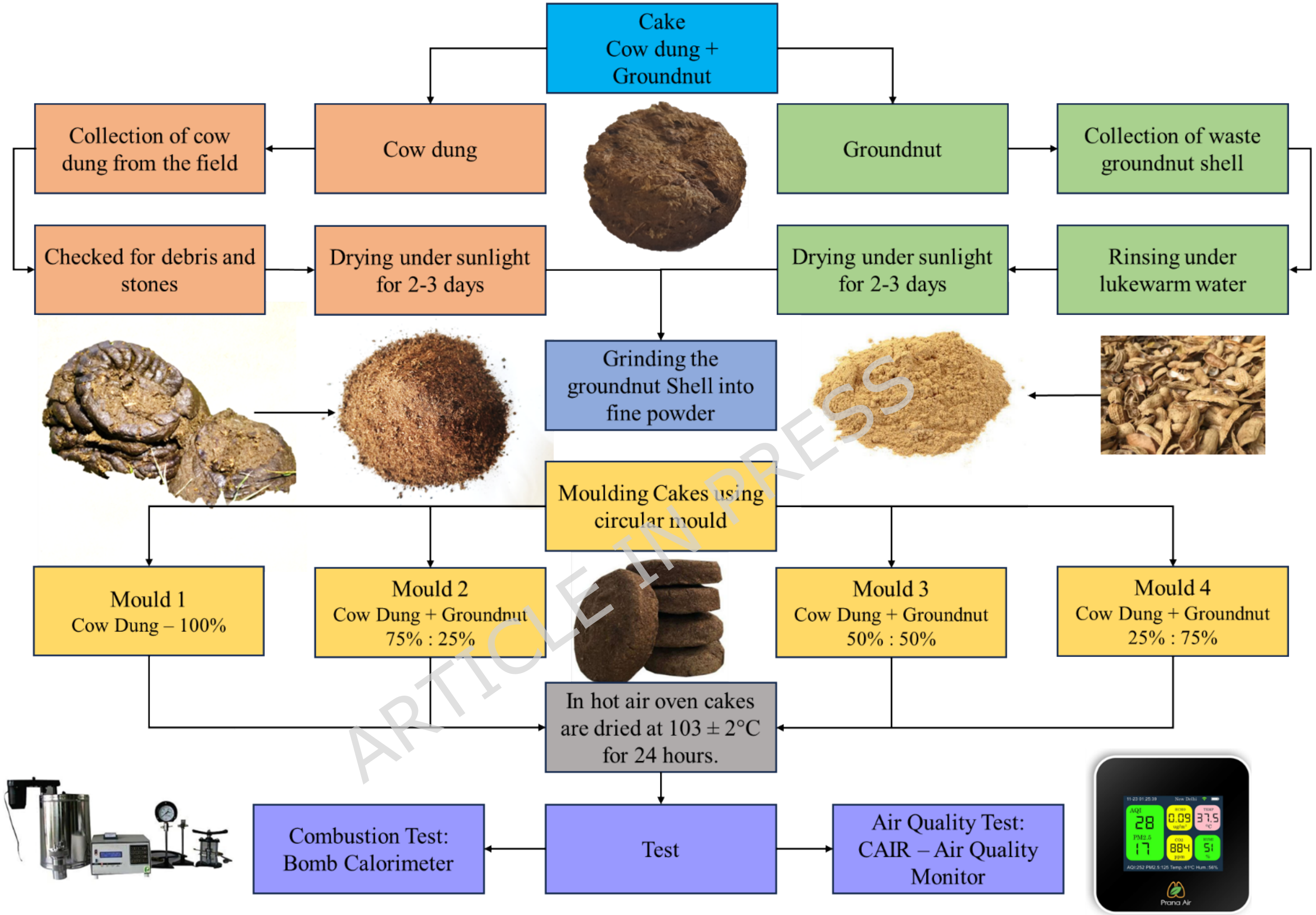

Figure 1. Flowchart for the preparation of a new combination cake.

To achieve a uniform consistency for molding, deionized water was gradually added to each mixture in the range of 18–22% by weight, depending on the cow-dung-to-groundnut-shell ratio. The higher cow-dung blends (C1 and C2) required slightly less water (≈18%), whereas the groundnut-shell-rich mixtures (C3 and C4) required up to 22% to attain a cohesive and malleable texture suitable for pressing. The optimal consistency was determined visually and manually to ensure the mixture neither cracked during molding nor adhered excessively to the die surface. The homogeneous mixtures were then transferred into the cylindrical molds, carefully leveled to ensure a uniform shape and consistent bulk density across all samples. This standardized preparation protocol was critical for minimizing structural variability and ensuring the reliability of subsequent performance evaluations.

2.4 Drying protocol

After the molding process, the bio-composite cakes developed in this study underwent a controlled drying protocol to ensure uniform moisture removal and produce a stable, reproducible fuel product. The molded cakes were placed in a hot air oven maintained at 103 ± 2°C for 24 hours which is a standard temperature for drying biomass that effectively evaporates moisture without degrading the organic matrix. To ensure uniform heat distribution and efficient drying, the samples were spaced adequately to allow proper air circulation around each piece. Although oven drying was used in this study for experimental consistency, in real-world rural production, solar or ambient air-drying methods can achieve comparable moisture levels (8–10%) at negligible cost. After the drying cycle, the cakes were immediately transferred to desiccator chambers containing silica gel to prevent moisture reabsorption from the surrounding environment, a critical step for maintaining product integrity and consistency.

Figure 2. The physical measurements of the cow dung-groundnut shell fuel cake are 4.0 cm in diameter and 1.6 cm in height.

2.5 Details of bio-composite fuel cake

The bio-composite fuel cake was aimed at decentralized applications of domestic energy generation using locally available biomass resources. Each fuel cake was made with uniform dimensions of 4.0 cm in diameter and 1.6 cm in height with an average mass of about 7 g/unit as shown in

Figure 2. The uniform geometry will ensure consistent combustion behavior and will ease the handling, stacking, storage and transportation. The small size also registers to be used directly in traditional and improved cook stoves that are usually employed, without modification [32]. The fuel cake is made from cow dung and groundnut shell powder which are mixed together to create a mechanically stable mixture. Cow dung gives natural bonding and structural integrity and also have the disadvantage of having a low calorific value and high ash content if used alone [27,28]. Groundnut shells are an agricultural by-product with high lignocellulosic content including cellulose, hemicellulose and lignin components, and these components are associated with more energy density and favorable combustion properties [35]. The combination of these materials ensures the improvement of the volatile/fixed carbon ratio while ensuring sufficient mechanical strength. The porous and fibrous nature of groundnut shell particles facilitates moisture diffusion during the drying period which facilitates good moisture reduction during solar and oven curing without cracking in structure. Decreased moisture content makes the light prefloat more stable and will accelerate combustion under the domestic operating conditions. The resulting bio-composite fuel cakes have enhanced calorific performance as compared to the cow dung-based fuels in terms of longer duration of combustion and less fuel usage per cycle of cooking. The optimized density as well as uniform shape is the contribution to stable burning and improved storage characteristics by limiting fungus growth and insect infestation. The process of fabrication only requires simple molds, drying platforms and low temperature ovens, which makes the

process suitable for decentralized production. The design is based on previous research that finds combination of biomass densification and composite formulation is better for combustion quality and emissions [36].

2.6 Experimental evaluation

Combustion tests were conducted under controlled laboratory conditions (ambient temperature 28 ± 2°C, relative humidity 58 ± 3%, and airflow rate 1.2 m s^{-1}) to ensure consistent burning behavior across all samples.

Energy content measurement: The gross calorific value (GCV) of each dried bio-composite sample is measured using a digital bomb calorimeter, which is calibrated prior to each test session to ensure high accuracy. The calorific value provides a direct measure of the fuel's energy content and is recorded in kilojoules per kilogram (kJ kg^{-1}). The GCV is computed using the standard formula.

$$GCV = \frac{(C_b + C_w) \times \Delta T - Q_c}{m_s},$$

here, C_b is heat capacity of the bomb (kJ K^{-1}), C_w is heat capacity of the water in the calorimeter (kJ K^{-1}), ΔT is temperature rise during combustion (K), Q_c is correction for heat losses (kJ), m_s is mass of the fuel sample (kg). The bomb calorimeter (Parr 6400, USA) was calibrated before each testing session using a certified benzoic acid standard (26,454 ± 10 J g^{-1}) to verify instrument accuracy and ensure reproducibility of calorific value measurements.

Emission Analysis: The emission characteristics of the fuel cakes were tested through controlled combustion in a laboratory-scale combustion chamber under standardized air flow. $PM_{2.5}$ and gaseous pollutants (CO_2

and HCHO) were monitored using high-precision optical and electrochemical sensors integrated with a real-time air quality monitoring system (CAIR Portable Air Quality Monitor, 2023). The analytical system continuously recorded pollutant concentrations with 1-second temporal resolution. Calibration was verified using reference filters and gas standards to ensure accuracy. The measured parameters included $PM_{2.5}$, CO_2, and HCHO, which are the major indoor pollutants associated with biomass combustion. The emission data were averaged over the stable combustion period for each sample set. Emissions are recorded at fixed time intervals to capture the dynamic profile of pollutant release, peak values and emission duration. Gaseous pollutant concentrations are quantified using the formula.

$$C_g = \frac{V_g}{V_a},$$

here, C_g is concentration of gas (μg m^{-3}), V_g is volume of the target gas emitted (mL), V_a is volume of air sampled (L).

Particulate concentration:

$$C_{PM2.5} = \frac{M_{PM2.5}}{V_a},$$

here, $C_{PM2.5}$ is concentration of $PM_{2.5}$ (μg m^{-3}), $M_{PM2.5}$ is mass of $PM_{2.5}$ collected (μg) V_a is volume of air sampled (L). $PM_{2.5}$ concentrations were measured using an optical particle counter, while CO_2 and HCHO were monitored through electrochemical gas sensors integrated into a real-time air-quality monitoring system. Each sensor was factory-calibrated and verified using zero and span calibration before testing.

3. Results and Discussion

3.1 Energy performance evaluation

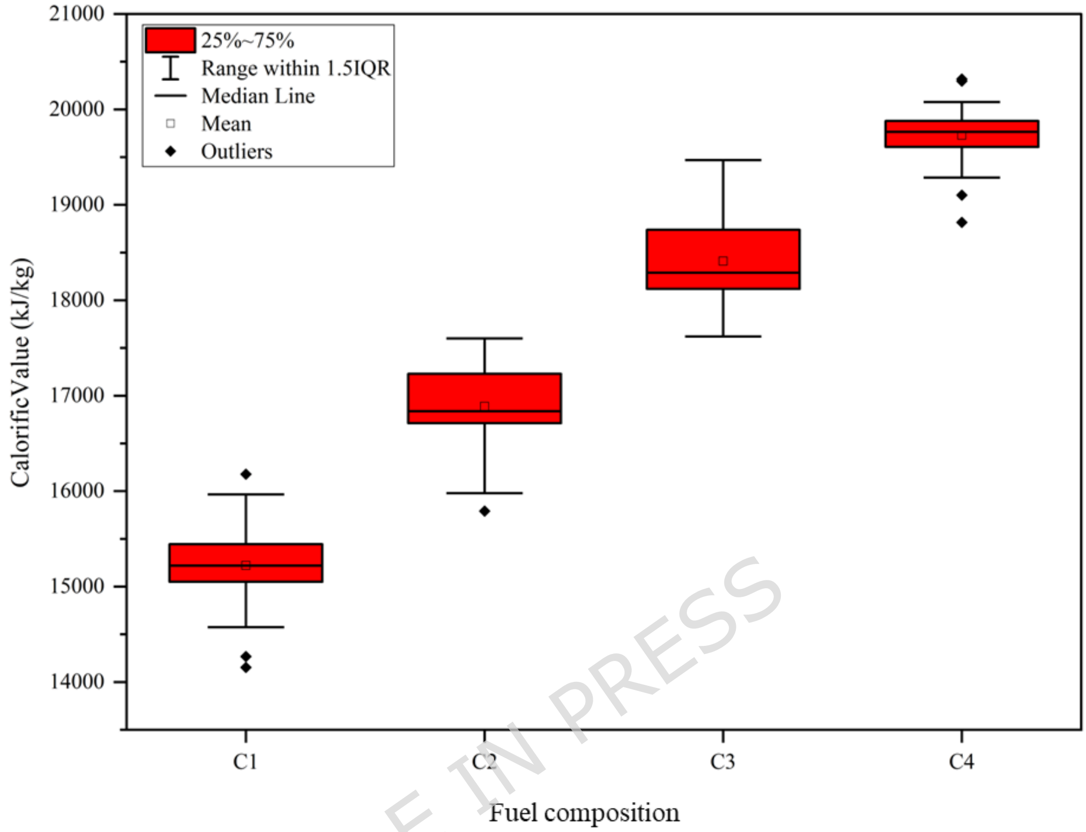

Figure 3. Variation of calorific value with fuel composition (C1–C4) of cow dung-groundnut shell blends.

Figure 3 shows the calorific values of the four fuel compositions (C1 to C4). The incorporation of groundnut shell into the mixture results in a notable and consistent enhancement of calorific value. The median calorific value of C1 is around 15,300 kJ kg^{-1}, with a range of 14,268 to 16,178 kJ kg^{-1}. Cow dung exhibits limited energy potential owing to elevated ash (15−25%) and moisture levels. C2 possesses a median of 16,950 kJ kg^{-1}, representing a 10.7% increase compared to C1. C3 has a median of 18,300 kJ kg^{-1}, whereas C4 has a median of 19,850 kJ kg^{-1}, with a maximum of 20,318 kJ kg^{-1}, which is 29.7% greater than C1. The increase in calorific value is attributed to the lignocellulosic composition of groundnut shells, which contain high proportions of cellulose, hemicellulose, and lignin [37]. These components result in increased fixed carbon and volatile matter during combustion. Groundnut shells possess a reduced ash concentration (1.5−2%) and intrinsic moisture, resulting in diminished unburnt residue and energy losses during vaporization. Each composition's calorific value and emission parameters were analyzed using one-way ANOVA, and differences among groups were statistically significant ($p < 0.05$). Data are reported as mean ± standard deviation with 95% confidence intervals.

As can be seen in Table 1, the calorific value increases progressively with groundnut shell content, reaching a maximum of 20,318 kJ kg^{-1} for C4. This is approximately 29.7% higher than the calorific value of pure cow dung. This enhancement is due to the groundnut shell's lignocellulosic composition and low ash content.

Table 1. Composition ratios of bio-composite fuel cakes and their maximum calorific values compared with individual feedstocks.

Fuel Code	Cow Dung (%)	Groundnut Shell (%)	Maximum Calorific Value (kJ kg^{-1})
C1	100	00	16,178
C2	75	25	17,560
C3	50	50	19,040
C4	25	75	20,318
Cow Dung (Pure)	100	00	16,178
Groundnut Shell (Pure)	00	100	20,100

The fibrous and porous composition of the shells facilitates improved air-fuel mixing, leading to enhanced oxidation and elevated flame temperature. Cow dung contains a significant inorganic content, resulting in increased residue and reduced energy density [33]. The diminished interquartile range (IQR) in C4 indicates its homogeneous composition and stable thermal output. These results are consistent with previous studies, including Ali et al. [20], which noted improved heating values in blended biomass over single-component biomass. This indicates that including groundnut shells with cow dung enhances the energy efficiency of fuel cakes, making them a cleaner and more sustainable biomass option for rural electricity systems. Overall, the results confirm that the inclusion of groundnut shell enhances the fuel's energy density, which is further examined in the following section in relation to its impact on emission characteristics.

3.2 Air quality impact assessment

The air quality performance of the developed bio-composite fuel cakes was evaluated under controlled combustion conditions using a calibrated air quality monitoring system, with a focus on three major pollutants: $PM_{2.5}$, CO_2, and HCHO. Figure 4 presents the emission levels of $PM_{2.5}$, CO_2, and HCHO resulting from the combustion of four distinct biofuel compositions. The results indicate that pollutant emissions decrease as the proportion of groundnut shell in the fuel mixture increases. C1 has the greatest $PM_{2.5}$ emissions at 384 $\mu g\ m^{-3}$, followed by C2 at 320 $\mu g\ m^{-3}$, C3 at 270 $\mu g\ m^{-3}$, and C4 at 220 $\mu g\ m^{-3}$. There is a 42.7% decrease from C1 to C4.

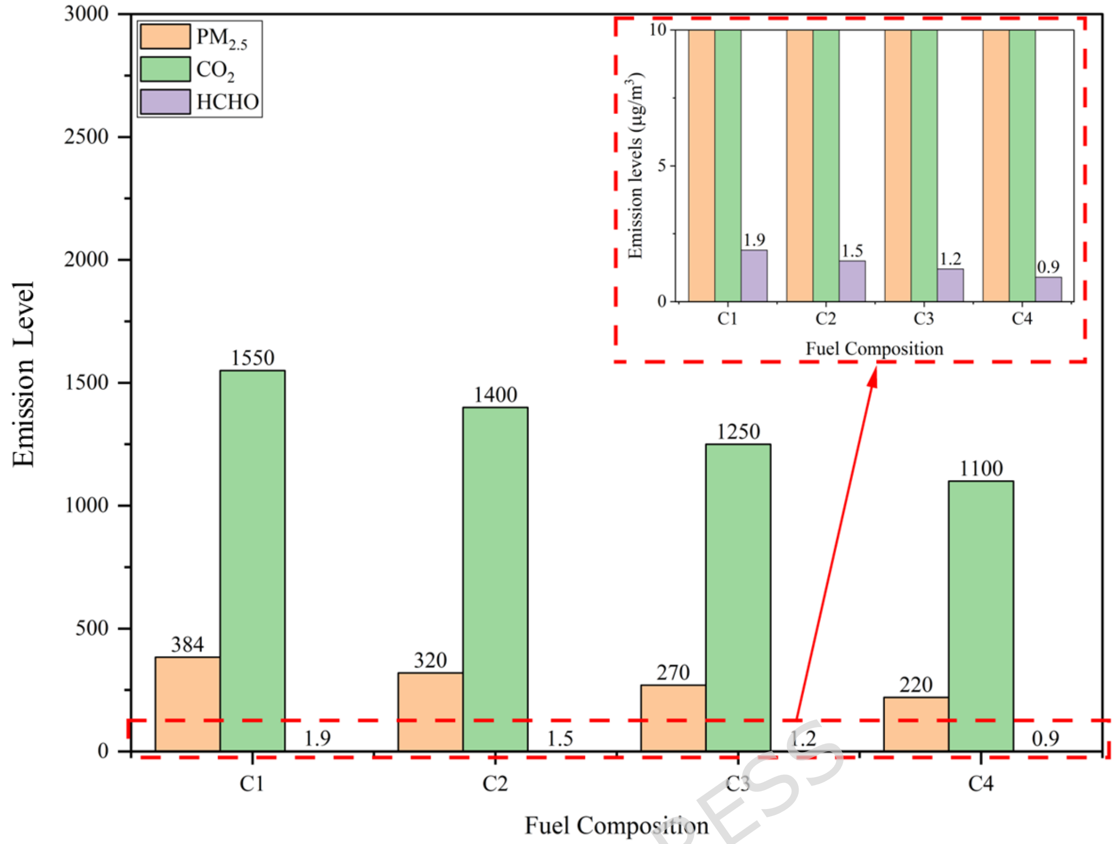

Figure 4. Emission levels of $PM_{2.5}$ (μg m^{-3}), CO_2 (ppmv), and HCHO (μg m^{-3}) decrease with increasing groundnut shell content across fuel compositions.

The declining trend of $PM_{2.5}$ signifies enhanced combustion efficiency with the incorporation of groundnut shells, which presumably facilitates improved volatile release and reduced ash production. CO_2 emissions have also decreased. C1 records the greatest concentration at 1,550 parts per million in volume (ppmv), followed by C2 at 1,400 ppmv, C3 at 1,250 ppmv, and C4 at 1,100 ppmv, reflecting an overall drop of 29%. While CO_2 is a product of full combustion, the observed reduction may result from enhanced combustion efficiency, diminished carbon content in cow dung, and improved oxidation dynamics in groundnut-rich compositions. A close examination of Figure 4 indicates that HCHO emissions experienced the most significant drop. C1 emits 1.9 μg m^{-3}, followed by C2 at 1.5 μg m^{-3}, C3 at 1.2 μg m^{-3}, and C4 at 0.9 μg m^{-3}, representing a drop of 52% from the baseline. HCHO is produced through the partial oxidation of carbonaceous volatiles. The decrease across the blends suggests that a higher groundnut shell percentage enhances combustion efficiency and reduces aldehyde emissions.

3.3 Comparative energy-emission analysis

Figure 5 illustrates the comprehensive energy and emission characteristics of two distinct fuel compositions (C1 and C4). The evaluated parameters include calorific value (kJ kg^{-1}), $PM_{2.5}$ (μg m^{-3}), CO_2 (ppmv), and HCHO (μg m^{-3}). The figure clearly demonstrates the dual advantage of C4: enhanced energy output and reduced emissions. The mean calorific value of C1 is 15,221.86 kJ kg^{-1}, while that of C4 is 19,728.67 kJ kg^{-1}, an increase of 29.6%.

This improvement is attributed to the lignocellulosic nature of groundnut shells, which contain higher levels of fixed carbon and volatile combustible matter compared to cow dung. Groundnut shells also provide low intrinsic moisture and ash content (< 2%), thereby reducing energy loss during vaporization and lowering thermal inertia during combustion. In contrast, cow dung typically has high moisture and ash content (□ 15−20%), which decreases energy density and suppresses peak combustion temperatures.

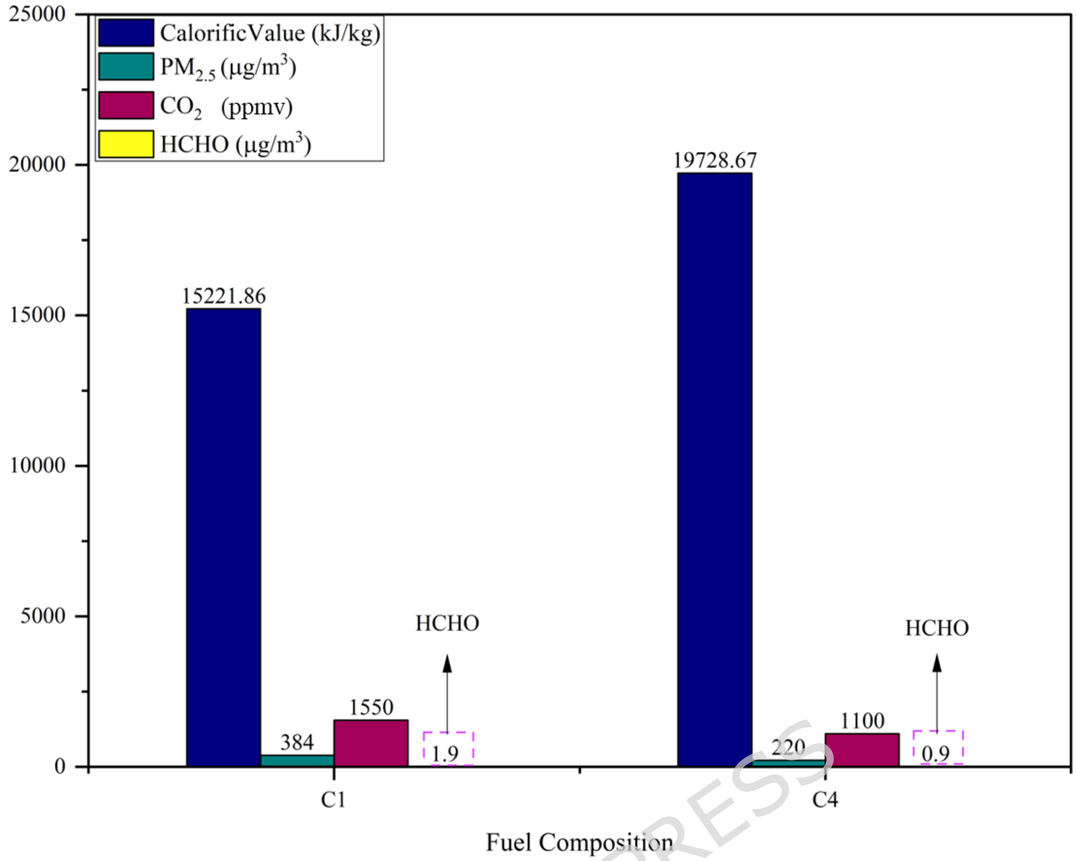

Figure 5. Performance comparison of C1 and C4 fuels showing higher calorific value and lower emissions for C4.

As the proportion of groundnut shell content increases, emissions decline significantly. $PM_{2.5}$ levels decrease from 384 µg m^{-3} in C1 to 220 µg m^{-3} in C4, representing a 42.7% reduction. The porous and fibrous structure of groundnut shells enhance air-fuel mixing, thereby promoting more complete combustion and reducing particulate emissions. CO_2 concentrations decrease from 1550 ppmv in C1 to 1100 ppmv in C4, a 29% reduction indicating that C4 enables more thorough oxidation with lower unburned carbon emissions. Similarly, HCHO levels drop from 1.9 µg m^{-3} in C1 to 0.9 µg m^{-3} in C4, a 52.6% decrease, further supporting the superior combustion efficiency of groundnut-rich blends. Since HCHO is typically produced under low-temperature pyrolysis conditions, its reduction in C4 suggests elevated flame temperatures and more complete thermal decomposition of volatile organic compounds.

3.4 Comparison with the literature

A comparative assessment was performed with previous studies involving cow dung and agricultural residue-based biomass fuels to evaluate the performance and relevance of the developed bio-composite fuel. Table 2 presents a consolidated comparison of feedstock type, processing methods, calorific value, ash content, emission parameters, and practical applicability. The results clearly show that earlier studies mostly focused on enhancing the calorific value of biomass composites, without considering emission analysis or user-level applicability.

For instance, Anwar et al [17] enhanced the gross calorific value (GCV) of cow dung-based fuel from 12.8 to 15.1 MJ kg^{-1} while reducing ash content by approximately 8%, but emission data were not reported. Similarly, Ali et al [38] optimized pellet composition using hybrid artificial intelligence (ANN–MOGA) techniques, achieving a GCV of 15.7 MJ kg^{-1} with reduced ash, yet the study lacked real-time air quality or emission characterization. In contrast, Iftikhar et al [39] focused on the role of cow dung as a binder for rice husk-wheat straw pellets, obtaining a moderate GCV of 14.98 MJ kg^{-1} but with high ash content (31.38%), which could limit combustion efficiency. The present study demonstrates a balanced improvement over these earlier works, with the optimized blend (C4: 25% cow dung + 75% groundnut shell) achieving a calorific value of 19.7 ± 0.37 MJ kg^{-1}, while simultaneously reducing $PM_{2.5}$ by 43%, CO_2 by 29%, and HCHO by 53%

compared to pure cow dung (C1). This dual enhancement in energy and emission performance has not been concurrently achieved in prior research. Additionally, the fuel's disc-shaped geometry allows direct use in existing rural cookstoves, eliminating the need for new infrastructure or behavioral changes. Thus, the developed bio-composite fuel achieves an optimal balance between high energy efficiency, low pollutant release, and practical usability. The integration of two abundant rural wastes cow dung and groundnut shell further reinforces the circular economy potential of this work.

Moreover, the findings of this study have strong practical relevance for rural household energy systems. The optimized blend (C4: 25% cow dung, 75% groundnut shell) demonstrates a 29.6% increase in calorific value compared to pure cow dung, along with reductions of 43% in $PM_{2.5}$, 29% in CO_2, and 53% in HCHO emissions. These improvements translate to cleaner and more efficient combustion in traditional cookstoves, offering immediate benefits for indoor air quality and user health. The use of locally available agricultural residues also supports waste valorization and reduces dependency on firewood, thereby contributing to environmental protection and resource sustainability. Such outcomes align directly with the goals of SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), highlighting the potential of this bio-composite fuel for large-scale rural deployment.

Table 2. Comparison of the present study with existing studies in the literature.

Ref	Feedstock / Approach	Processing Method	Calorific Value (MJ kg^{-1})	Emission / Environmental Focus	Key Outcome / Limitation	Comparison with Present Study
Anwar et al [17]	Cow dung + agricultural waste	Blending and pelletization	12.80	Not reported	Improved calorific value and volatile matter but no emission analysis	Lower energy and no emission study; present work adds emission quantification and higher GCV (19.7 MJ kg^{-1})
Ali et al [38]	Paddy straw + sawdust + cow dung (ANN–MOGA optimized)	Pellet fabrication & modeling	15.70	Not reported	AI-optimized blend improved CV by 7 % but lacked emission study	Slightly lower energy density; present study provides experimental validation & emission reduction ($PM_{2.5}$ ↓ 43 %)
Iftikhar et al [39]	Wheat straw + rice husk + cow dung binder	Response Surface Methodology optimization	14.98	Not reported	Cow dung increased durability but also ash content	Present study achieves > 30 % higher GCV and 65 % less ash with simultaneous pollutant decline
Present study	Cow dung + groundnut shell powder (25 : 75 %)	Direct blending → oven drying → disc-shaped fuel cakes	19.70 ± 00.37	$PM_{2.5}$ ↓ 43 %; CO_2 ↓ 29 %; HCHO ↓ 53 %	Scalable, low-cost, emission optimized, cookstove-compatible solid bio-composite	Demonstrates dual advantage: high calorific efficiency + quantified emission mitigation under real-use conditions

Future work will focus on scaling up the production of the bio-composite fuel for use in field-level cookstove trials in rural households, in order to evaluate its long-term performance under real usage conditions. Advanced modeling and artificial intelligence techniques can be employed to optimize the blend composition and predict dynamic emission behavior. Further studies will also investigate the thermal-structural behavior of the fuel during prolonged combustion, life cycle analysis, and potential integration with hybrid waste-to-energy systems. These efforts could pave the way for developing next-generation emission-optimized biomass fuels that contribute toward national clean energy goals and climate resilience.

4. Conclusions

This study developed and experimentally evaluated a solid bio-composite fuel composed of cow dung and groundnut shell for cleaner household energy applications. Among the tested compositions, the optimized blend (C4: 25% cow dung, 75% groundnut shell) achieved the best performance, showing a 29.6% higher calorific value (19,700 kJ kg^{-1}) compared to pure cow dung and a substantial reduction in emissions 43% lower $PM_{2.5}$, 29% lower CO_2, and 53% lower HCHO concentrations. These results confirm that blending cow dung with groundnut shell enhances both energy yield and combustion cleanliness.

Practically, the bio-composite fuel can be used directly in existing rural cookstoves without design modification, making it highly suitable for household adoption. The results demonstrate that the developed bio-composite fuel supports the objectives of SDG 7 (ffordable and clean energy) and SDG 13 (climate action) by reducing emissions and improving energy efficiency, thereby offering a practical pathway toward cleaner rural energy use. Future investigations should include detailed profiling of CO, NOx, and PAHs to provide a more comprehensive emission characterization of the developed bio-composite fuel. Future studies will focus on scale-up testing, durability and storage stability assessments, field trials in rural households, and socio-economic analyses to validate large-scale applicability and long-term sustainability.

Author contribution

S.G. conceived the study and developed the research framework. G.L.A. conducted data analysis and contributed to methodology development. S.G. and B.L.R. were involved in data collection and field investigations. S.G. contributed to the literature review and manuscript formatting. C.-H.H. provided expert guidance on climate data interpretation and validated the modeling outcomes. S.G. and B.L.R. wrote the main manuscript text and prepared figures. All authors reviewed and approved the final manuscript.

Conflict of interest statement

The authors declare no conflicts of interest.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Funding

The work of Chang-Hoi Ho was supported by the National Research Foundation of Korea (NRF) funded by Korean Government (MSIT) under Grant RS-2025-00555756.

Acknowledgments

The authors would like to thank Karunya Institute of Technology and Sciences to provide all required facilities throughout the research work.

Reference

[1] B.L. Rakshith, L.G. Asirvatham, A.A. Angeline, S. Manova, J.R. Bose, J.P. Selvin Raj, O. Mahian, S. Wongwises, Cooling of high heat flux miniaturized electronic devices using thermal ground plane: An overview, Renew. Sustain. Energy Rev. 170 (2022) 112956. https://doi.org/10.1016/j.rser.2022.112956.

[2] CCAC, Opportunities for 1.5˚C consistent black carbon mitigation, Clim. Clean Air Coalit. (2020). https://www.ccacoalition.org/resources/opportunities-15c-consistent-black-carbon-mitigation (accessed July 5, 2025).

[3] R. Wathore, A. Patel, Household air pollution, in: Textb. Child. Environ. Heal. Second Ed., 2024: pp. 332–346. https://doi.org/10.1093/oso/9780197662526.003.0026.

[4] M.N. Anwar, M. Shabbir, E. Tahir, M. Iftikhar, H. Saif, A. Tahir, M.A. Murtaza, M.F. Khokhar, M. Rehan, M. Aghbashlo, M. Tabatabaei, A.-S. Nizami, Emerging challenges of air pollution and particulate matter in China, India, and Pakistan and mitigating solutions, J. Hazard. Mater. 416 (2021) 125851. https://doi.org/10.1016/j.jhazmat.2021.125851.

[5] T. Rasheed, M.T. Anwar, N. Ahmad, F. Sher, S.U.-D. Khan, A. Ahmad, R. Khan, I. Wazeer, Valorisation and emerging perspective of biomass based waste-to-energy technologies and their socio-environmental impact:

A review, J. Environ. Manage. 287 (2021) 112257. https://doi.org/10.1016/j.jenvman.2021.112257.

[6] A. Adams, E.T. Jumpah, H.S. Dramani, Dynamics of Clean and Sustainable Households' Energy Technologies in Developing Countries: The Case of Improved Cookstoves in Ghana, Sustain. Futur. 5 (2023) 100108. https://doi.org/10.1016/j.sftr.2023.100108.

[7] EPA, Understanding the Issue: Household Energy and Clean Air, United States Environ. Prot. Agency (2025). https://www.epa.gov/indoor-air-quality-iaq/understanding-issue-household-energy-and-clean-air?utm_source=chatgpt.com (accessed July 5, 2025).

[8] The Times of India, biomass: 41% in India still rely on biomass for cooking, emitting 340 million tonnes of CO2 annually, says report - The Economic Times, The Times of India (2024). https://timesofindia.indiatimes.com/home/environment/41-in-india-still-rely-on-biomass-for-cooking-emitting-340-mn-tonnes-of-co2-annually-report/articleshow/107237844.cms (accessed July 5, 2025).

[9] H. Yue, C. He, Q. Huang, D. Zhang, P. Shi, E.A. Moallemi, F. Xu, Y. Yang, X. Qi, Q. Ma, B.A. Bryan, Substantially reducing global PM2.5-related deaths under SDG3.9 requires better air pollution control and healthcare, Nat. Commun. 15 (2024) 2729. https://doi.org/10.1038/s41467-024-46969-3.

[10] World Helath Organization, Mortality from environmental pollution, World Helath Organ. (2019). https://www.who.int/data/gho/data/themes/topics/sdg-target-3_9-mortality-from-environmental-pollution (accessed July 5, 2025).

[11] B.L. Rakshith, L.G. Asirvatham, A.A. Angeline, B. Lancy, J.P.S. Raj, J.R. Bose, S. Wongwises, Thermal management performance of a novel elliptically grooved flat heat pipe system embedded with internally cooled condenser, Energy Convers. Manag. X 24 (2024) 100717. https://doi.org/10.1016/j.ecmx.2024.100717.

[12] A. Alengebawy, Y. Ran, A.I. Osman, K. Jin, M. Samer, P. Ai, Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: a review, Environ. Chem. Lett. 22 (2024) 2641–2668. https://doi.org/10.1007/s10311-024-01789-1.

[13] T.F. Adu, L.D. Mensah, M.A.D. Rockson, F. Kemausuor, Decision support systems for waste-to-energy technologies: A systematic literature review of methods and future directions for sustainable implementation in Ghana, Heliyon 11 (2025). https://doi.org/10.1016/j.heliyon.2025.e42353.

[14] SSCGJ, Solid Waste Management: Rural (Farm) Waste: Identification of Green Business Potential in India, n.d. https://sscgj.in/publications/ (accessed July 5, 2025).

[15] UnitedNations, 809iuytreds`1234579-0epartment of Economic and Social Affairs, United Nations (2025) 1. https://sdgs.un.org/goals/goal7 (accessed July 5, 2025).

[16] U. Nations, Goal 13 | Department of Economic and Social Affairs, United Nations (2023). https://sdgs.un.org/goals/goal13 (accessed July 5, 2025).

[17] M.T. Anwar, N. Ullah, S. Khalid, N. Ahmad, M. Shahzeb Khan, Fuel Composites Development Using Cow Dung and Agricultural Biomass, Mater. Proc. 17 (2024). https://doi.org/10.3390/materproc2024017023.

[18] M. Lubwama, A. Birungi, A. Nuwamanya, V.A. Yiga, Characteristics of rice husk biochar briquettes with municipal solid waste cassava, sweet potato and matooke peelings as binders, Mater. Renew. Sustain. Energy 13 (2024) 243–254. https://doi.org/10.1007/s40243-024-00262-x.

[19] A.P. Wulandari, N. Rossiana, F.R. Zahdi, R. Nuraulia, R. Nur'anifah, C.I. Kartika, L.A. Rahmah, J. Kusmoro, Madihah, Yusnaidar, Formulation and Characterization of Bio-Briquettes and Bio-Pellets from Ramie (Boehmeria nivea) Biomass as Renewable Fuel, Sustainability 16 (2024). https://doi.org/10.3390/su162410930.

[20] A. Ali, D. Chhabra, M. Kumari, Manisha, Pinkey, S. Tiwari, R.K. Sahdev, Optimization and characterization of hybrid bio-briquettes produced from the mixture of sawdust, sugarcane bagasse, and paddy

straw, Environ. Sci. Pollut. Res. 31 (2024) 15467–15490. https://doi.org/10.1007/s11356-024-32171-x.

[21] S. Kujawiak, M. Makowska, D. Janczak, W. Czekała, W. Krzesiński, A. Antonowicz, K. Kupryaniuk, An Analysis of the Physicochemical and Energy Parameters of Briquettes Manufactured from Sewage Sludge Mixtures and Selected Organic Additives, Energies 17 (2024). https://doi.org/10.3390/en17184573.

[22] A.S. Salifu, M. Commeh, F. Ampiaw, M. Oteng-Peprah, B. Agyei-Tuffour, D. Dodoo-Arhin, Mechanical Properties and Performance Characteristics of Shea Kernel–Groundnut Shell–Derived Bio-Briquettes for Rural Energy Applications, Adv. Mater. Sci. Eng. 2025 (2025) 6779168. https://doi.org/10.1155/amse/6779168.

[23] M.A. Piarpuezán Enríquez, D.R. Zapata Hidalgo, F. Pantoja-Suárez, Characterization of Briquettes from Potato Stalk Residues for Sustainable Solid Biofuel Production, Processes 13 (2025). https://doi.org/10.3390/pr13061851.

[24] A. Nikiforov, A. Kinzhibekova, E. Prikhodko, A. Karmanov, S. Nurkina, Analysis of the Characteristics of Bio-Coal Briquettes from Agricultural and Coal Industry Waste, Energies 16 (2023). https://doi.org/10.3390/en16083527.

[25] A.U. Khan, Q.M. Jan, M. Abas, K. Muhammad, Q.M. Ali, D. Zimon, Utilization of Biowaste for Sustainable Production of Coal Briquettes, Energies 16 (2023). https://doi.org/10.3390/en16207025.

[26] Z. He, S. Nam, H. Tewolde, C. V Ford, R. Dhandapani, R. Barretto, D. Wang, Morphologic Features and Thermal Characteristics of Nine Cotton Biomass Byproducts, Biomass 5 (2025). https://doi.org/10.3390/biomass5010012.

[27] V.A. Ajayi, A. Lateef, Biotechnological valorization of agrowastes for circular bioeconomy: Melon seed shell, groundnut shell and groundnut peel, Clean. Circ. Bioeconomy 4 (2023) 100039. https://doi.org/10.1016/j.clcb.2023.100039.

[28] V. Thangappan, S. Suji, Production and characterization of cattle manure briquettes using starch as binder in comparison with cow dung, AIP Conf. Proc. 3193 (2024) 20056. https://doi.org/10.1063/5.0233000.

[29] P. Sivakumar, R. Saravanane, S. Mohan, B. Sankar, Biochar as a catalyst for methane enhancement in anaerobic digestor containing cow dung, food waste, and rice straw: An experimental and statistical study, Clean. Waste Syst. 12 (2025) 100388. https://doi.org/10.1016/j.clwas.2025.100388.

[30] S. Demirci, Production and characterization of briquettes obtained from dung, hazelnut shell and molasses for sustainable environment,

Biofuels 16 (2025) 971–980. https://doi.org/10.1080/17597269.2025.2477868.

[31] M. Kurmanbekova, J. Du, S. Sharples, A Review of Indoor Air Quality in Social Housing Across Low- and Middle-Income Countries, Appl. Sci. 15 (2025). https://doi.org/10.3390/app15041858.

[32] M.P. Kshirsagar, V.R. Kalamkar, A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design, Renew. Sustain. Energy Rev. 30 (2014) 580–603. https://doi.org/10.1016/j.rser.2013.10.039.

[33] A. Szymajda, G. Łaska, M. Joka, Assessment of Cow Dung Pellets as a Renewable Solid Fuel in Direct Combustion Technologies, Energies 14 (2021). https://doi.org/10.3390/en14041192.

[34] G.A. Geberehiet, T.G. Gebreegziabher, A.G. Mekonen, G.K. Hagos, T.N. Gebresilasie, Development of briquettes suitable for energy generation from residue of sorghum stalk and groundnut husk, Mater. Renew. Sustain. Energy 14 (2025) 35. https://doi.org/10.1007/s40243-025-00309-7.

[35] M.-A. Perea-Moreno, F. Manzano-Agugliaro, Q. Hernandez-Escobedo, A.-J. Perea-Moreno, Peanut Shell for Energy: Properties and Its Potential to Respect the Environment, Sustainability 10 (2018). https://doi.org/10.3390/su10093254.

[36] M. Morales-Máximo, V.M. Ruíz-García, J.G. Rutiaga-Quiñones, L.B. López-Sosa, Design and Implementation of a Low-Pressure Briquetting Machine for the Use of Pinus spp. Wood Residues: An Approach to Appropriate Rural Technology, Clean Technol. 7 (2025). https://doi.org/10.3390/cleantechnol7010022.

[37] S.P. Thota, P.K. Badiya, Y.N. Guragain, P.V. Vadlani, M. Pandey, R.B. Dandamudi, S.S. Ramamurthy, S.K. Belliraj, Innovative Consortia of Micro and Macro Fungal Systems: Cellulolytic Enzyme Production from Groundnut Shell Biomass and Supportive Structural Analysis, J. Sustain. Bioenergy Syst. 08 (2018) 47–66. https://doi.org/10.4236/jsbs.2018.83004.

[38] A. Ali, M. Kumari, J.S. Laura, M. Rizwanullah, Manisha, D. Chhabra, R.K. Sahdev, Optimal composition of biomass pellet for enhancing calorific value using MOGA-ANN: a mixture of paddy straw, sawdust, cow dung, and paper pulp, Biomass Convers. Biorefinery 15 (2025) 25747–25763. https://doi.org/10.1007/s13399-023-04490-5.

[39] M. Iftikhar, A. Asghar, N. Ramzan, B. Sajjadi, W. Chen, Biomass densification: Effect of cow dung on the physicochemical properties of wheat straw and rice husk based biomass pellets, Biomass and Bioenergy 122 (2019) 1–16. https://doi.org/10.1016/j.biombioe.2019.01.005.