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Physicochemical Characterization of Soot Particles from Selected Combustion Sources: Implications for Environmental Pollution and Resource Utilization

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Abstract

Soot generated from incomplete combustion of fossil fuels and biomass constitutes a major component of atmospheric particulate matter and poses significant environmental and public health concerns. The physicochemical properties of soot influence its atmospheric behaviour, environmental persistence, pollutant transport, and potential utilization as a carbonaceous precursor for industrial and environmental applications. This study comparatively evaluated the physicochemical characteristics of soot particles collected from five common combustion sources, namely kerosene stove, firewood, diesel generator, diesel vehicle exhaust, and kerosene lamp. The samples were collected from selected combustion sources within Jos Metropolis, Plateau State, Nigeria, representing common domestic and transportation-related emission sources in the study area. Soot samples were collected under normal operating conditions and analysed for moisture content, bulk density, pH, electrical conductivity, apparent density, particle number density, attrition, and solubility using standard analytical procedures. The results revealed marked variations among the soot samples, reflecting differences in combustion conditions and fuel composition. Moisture content ranged from 1.05% ± 0.01% in diesel soot to 2.27% ± 0.01% in kerosene lamp soot, whereas bulk density varied from 0.0547 ± 0.0001 g/mL to 0.2983 ± 0.0001 g/mL. Kerosene stove soot exhibited the highest pH (8.63 ± 0.06), indicating an alkaline nature, while diesel vehicle soot recorded the lowest pH (5.10 ± 0.08). Electrical conductivity ranged between 20.81 ± 0.01 µS/cm and 77.77 ± 0.23 µS/cm, suggesting variations in soluble ionic constituents among the combustion-derived particles. Apparent density values

ranged from 0.0948 ± 0.0010 g/mL to 0.5166 ± 0.0010 g/mL, whereas particle number density showed only slight variation among samples, ranging from 0.0147 ± 0.0003 to 0.0178 ± 0.0001 g/mL. Attrition values remained below 0.07%, indicating relatively stable particulate structures, while the uniformly low solubility values confirmed the predominantly insoluble and hydrophobic nature of the soot particles. Overall, the study demonstrated that physicochemical characteristics differed among soot samples collected from the selected combustion sources, with implications for atmospheric transport, environmental behaviour, pollution monitoring, and potential valorisation of soot as a carbonaceous material. These findings provide baseline information for environmental risk assessment and sustainable management of combustion-derived particulate matter.

Subject Areas

Atmospheric Chemistry

Keywords

Soot, Combustion Source, Physicochemical Properties, Particulate Matter, Biomass Combustion, Diesel Emissions, Environmental Pollution, Carbonaceous Materials

1. Introduction

Atmospheric particulate matter (PM) remains one of the most serious environmental pollutants affecting human health, ecosystem stability, and global climate. Among the various constituents of particulate matter, soot is one of the most abundant carbonaceous aerosols generated during the incomplete combustion of fossil fuels and biomass. Soot particles are composed primarily of elemental carbon with varying proportions of organic carbon, inorganic ash, trace metals, and oxygen-containing functional groups. Their physicochemical properties are largely governed by fuel composition, combustion temperature, oxygen availability, combustion efficiency, and atmospheric ageing processes, all of which determine their environmental behaviour and climatic effects [1]-[3].

The continued reliance on biomass fuels, kerosene, and diesel-powered engines for domestic cooking, lighting, transportation, and electricity generation has resulted in increasing soot emissions, particularly in developing countries. Combustion-derived soot contributes significantly to ambient $PM_{2.5}$ concentrations and has been associated with adverse respiratory and cardiovascular diseases, reduced visibility, atmospheric warming through solar radiation absorption, and deterioration of environmental quality [1] [4]. Freshly emitted soot particles also undergo continuous physical and chemical transformations in the atmosphere, leading to changes in morphology, particle size, mixing state, and surface chemistry that further influence their environmental persistence and toxicity [1] [4].

The physicochemical properties of soot play a critical role in determining its environmental fate and potential applications. Parameters such as moisture content, bulk density, apparent density, pH, electrical conductivity, particle number density, attrition resistance, and aqueous solubility influence particle transport, deposition, aggregation, adsorption behaviour, and interactions with environmental contaminants. These properties also determine the suitability of soot as a precursor material for activated carbon production, catalyst supports, electrode materials, and low-cost adsorbents for wastewater treatment and environmental remediation [2] [3] [5].

The characteristics of soot vary considerably with combustion source because differences in fuel composition and combustion conditions directly affect particle formation and growth. Biomass combustion generally produces soot with higher ash content and greater physicochemical heterogeneity, whereas diesel combustion typically generates finer particles enriched in elemental carbon. Likewise, soot generated from kerosene combustion may differ substantially from diesel-derived soot due to variations in flame temperature, fuel volatility, aromatic composition, and combustion efficiency. These differences ultimately influence particle morphology, density, reactivity, atmospheric residence time, and environmental behaviour [2] [4] [6].

Recent studies have focused extensively on soot formation mechanisms, atmospheric ageing, oxidation behaviour, optical properties, and climate impacts. Advances in analytical techniques have considerably improved understanding of the physical and chemical evolution of soot particles; however, comparative investigations of the fundamental physicochemical properties of soot generated from commonly encountered domestic and transportation-related combustion sources remain limited. Such comparative studies are essential for understanding how combustion source influences soot quality and for identifying potential environmental and industrial applications of these carbonaceous materials [1] [2] [5].

Growing interest in sustainable resource utilization has further increased the importance of evaluating soot as a potential carbon-rich material rather than merely an environmental pollutant. Depending on its physicochemical characteristics, combustion-derived soot may be converted into activated carbon, catalyst supports, electrode materials, adsorbents, and other value-added carbon products. Comprehensive physicochemical characterization therefore provides important baseline information for pollution assessment, waste valorization, and the development of environmentally sustainable technologies [3] [5] [7].

Jos Metropolis, the administrative and commercial hub of Plateau State, Nigeria, experiences substantial emissions from domestic cooking, kerosene lighting, diesel-powered electricity generation, and vehicular transportation due to rapid urbanization and increasing energy demand. Despite the widespread occurrence of combustion-derived particulate emissions within the metropolis, information on the physicochemical characteristics of soot generated from these common sources remains limited. This study was therefore undertaken to provide baseline

data for environmental pollution assessment and sustainable resource utilization within the study area.

2. Materials and Methods

2.1. Materials

All reagents used in this study were of analytical grade and were used without further purification. Distilled water was used throughout the analyses. Standard laboratory equipment, including a digital analytical balance (±0.001 g), hot-air oven, digital pH meter, digital conductivity meter, graduated measuring cylinders, porcelain crucibles, desiccator, laboratory sieve (250 μm), stainless-steel spatulas, glass beakers, and airtight sample containers, were used for the physicochemical analyses.

2.2. Study Area

The study was conducted in Jos Metropolis, Plateau State, North-Central Nigeria. Jos Metropolis comprises Jos North, Jos South, and parts of Jos East Local Government Areas and is characterized by a rapidly growing urban population, extensive commercial activities, and diverse domestic and transportation-related combustion sources. The city experiences a tropical highland climate with distinct wet and dry seasons, and combustion emissions from household cooking, kerosene lighting, diesel-powered electricity generators, and motor vehicles constitute important contributors to ambient particulate matter within the metropolis.

2.3. Sample Collection

Soot samples were collected from five common combustion sources within Jos Metropolis, Plateau State, Nigeria, namely kerosene stove, firewood, diesel generator, diesel vehicle exhaust, and kerosene lamp. One representative unit was sampled for each combustion source. The kerosene stove soot was collected from a local restaurant, firewood soot from a cooking fire at the Central Market, diesel generator soot from a hotel standby generator, diesel vehicle soot from the exhaust of a recently driven diesel-powered vehicle, and kerosene lamp soot from a residential household. These sources were selected because they represent common domestic and transportation-related combustion activities within the study area [8] [9].

The kerosene stove and kerosene lamp were operated using commercially available household kerosene, while the diesel generator and diesel vehicle were fuelled with Automotive Gas Oil (AGO) obtained from commercial filling stations. Firewood used for the cooking fire consisted of mixed species commonly sold in the Central Market, reflecting the typical biomass fuel used for domestic cooking in the study area.

To ensure representative soot formation under normal operating conditions, soot was collected only after combustion systems had reached stable operation. The kerosene stove and kerosene lamp had been continuously operated for ap-

proximately 8 h before sampling. The diesel generator was sampled while operating under normal electrical load, whereas soot from the diesel vehicle was collected immediately after routine operation while the engine was still at normal operating temperature. Following cessation of combustion, deposited soot was carefully scraped from the inner surfaces of combustion chambers, burner assemblies, cooking vessels, exhaust outlets, and lamp chimneys using clean stainless-steel spatulas. Approximately equal quantities of soot were collected from each source, transferred into clean airtight glass containers, labelled according to combustion source, and transported to the laboratory for analysis. Visible contaminants such as ash particles, metallic fragments, fibres, and coarse debris were manually removed before sample preparation to minimize analytical interference [10].

2.4. Sample Preparation

The collected soot samples were air-dried at ambient laboratory temperature (27˚C ± 2˚C) for 24 h to remove loosely bound moisture. Each sample was subsequently homogenized separately using an agate mortar and pestle before passing through a 250 μm stainless-steel sieve to obtain uniform particle size. The prepared samples were transferred into airtight sample bottles and stored in a desiccator until analysis to prevent atmospheric moisture uptake. All physicochemical measurements were performed in triplicate as analytical replicates on each homogenized soot sample to evaluate measurement precision. The triplicate measurements were repeated on the same sample rather than on independently collected soot samples, and the results are presented as mean ± standard deviation.

2.5. Determination of Moisture Content

Moisture content was determined using the gravimetric oven-drying method described by ASTM D3173 with slight modification [11]. Approximately 2.00 g of each soot sample was weighed into a previously dried and pre-weighed porcelain crucible and dried in a thermostatically controlled oven at 105˚C until constant weight was attained. The crucibles were transferred into a desiccator, cooled to room temperature, and reweighed. Moisture content was calculated as the percentage weight loss relative to the initial sample weight.

2.6. Determination of Bulk Density

Bulk density was determined using the loose bulk density method described for powdered carbonaceous materials [12]. Five grams of each soot sample were gently introduced into a 100 mL graduated measuring cylinder without compaction, and the corresponding bulk volume was recorded. Bulk density was calculated as the ratio of sample mass to the bulk volume occupied and expressed as g/mL.

2.7. Determination of pH

The pH of the soot samples was determined according to the method described by [13]. One gram of soot was mixed with 20 mL of distilled water and agitated

for 30 min to obtain a homogeneous suspension. The mixture was allowed to stand for 30 min before measurement using a calibrated digital pH meter. Calibration was performed using standard buffer solutions of pH 4.00, 7.00, and 10.00 prior to analysis.

2.8. Determination of Electrical Conductivity

Electrical conductivity was determined using the aqueous suspension prepared for pH determination. After equilibration, conductivity was measured using a calibrated digital conductivity meter at room temperature and expressed as μS/cm. The conductivity values reflected the concentration of soluble ionic constituents present in each soot sample [14].

2.9. Determination of Apparent Density

Apparent density was determined by gently tapping the graduated measuring cylinder containing the soot sample until no further reduction in sample volume was observed. The apparent density was calculated as the ratio of sample mass to the tapped volume and expressed in g/mL [12].

2.10. Determination of Particle Number Density

Particle number density was estimated from the measured particle mass and occupied volume using standard particulate density relationships commonly employed for fine carbonaceous materials [15]. The calculated values were used to compare the relative packing characteristics of soot generated from different combustion sources.

2.11. Determination of Attrition

Attrition was determined to evaluate the mechanical stability of the soot particles. Approximately 5.00 g of each sample was subjected to controlled mechanical agitation in a laboratory shaker for 30 min. The sample was subsequently sieved through a 250 μm sieve, and the percentage loss due to abrasion was determined gravimetrically following the method of ASTM D4058 [16]. Lower attrition values indicated greater resistance to particle breakdown.

2.12. Determination of Solubility

Water solubility was determined gravimetrically. One gram of each soot sample was dispersed in 100 mL of distilled water and agitated continuously for 24 h at room temperature. The suspension was filtered through Whatman No. 1 filter paper, and the filtrate was evaporated to dryness in a pre-weighed evaporating dish. The mass of dissolved residue was determined, and the solubility was expressed as grams per litre (g/L) [17].

2.13. Statistical Analysis

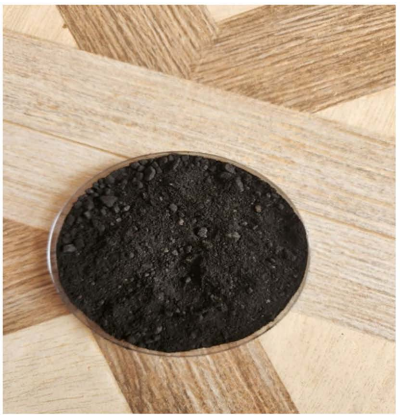
All physicochemical measurements were performed in triplicate as analytical rep-

licates on each soot sample, and the results are presented as mean ± standard deviation (SD). Statistical analysis was performed using Microsoft Excel 2021 (Microsoft Corporation, Redmond, WA, USA). Because only one representative sample was collected from each combustion source, the statistical analysis was limited to descriptive statistics, and no inferential statistical tests were performed.

3. Results and Discussion

(a) Kerosene stove soot

(b) Firewood soot



(c) Diesel generator soot

(d) Diesel vehicle soot

(e) Kerosene lamp soot

Figure 1. (a)-(e): Pictures of soot samples.

Table 1. Physicochemical properties of soot samples.

Sample	Moisture Content (%)	Bulk Density (g/mL)	pH	Conductivity (μS/cm)	Apparent Density (g/mL)	Particle Number Density (g/mL)	Attrition (%)	Solubility (g/L)
Kerosene Stove Soot	1.87 ± 0.10	0.0603 ± 0.0001	8.63 ± 0.06	44.87 ± 0.06	0.1044 ± 0.0010	0.0170 ± 0.0001	0.0487 ± 0.0002	0.0482 ± 0.0005
Firewood Soot	1.24 ± 0.01	0.2867 ± 0.0001	7.43 ± 0.06	77.77 ± 0.23	0.4965 ± 0.0030	0.0147 ± 0.0003	0.0391 ± 0.0005	0.0479 ± 0.0005
Diesel Soot	1.05 ± 0.01	0.2983 ± 0.0001	5.73 ± 0.06	36.17 ± 0.06	0.5166 ± 0.0010	0.0178 ± 0.0001	0.0570 ± 0.0003	0.0487 ± 0.0005
Diesel Vehicle Soot	1.76 ± 0.05	0.0623 ± 0.0001	5.10 ± 0.08	47.67 ± 0.24	0.1079 ± 0.0040	0.0172 ± 0.0001	0.0511 ± 0.0001	0.0479 ± 0.0005
Kerosene Lamp Soot	2.27 ± 0.01	0.0547 ± 0.0001	5.53 ± 0.06	20.81 ± 0.01	0.0948 ± 0.0010	0.0175 ± 0.0003	0.0670 ± 0.0003	0.0483 ± 0.0005

Note: Values are presented as mean ± standard deviation (n = 3).

3.1. Physical Appearance of the Collected Soot Samples

The Soot samples collected from the five combustion sources are displayed in Figure 1(a)-(e). The samples exhibited noticeable differences in colour, texture, fineness, and degree of particle agglomeration, reflecting variations in combustion conditions and fuel composition. Diesel generator and diesel vehicle soot appeared as fine, intensely black powders with relatively uniform particle distribution, indicating the formation of carbon-rich particles under high-temperature combustion. In contrast, firewood soot was relatively coarse and contained visible ash-like particles, which may be attributed to the incomplete combustion of lignocellulosic biomass and the presence of inorganic mineral residues. Kerosene stove and kerosene lamp soot exhibited intermediate characteristics, although the soot obtained from the kerosene lamp appeared finer and more loosely agglomerated than that from the kerosene stove.

The observed differences are consistent with previous reports indicating that combustion temperature, fuel composition, oxygen availability, and residence time significantly influence soot formation, particle morphology, and carbonization during combustion [18]-[20]. Biomass combustion generally produces heterogeneous particles containing appreciable inorganic ash, whereas diesel combustion yields finer soot with a greater proportion of elemental carbon and lower mineral content [5] [19]. Such variations influence the physicochemical behaviour of soot, including density, moisture retention, adsorption characteristics, and environmental persistence.

3.2. Physicochemical Properties of Soot Samples

The physicochemical properties of soot particles generated from different combustion sources are presented in Table 1. The measured parameters include moisture content, bulk density, pH, electrical conductivity, apparent density, particle number density, attrition, and solubility. These properties provide important in-

formation regarding the environmental behaviour, storage stability, handling characteristics, and potential utilization of soot as a carbonaceous material.

3.2.1. Moisture Content

Moisture content ranged from 1.05% ± 0.01% in diesel soot to 2.27% ± 0.01% in kerosene lamp soot, while kerosene stove, firewood, and diesel vehicle soot contained 1.87% ± 0.10%, 1.24% ± 0.01%, and 1.76% ± 0.05%, respectively.

The relatively low moisture contents observed in all soot samples indicate that the materials contained only small amounts of retained moisture, which is advantageous for storage stability and may reduce the likelihood of microbial deterioration during storage. The comparatively higher moisture content of kerosene lamp soot may reflect differences in the physicochemical characteristics of the soot produced under the combustion conditions of kerosene lamps. One possible explanation is the presence of more moisture-retaining surface characteristics resulting from less efficient combustion; however, surface functional groups and combustion temperature were not directly evaluated in the present study. Conversely, the lower moisture content observed for diesel soot may be associated with differences in soot formation during diesel combustion, although the degree of carbonization and graphitization was not directly determined.

Previous studies have reported that soot produced under relatively high-temperature combustion may exhibit lower moisture retention because of changes in its structural and surface characteristics [2] [19]. Moisture content is an important parameter because it influences storage stability, particle aggregation, handling characteristics, and the subsequent utilization of soot as a precursor for carbon-based materials [5] [21].

3.2.2. Bulk Density

Bulk density is an important physical property that influences the storage, transportation, handling characteristics, and environmental behaviour of particulate materials. The bulk density of the soot samples varied considerably among the combustion sources, ranging from 0.0547 ± 0.0001 g/mL for kerosene lamp soot to 0.2983 ± 0.0001 g/mL for diesel generator soot. Firewood soot also exhibited a relatively high bulk density (0.2867 ± 0.0001 g/mL), whereas kerosene stove and diesel vehicle soot recorded comparatively lower values of 0.0603 ± 0.0001 g/mL and 0.0623 ± 0.0001 g/mL, respectively.

The relatively higher bulk densities observed for diesel generator and firewood soot indicate more compact particle packing and reduced interparticle void spaces. This behaviour may be attributed to the formation of particles with greater mineral content or more compact aggregate structures resulting from prolonged combustion. Conversely, the lower bulk densities recorded for kerosene-derived soot suggest the formation of finer, highly porous aggregates with greater void volumes between particles. Such low-density materials are generally more susceptible to atmospheric suspension and long-range transport, thereby increasing their contribution to ambient particulate pollution [2] [6].

Bulk density is directly related to particle morphology and aggregation behaviour. Soot particles generated under high-temperature combustion often consist of chain-like aggregates that occupy relatively large volumes despite having low mass, thereby reducing bulk density. In contrast, biomass-derived soot may contain appreciable inorganic ash that increases packing efficiency and consequently increases bulk density [2] [5]. Similar observations have been reported for combustion-derived carbonaceous materials where variations in combustion efficiency significantly affected particle packing characteristics and storage behaviour [2] [5].

From an environmental perspective, lower bulk density enhances atmospheric residence time because lighter particles remain suspended for longer periods before gravitational settling. Consequently, kerosene stove, diesel vehicle, and kerosene lamp soot may possess greater dispersion potential than diesel generator and firewood soot. In addition, bulk density influences the processing characteristics of soot during briquetting, pelletization, activated carbon production, and other carbon-based material applications, where optimum packing behaviour contributes to improved mechanical strength and process efficiency [5] [21].

3.2.3. pH

The pH values of the soot samples ranged from 5.10 ± 0.08 to 8.63 ± 0.06, indicating appreciable variation in surface acidity and alkalinity among the combustion sources. Kerosene stove soot exhibited the highest pH (8.63 ± 0.06), indicating an alkaline nature, while firewood soot was nearly neutral (7.43 ± 0.06). Diesel generator soot (5.73 ± 0.06), diesel vehicle soot (5.10 ± 0.08), and kerosene lamp soot (5.53 ± 0.06) were moderately acidic.

The alkaline nature of kerosene stove soot may be attributed to the presence of alkaline inorganic constituents such as calcium, potassium, sodium, and magnesium compounds formed during combustion. These basic mineral components increase the alkalinity of the soot-water suspension. Conversely, the acidic nature of diesel-derived soot may result from the formation of oxygenated organic compounds, sulfur-containing species, nitrogen oxides, and other acidic combustion products deposited on the particle surface during combustion and atmospheric cooling [3] [18].

Surface pH strongly influences the environmental behaviour of soot by affecting adsorption capacity, surface charge, ion exchange, and interactions with dissolved contaminants. Alkaline carbonaceous materials generally exhibit greater affinity for acidic pollutants and certain heavy metal ions through electrostatic attraction and surface complexation mechanisms, whereas acidic soot may favour adsorption of basic compounds [2] [5]. Consequently, the observed variation in pH suggests that soot from different combustion sources may exhibit different adsorption behaviours toward environmental pollutants.

The pH of soot also influences its compatibility as a precursor material for activated carbon production and soil amendment applications. Carbonaceous materials possessing near-neutral to mildly alkaline pH are often considered more

suitable for environmental remediation because they can reduce soil acidity and improve nutrient availability. The nearly neutral pH observed for firewood soot suggests potential environmental applicability following appropriate purification, while the acidic diesel-derived soot may require pretreatment before similar applications [5] [17] [21].

3.2.4. Electrical Conductivity

Electrical conductivity of the aqueous soot extracts varied considerably among the combustion sources, indicating differences in the concentration of water-soluble ionic constituents released into solution during aqueous extraction. Firewood soot exhibited the highest electrical conductivity (77.77 ± 0.23 μS/cm), followed by diesel vehicle soot (47.67 ± 0.24 μS/cm), kerosene stove soot (44.87 ± 0.06 μS/cm), diesel generator soot (36.17 ± 0.06 μS/cm), and kerosene lamp soot (20.81 ± 0.01 μS/cm).

The conductivity values obtained in this study represent the electrical conductivity of the aqueous extracts rather than that of the dry soot particles. During extraction, water-soluble ionic species associated with the soot dissolve into the aqueous medium, and the measured conductivity therefore reflects the concentration of dissolved ions present in the extract. Consequently, higher conductivity values indicate greater quantities of extractable ionic constituents, whereas lower values suggest a lower abundance of water-soluble inorganic species in the soot.

The comparatively high conductivity observed for firewood soot may be attributed to the dissolution of inorganic ash constituents and mineral salts commonly associated with biomass combustion, while the relatively low conductivity of kerosene lamp soot suggests a lower concentration of water-soluble ionic species. Differences observed among the soot samples are consistent with variations in fuel composition, combustion conditions, and the chemical composition of the extractable inorganic fraction. Similar observations have been reported for combustion-derived particulate matter, where electrical conductivity of aqueous extracts reflects the abundance of soluble inorganic constituents rather than the intrinsic electrical conductivity of the carbonaceous particles [5] [22].

3.2.5. Apparent Density

The apparent density of the soot samples ranged from 0.0948 ± 0.0010 g/mL for kerosene lamp soot to 0.5166 ± 0.0010 g/mL for diesel generator soot. Firewood soot also exhibited a relatively high apparent density (0.4965 ± 0.0030 g/mL), whereas kerosene stove and diesel vehicle soot recorded considerably lower values of 0.1044 ± 0.0010 g/mL and 0.1079 ± 0.0040 g/mL, respectively.

The trend observed for apparent density closely followed that of bulk density, indicating differences in particle packing characteristics among soot samples collected from the selected combustion sources. Diesel generator soot exhibited the greatest apparent density, suggesting that the particles possessed relatively compact aggregate structures with reduced internal pore spaces. In contrast, kerosene-derived soot exhibited considerably lower apparent densities, reflecting the formation of loosely packed aggregates containing larger interparticle voids.

Differences in apparent density are primarily associated with variations in combustion temperature, particle morphology, aggregate structure, and mineral composition. High-temperature combustion generally promotes particle sintering and aggregation, producing denser soot particles, whereas incomplete combustion favours the formation of highly porous carbonaceous aggregates with lower packing efficiency [2] [5]. Biomass combustion may further increase apparent density through incorporation of inorganic ash particles within the soot matrix [6].

Apparent density is an important parameter in the processing and utilization of particulate carbon materials because it influences material handling, storage capacity, pelletization behaviour, and the mechanical properties of compressed products. Materials possessing relatively high apparent density generally exhibit improved compaction characteristics during briquetting and tablet production, while lower-density materials often possess higher external surface areas and greater accessibility of adsorption sites. Consequently, the relatively low apparent density observed for kerosene-derived soot may favour adsorption applications, whereas the denser diesel generator soot may be advantageous where higher packing efficiency is required.

3.2.6. Apparent Particulate Density

Apparent particulate density provides an indication of the mass of particulate matter occupying a given sample volume and is useful for assessing the packing characteristics of particulate materials. The soot samples exhibited only slight variations in apparent particulate density, with values ranging from 0.0147 ± 0.0003 g/mL for firewood soot to 0.0178 ± 0.0001 g/mL for diesel generator soot. Kerosene stove, diesel vehicle, and kerosene lamp soot recorded values of 0.0170 ± 0.0001 g/mL, 0.0172 ± 0.0001 g/mL, and 0.0175 ± 0.0003 g/mL, respectively.

The relatively narrow range of apparent particulate density observed among the soot samples suggests that, despite differences in combustion source, the soot particles exhibited broadly similar packing behaviour. The slightly higher apparent particulate density of diesel generator soot may reflect differences in particle packing associated with combustion conditions. Differences in aggregate structure provide one possible explanation; however, particle morphology and aggregate structure were not directly characterized in this study. Conversely, the lower value obtained for firewood soot may be associated with irregularly shaped particles and the presence of mineral ash that reduce packing efficiency and increase interparticle void spaces [13] [23].

Apparent particulate density is influenced by factors such as combustion temperature, fuel composition, particle morphology, ash content, and the degree of particle aggregation during soot formation. These factors determine the compactness of soot particles and consequently affect their bulk handling characteristics and storage behaviour. Previous studies have reported that diesel combustion may produce carbonaceous particles with relatively compact aggregate structures, whereas biomass combustion may generate more heterogeneous particulate matter. However, aggregate morphology was not directly examined in the present

study [5] [22].

From an environmental and materials perspective, apparent particulate density is an important parameter because it influences the transport, storage, handling, and utilization of particulate materials. Variations in particle packing characteristics may also affect the accessibility of internal pore structures and exposed surface area, thereby influencing adsorption behaviour and the suitability of soot as a precursor for carbon-based materials and environmental remediation applications [24].

3.2.7. Attrition

Attrition is an important indicator of the mechanical stability and durability of particulate materials during handling, transportation, storage, and processing. The attrition values of the soot samples ranged from 0.0391% ± 0.0005% for firewood soot to 0.0670% ± 0.0003% for kerosene lamp soot. Intermediate values were obtained for kerosene stove (0.0487% ± 0.0002%), diesel generator (0.0570% ± 0.0003%), and diesel vehicle soot (0.0511% ± 0.0001%).

The generally low attrition values obtained for all samples indicate that the soot particles possess relatively good mechanical stability despite differences in combustion source. Firewood soot exhibited the lowest attrition, suggesting greater resistance to mechanical degradation, possibly due to the presence of inorganic ash particles that reinforce the particulate structure. In contrast, kerosene lamp soot exhibited the highest attrition, indicating comparatively weaker particle cohesion and a greater tendency to generate fines during handling.

Mechanical stability is influenced by particle morphology, aggregate structure, carbonization degree, and mineral composition. Soot produced under high-temperature combustion generally contains highly carbonized particles with stronger aggregate bonding, whereas particles produced under less efficient combustion may possess weaker structural integrity owing to incomplete carbonization and higher concentrations of volatile organic compounds [5] [6]. The relatively small differences observed among the combustion sources indicate that all soot samples retained acceptable structural stability for laboratory handling and potential processing.

From an application perspective, attrition resistance is an important quality parameter for carbonaceous materials intended for adsorption, catalyst support, briquetting, or pellet production. Materials exhibiting low attrition generate fewer dust particles during handling, thereby minimizing material loss and improving operational efficiency. Consequently, the low attrition values recorded in this study suggest that the soot samples possess favourable handling characteristics for potential environmental and industrial applications.

3.2.8. Solubility

Solubility is an important physicochemical property that influences the environmental mobility, persistence, and potential applications of particulate materials. The solubility values of the soot samples were uniformly low, ranging from 0.0479

± 0.0005 g/L to 0.0487 ± 0.0005 g/L. Firewood soot and diesel vehicle soot exhibited the lowest solubility (0.0479 ± 0.0005 g/L), whereas diesel generator soot showed the highest value (0.0487 ± 0.0005 g/L). Kerosene stove and kerosene lamp soot recorded values of 0.0482 ± 0.0005 g/L and 0.0483 ± 0.0005 g/L, respectively. The minimal variation observed among the combustion sources indicates that all soot samples were predominantly composed of water-insoluble carbonaceous materials.

The low aqueous solubility observed is consistent with the chemical nature of soot, which consists largely of elemental carbon and condensed aromatic structures that exhibit strong hydrophobic behaviour. During combustion, carbon atoms undergo polymerization and graphitization to form stable carbonaceous aggregates with limited affinity for water molecules. Consequently, only a small fraction of inorganic salts and oxygenated organic compounds present on the particle surfaces dissolve in aqueous media, while the bulk of the soot remains insoluble [19] [25].

Although the differences in solubility among the soot samples were relatively small, the slightly higher solubility recorded for diesel generator soot may be attributed to the presence of small quantities of oxygenated organic compounds or soluble inorganic constituents generated during fuel combustion. In contrast, the lower solubility observed for firewood soot and diesel vehicle soot suggests a relatively greater proportion of hydrophobic carbonaceous material. Similar findings have been reported for combustion-derived carbon particles, where water-soluble components constitute only a minor fraction of the total particulate mass, with elemental carbon dominating the particle composition [10] [19].

The low solubility of soot has important environmental implications. Insoluble particles tend to persist longer in soils and sediments after atmospheric deposition because they are not readily dissolved or leached by rainfall. This persistence enhances their potential to accumulate in terrestrial and aquatic environments, where they may act as carriers for heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other environmental contaminants through adsorption mechanisms [2] [6]. Furthermore, the hydrophobic nature of soot contributes to its high affinity for non-polar organic pollutants, making it a potentially valuable precursor for adsorbents used in wastewater treatment and environmental remediation [1] [5].

From an application standpoint, the low water solubility observed for all soot samples is advantageous for the development of carbon-based adsorbents because insoluble carbon materials generally exhibit greater chemical stability and resistance to dissolution during repeated adsorption cycles. These characteristics enhance their suitability for applications such as pollutant removal, catalyst support materials, activated carbon production, and other environmental technologies. Therefore, despite being regarded as an atmospheric pollutant, combustion-derived soot possesses physicochemical properties that support its potential valorization as a low-cost carbonaceous resource following appropriate purification and processing.

4. Conclusions

This study comparatively evaluated the physicochemical properties of soot obtained from five common combustion sources, namely kerosene stove, firewood, diesel generator, diesel vehicle, and kerosene lamp, collected within Jos Metropolis, Plateau State, Nigeria. Observable differences were found among the soot samples in their physicochemical properties. Bulk density ranged from 0.0547 ± 0.0001 to 0.2983 ± 0.0001 g/mL, apparent density from 0.0948 ± 0.0010 to 0.5166 ± 0.0010 g/mL, and particle number density ranged from 0.0147 ± 0.0003 to 0.0178 ± 0.0001 g/mL. The pH values varied from 5.10 ± 0.08 to 8.63 ± 0.06, while the electrical conductivity of the aqueous extracts ranged from 20.81 ± 0.01 to 77.77 ± 0.23 μS/cm.

Moisture content ranged from 1.05% ± 0.01% to 2.27% ± 0.01%, ash content from 4.39% ± 0.01% to 32.55% ± 0.01%, volatile matter from 27.40% ± 0.01% to 69.20% ± 0.01%, and fixed carbon from 25.85% ± 0.01% to 67.21% ± 0.01%. Diesel soot exhibited the highest particle number density (0.0178 ± 0.0001 g/mL), whereas firewood soot showed the highest electrical conductivity (77.77 ± 0.23 μS/cm) and ash content (32.55% ± 0.01%). Kerosene lamp soot possessed the highest moisture content (2.27% ± 0.01%) and the lowest electrical conductivity (20.81 ± 0.01 μS/cm), while diesel soot recorded the lowest moisture content (1.05% ± 0.01%) and the highest fixed carbon content (67.21% ± 0.01%).

These observed variations likely reflect differences in fuel type and combustion conditions among the selected combustion sources. However, properties such as particle size, particle morphology, porosity, graphitization, elemental composition, and surface functional groups were not directly characterized in the present study; therefore, any mechanistic explanations relating these properties to the observed physicochemical characteristics should be regarded as plausible hypotheses rather than definitive conclusions.

Overall, the findings provide baseline physicochemical data for soot generated from common domestic and transportation-related combustion sources in Jos Metropolis and contribute to a better understanding of their environmental behaviour, storage characteristics, and potential utilization as carbonaceous materials. Future studies should include multiple independent samples from each combustion source together with advanced characterization techniques, such as particle size analysis, microscopic imaging, elemental analysis, and surface chemistry characterization, to further elucidate the mechanisms underlying the observed differences and improve the representativeness of the findings.

Author Contributions

Conceptualization, Adams Udoji Itodo, and Roselyn Benjamin Sumi; methodology, Roselyn Benjamin Sumi; software, Agodwin Owoicho Awodi; validation, Adams Udoji Itodo, Ishaq Shuaibu Eneji, and Moses Saviour Iorungwa; formal analysis, Roselyn Benjamin Sumi; investigation, Roselyn Benjamin Sumi; resources, Roselyn Benjamin Sumi.; data curation, Godwin Owoicho Awodi; writing—orig-

inal draft preparation, Roselyn Benjamin Sumi; writing—review and editing, Godwin Owoich Awodi; visualization, Adams Udoji Itodo; supervision, Adams Udoji Itodo; project administration, Roselyn Benjamin Sumi; funding acquisition, Roselyn Benjamin Sumi. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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