

Comparative Physicochemical Characterization of Particulate Matter Emitted from Diya

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Abstract. Particulate matter (PM) or carbon soot generated from combustion process can be a primary contributor to indoor air pollution and associated health risks, predominantly through the sequestration of carcinogenic polycyclic aromatic hydrocarbons (PAHs). This study conducted a comparative physicochemical analysis of PM generated from the combustion of kerosene, four common vegetable oils (mustard, peanut, coconut, castor), and two types of animal ghee (cow and buffalo) to establish a clear chemical hazard gradient. PM samples were characterized using Fourier-Transform Infrared Spectroscopy (FTIR), UV-Visible spectroscopy, Thermogravimetric Analysis (TGA), and Dynamic Light Scattering (DLS). UV-Visible analysis showed Kerosene PM exhibited the highest overall absorbance, directly corresponding to the maximum concentration of toxic, high-molecular-weight (HMW) PAHs. This was substantiated by TGA, which confirmed Kerosene PM has the highest thermal stability, indicative of a highly condensed elemental carbon (EC) structure necessary for PAH binding. Conversely, Ghee PM consistently demonstrated lower aromatic signature and visible light absorption, and also the least thermal stability, suggesting a PM structure dominated by highly volatile organic carbon and a negligible concentration of condensed, hazardous PAHs. DLS analysis further confirmed Kerosene PM forms large, highly aggregated soot clusters, distinct from the finer lipid-based PM. The data demonstrate that PM from ghee combustion is structurally less condensed and volatile, supporting the observation that ghee-derived PM may pose a lower respiratory risk profile than kerosene PM.

Keywords. Particulate matter, Diya, Spectroscopy, clarified butter (Ghee)

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Introduction

The Vedic fire ritual, known as Yagya is a controlled process of herbal sublimation, fumigation, and inhalation. Embedded in the Yajurveda and Atharvaveda, it is labelled as means to purify the environment, eliminate airborne pathogens, and promote holistic well-being. Ancient texts highlight its antimicrobial and air-purifying properties, but scientific validation of these effects remains limited. Hence it is mandate to analyze the physicochemical characteristics of particulate matter (PM) or carbon soot generated during Yagya. Exposure to fine particulate matter PM_{2.5} and ultrafine particles originating from the incomplete combustion of household fuels represents a pervasive global public health challenge [1]. Worldwide, residential combustion for cooking and heating remains a primary source of indoor air pollution, exposing billions to high concentrations of airborne pollutants, which is known to lead to numerous adverse health outcomes [1]. The danger posed by this combustion-derived PM is not merely a function of the particle's size and mass, but critically hinges on its chemical composition, particularly the presence and concentration of toxic organic compounds. The key chemical risk factor associated with combustion aerosols is the presence of polycyclic aromatic hydrocarbons (PAHs). PAHs are molecules consisting of two or more fused aromatic rings [2]. These compounds are formed during the incomplete thermal breakdown of organic matter and subsequently condense onto the surface of carbonaceous particles [3], often termed soot or black carbon. The toxicity of PAH-laden PM is directly proportional to the size and complexity of the aromatic molecules present. High-molecular-weight (HMW) PAHs, defined as those possessing five or more aromatic rings, are particularly hazardous, classified as potent carcinogens and mutagenic agents. These HMW-PAHs exhibit low volatility and are predominantly bound to the particulate phase, especially the fine particle fraction PM_{2.5} [4]. Therefore, establishing a comparative hazard potential between different fuel types requires rigorous physicochemical characterization of the produced PM, focusing specifically on the degree of PAH formation and carbon condensation. The inherent molecular structure of a fuel profoundly dictates the mechanism and efficiency of PAH and soot formation. We analyse two distinct categories of fuels: petroleum distillates and natural triglycerides.

Kerosene, a distillate fuel oil, is structurally composed of complex mixtures of alkanes, naphthene, and pre-existing aromatic compounds [5]. During the high-temperature conditions of combustion, these components readily undergo cyclization, dehydro-

genation, and polymerization reactions, accelerating the formation of PAH ring systems [6]. This inherent structural composition-containing aromatic and cyclic precursors-significantly lowers the energy barrier for soot nucleation[7], leading to a highly efficient pathway for generating mature, condensed carbon structures, often referred to as Elemental Carbon (EC). This EC soot provides a chemically stable matrix with a high surface area, which is essential for the irreversible sequestration of toxic, non-volatile HMW-PAHs [3]. Previous studies have confirmed that kerosene burning yields substantial emission factors for highly carcinogenic compounds like Benzo[a]pyrene (B[a]P) [8]. This established chemical pathway suggests that PM generated from kerosene combustion should exhibit maximum condensation and PAH burden. In stark contrast to kerosene, animal ghee is a saturated fat composed primarily of triglycerides with long-chain fatty acid esters. For PAH formation to occur in lipid combustion, the complex fatty acids must first be thermally cracked into smaller, simpler hydrocarbon fragments, such as acetylene or benzene precursors, before cyclization can begin [6]. This initial decomposition step acts as a chemical bottleneck for subsequent PAH formation. More importantly, highly saturated fats, such as ghee, possess a high molar hydrogen-to-carbon (H/C) ratio. Scientific evidence indicates that an increased H/C ratio in the fuel actively suppresses soot and hydrocarbon emissions [9]. The lack of double bonds in saturated chains minimizes the availability of allylic and bis-allylic radicals necessary for the initial stages of high-efficiency soot nucleation [10]. Therefore, the fundamental chemical structure of animal ghee suggests a combustion environment that is significantly less conducive to forming condensed aromatic structures and stable EC soot compared to kerosene.

Integrating traditional wisdom with modern scientific techniques, this study will provide evidence-based comparative physicochemical characterization of PM Emitted from Yagya. The objective of this study is to perform a detailed comparative analysis of the particulate matter generated from kerosene, animal ghee, and various vegetable oils, focusing on the structural differences that dictate the final chemical nature and stability of the emissions. We aim to compare the physicochemical properties of the PM derived from kerosene and ghee to confirm the difference in their condensation levels. Vegetable oil samples (mustard, peanut, coconut, and castor) were included to provide a comprehensive analysis across the spectrum of lipid-based fuels. Based on the distinct differences in fuel chemistry-the highly satu-

rated, high H/C ratio of animal ghee versus the aromatic precursor-rich composition of kerosene—our comparative analysis claims that the PM generated from ghee samples displays properties that are potentially less deleterious than the PM generated from kerosene samples.

Materials and Methods

Fuel Selection

To establish a comparative chemical hazard gradient in combustion-derived particulate matter (PM), lipid-based fuels of both plant and animal origin were selected. The study included four commonly used vegetable oils—mustard oil (Patanjali Ayurved India), peanut oil (Gulab Oils, India), coconut oil (Parachute–Marico, India), and castor oil (Trisul, India)—along with two types of animal-derived clarified butter (ghee), namely cow ghee and buffalo ghee. All vegetable oils were procured as commercially available food-grade products. The animal ghee samples were prepared in-house to ensure compositional authenticity and eliminate processing-related variability.

Preparation of Animal Ghee

Both cow and buffalo ghee were prepared using a traditional fermentation and churning method. Fresh milk (1 L) was boiled, allowed to cool naturally, and left undisturbed for 24 h to facilitate cream separation. The upper cream layer was collected daily into a stainless-steel container. On the first day, 5 g of curd was added as a starter culture; no further curd was added during subsequent collections. This process was repeated for seven consecutive days.

After completion of cream collection, the accumulated cream was transferred to a larger vessel, and warm water (approximately 40 °C) was added. The mixture was manually churned using a wooden churning stick until butter (makkhan) separated. The butter was then heated in a stainless-steel container until clarified butter separated completely from the milk solids. The resulting ghee was filtered through a clean cloth and stored in airtight glass containers at ambient temperature until further use. Identical procedures were followed for the preparation of both cow and buffalo ghee.

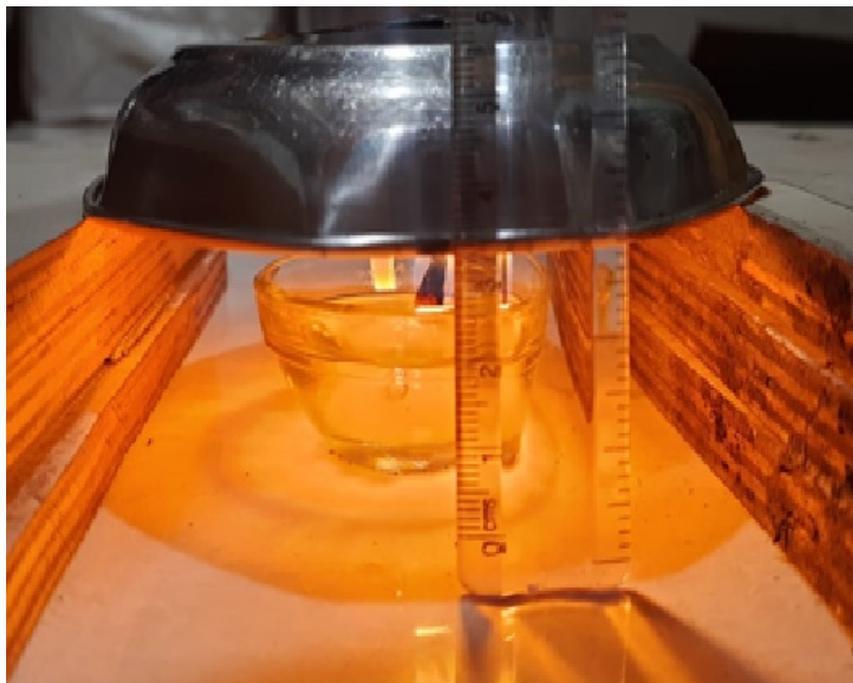


Figure 1: An image captured after Diya set up for collecting PM of vegetable oils and animal ghee.

Combustion Experiment

Combustion experiments were conducted using traditional oil lamps (diyas), each consisting of a

small cup-shaped glass container fitted with a cotton wick. For each experiment, 10 g of the respective fuel was added to a diya, and the wick was ignited under

ambient laboratory conditions. Each fuel sample was burned continuously for approximately 20–30 min to ensure stable combustion and sufficient particulate generation.

Particulate Matter Collection

Carbonaceous particulate matter (soot) generated during combustion was collected using a stainless-steel bowl positioned approximately 4 cm above the

flame. The bowl acted as a passive deposition surface, allowing direct collection of freshly formed particulate matter without filtration or dilution. The experimental configuration was maintained consistently across all fuel types. The overall experimental setup is illustrated schematically in Fig. 1.

The collected particulate matter was carefully scraped from the bowl surface after each experiment and stored in pre-cleaned containers for subsequent physicochemical characterization.

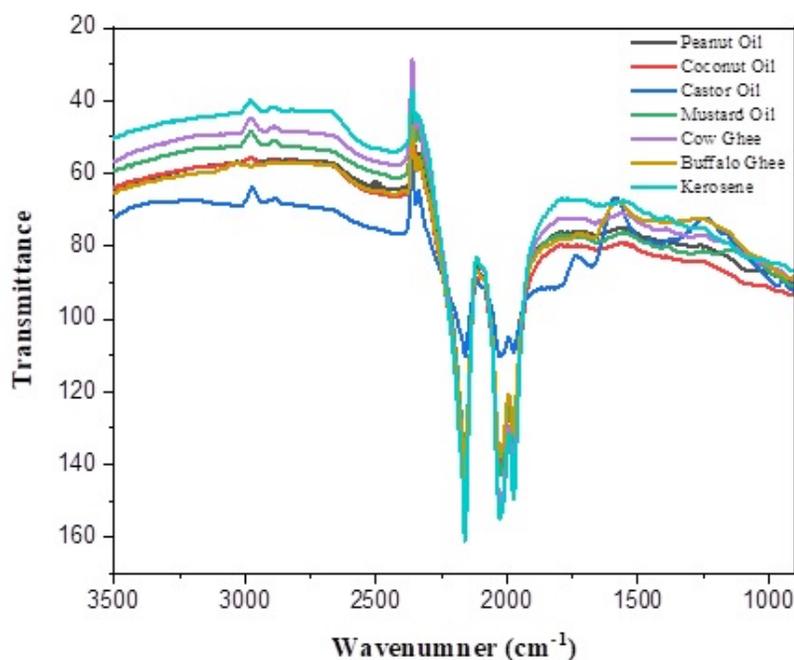


Figure 2: Comparative FTIR spectra of PM generated from various oil and ghee samples.

Result

FTIR Spectroscopy

The FT-IR data shows a remarkably similar chemical fingerprint across all seven samples of generated particulate matter, consistent with observations in soot from various fuel sources (Fig. 2) [11]. The slight shoulder bands around 3000 cm^{-1} are due to

the stretching vibrations of aliphatic and aromatic C–H bonds. While the strongest and most defining peaks appear in the 2100 cm^{-1} to 2400 cm^{-1} range, a region typically associated with triple bonds ($\text{C}\equiv\text{C}$) or highly volatile CO_2 gas or perhaps nitrile/cyanate compounds from incomplete combustion [13]. A notable feature is the near-total absence of major char-

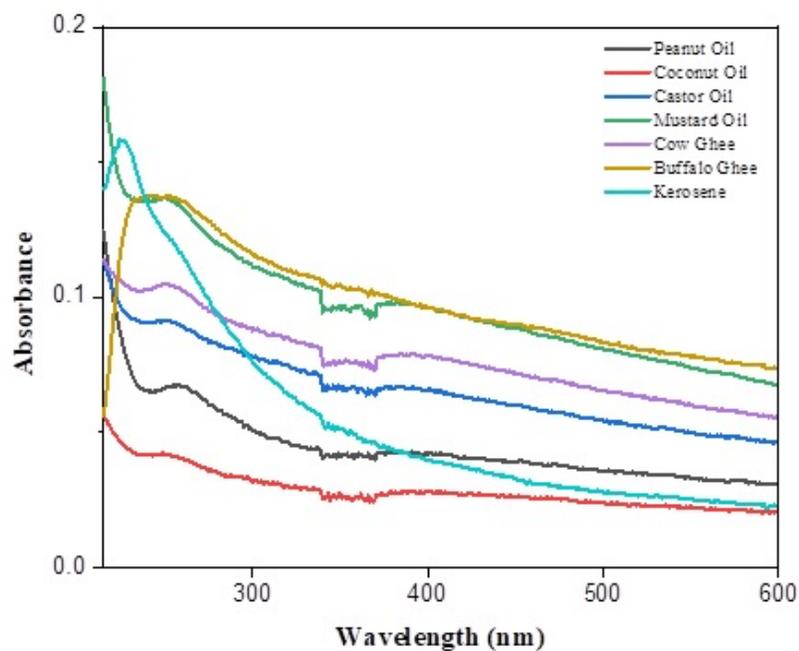


Figure 3: UV-Visible spectroscopic analysis depicting relative absorbance of all samples.

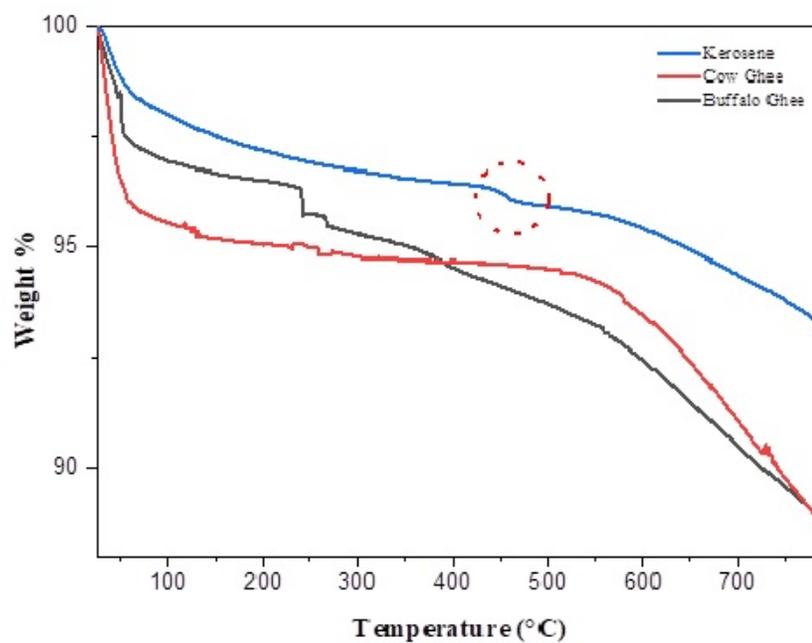


Figure 4: TGA plot comparing thermal stability of Kerosene with Ghee PMs.

acteristic peaks for O-H (3300 cm^{-1}), C=O (1700 cm^{-1}), and C-H stretches ($2800\text{--}3000\text{ cm}^{-1}$) which

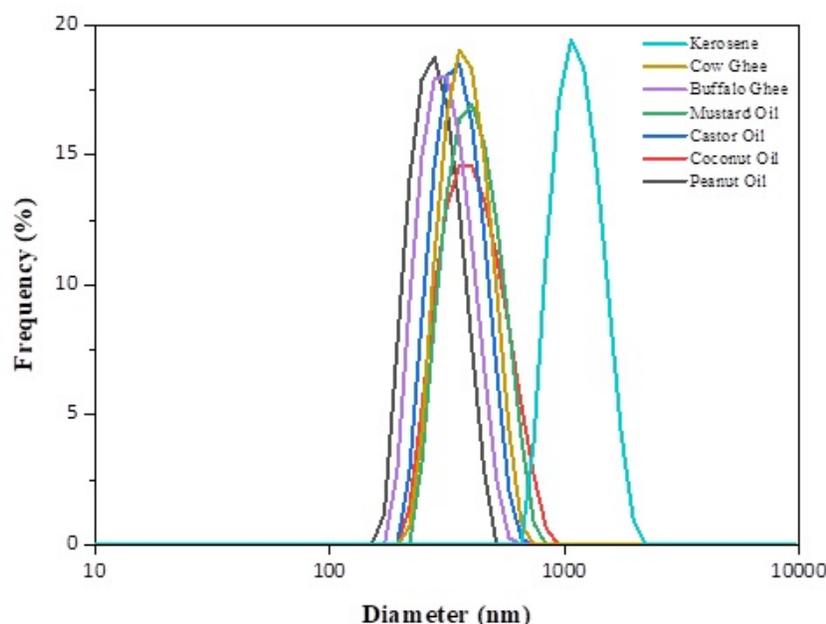


Figure 5: Particle Size Distribution of all PM samples using DLS.

are abundant in the parent oils/ghee/kerosene, which is in line with findings from Shankar et al. (2022), which report that combustion-derived PM often loses complex functional groups and is dominated by carbonaceous structure [14]. Moreover, in the context of combustion and particulate matter, the highly intense, sharp inverted doublets are often the result of atmospheric CO_2 interacting with the detector [15]. Also, there is a weak absorption shoulder (low transmittance) for most samples around 1750 cm^{-1} , which is commonly observed in combustion-derived particulate matter or organic aerosols and is attributed to residual carbonyl ($\text{C}=\text{O}$) or carboxyl functionalities formed by incomplete oxidation [16]. Hence, the FT-IR spectra indicates that the PM collected is highly carbonaceous with a simplified structure. The combustion process has largely broken down the complex C-H chains (fatty acids/alkanes) into elementary carbon (soot) and simple combustion by-products. The IR differences between the seven samples are minimal, suggesting that the final chemical nature of the solid PM generated is similar, regardless of the initial fuel source (fat, oil, or alkane).

UV-Visible Spectroscopy

For UV-Visible spectroscopic measurements, particulate matter (PM) samples obtained from each

combustion source were subjected to a standardized dispersion protocol to ensure uniformity and reproducibility. Approximately 0.2 mg of each dried PM sample was dispersed in 15 mL of distilled water. The suspension was sonicated for 5 minutes in an ultrasonic bath and then filtered through a Grade 1 Whatman filter paper having pore size of 11 micrometer to remove larger particulates and undispersed residues. The clear filtrate was collected and spectral analysis was performed after diluting 1 mL of the filtrate with 4 mL of distilled water. The resulting working solutions (1:5 dilution) were analyzed in the wavelength range of $200\text{-}800\text{ nm}$, employing distilled water as the baseline reference. The spectra characterize the PM's electronic structure, which is related to the presence of conjugated double bonds (like those found in PAH) and the overall degree of graphitization (carbonization). All the spectra in general, display a broad, continuous absorption profile that decreases with increasing wavelength, indicating the classic signature of $\pi \rightarrow \pi^*$ transitions common in amorphous carbonaceous materials [17], confirming that PM from all sources is fundamentally carbon-based. The varying absorbance reflects differences in the degree of PAH formation and carbon condensation. As observed from Fig.3 Kerosene exhibits a large, sharp peak in the $200\text{-}300\text{ nm}$ range and high overall ab-

sorbance. This strong absorption in the UV region is characteristic of highly unsaturated compounds and PAH [18], suggesting that kerosene combustion produces a significant amount of high-energy toxic intermediates in the PM. When discussing about the two ghee samples, cow ghee shows an intermediate absorbance profile, notably lower than Kerosene but higher than most oils, maintaining a clear spectral shoulder around 250 nm. This indicates the Cow ghee is moderately carbonized and contains fewer aromatic/conjugated structures compared to Kerosene, but more than Coconut, Peanut and Castor oils. Buffalo ghee however maintains a higher absorbance profile than Cow Ghee, indicating a greater degree of PAH formation or soot condensation compared to the other Ghee and Oil samples, but its slight lower value of absorbance than Kerosene, across the visible range, suggests that Buffalo Ghee PM is less carbonized than kerosene. Amongst oils, Mustard oil shows the highest absorbance across the entire spectrum, indicating high optical density and highest concentration of light-absorbing PAH among all oils, while Coconut oil, showing the lowest absorbance, is likely the least carbonized and contains the lowest concentration of PAH and chromophores. The unique UV-Visible profiles of Kerosene and Buffalo Ghee sample suggest that the combustion mechanisms of these fuels differ significantly from those of vegetable oils, justifying the decision to proceed with Thermogravimetric Analysis (TGA) on only these samples to assess their thermal stability and residual volatile content.

Thermogravimetric Analysis

Approximately 5-6 mg of each PM sample was directly loaded into the platinum sample pan of the thermogravimetric analyser (TGA) without any further pretreatment. The analysis was conducted over a temperature range of 30°C to 800°C under an inert nitrogen atmosphere, with a constant heating rate of 10°C min⁻¹ (Fig. 4). The weight change as a function of temperature was recorded to evaluate the thermal stability, volatile content, and decomposition behaviour of the samples. Initially, Kerosene, Gir Cow Ghee, and Buffalo Ghee all show a rapid 3-5% weight loss before 200°C. This initial loss is likely due to the evaporation of adsorbed water or very volatile organic components (VOCs) that were trapped within the PM structure. As observed, kerosene has the highest overall thermal stability, maintaining a higher weight percentage than the ghee until the very end of the run. Indicating that kerosene PM is composed of longer, more stable hydrocarbon chains (or more condensed carbon structures) [19] that require higher temperatures to decompose. Both

the ghee samples however show a more gradual and steeper weight loss curve compared to kerosene between 200°C and 700°C. This indicates that the PM from animal fats contains more thermally degradable components [20] (such as residual long-chain fatty acids or less-condensed carbon structures) compared to the 'purer' carbon soot from kerosene. A slight, circled "shoulder" in the kerosene spectrum, visible near 450°C, could possibly represent the decomposition of a specific, slightly less stable component trapped within the PM. [21] Also, the Buffalo Ghee sample shows a slightly lower thermal resistance than Gir Cow Ghee, suggesting that Buffalo Ghee is the least stable overall.

DLS Analysis

Dynamic light scattering (DLS) provides an estimate of the hydrodynamic size of particles in suspension and is commonly applied to soot or carbonaceous particulate matter [22]. It is to be noted that the DLS measurements report the size distribution of PM in its aggregated state post-collection and not the nascent primary ultrafine particles produced during combustion. Since the nascent particles undergo significant agglomeration into larger clusters during the subsequent processes of cooling and collection, they are generally characterized in real-time using Scanning Mobility Particle Sizer (SMPS). While SMPS is the ideal standard for capturing nascent particle distributions, the current DLS data analysis is a reliable characterization of the stable aggregates. The DLS data provides a critical comparison of the physical size of the generated particles, which directly impacts their health and atmospheric effects by correlating with the ability of PM to be inhaled and penetrate deep into the respiratory tract. Approximately 0.2 mg of each PM sample was dispersed in 15 mL of distilled water and subjected to ultrasonic agitation for 5 min to achieve a stable colloidal suspension and to minimize aggregation. The well-dispersed suspensions were subsequently analyzed by DLS to determine the distribution of the particulates. As indicated by the cyan coloured line in Fig.5, a highly distinct, single peak around 1000 nm (1.0 µm) is observed for kerosene. Indicating that kerosene generates the largest PM. This size is near the PM10 range, suggesting agglomeration or a different mechanism of soot formation due to kerosene's purely hydrocarbon, non-fatty-acid composition. All other samples (oils and ghee) cluster tightly, with peak diameters generally between 200 nm and 400 nm. This indicates that all natural lipid fuels (oils and ghee) produce PM that is consistently in the fine particle (PM2.5) and ultrafine range [23]. While these are in the ultra-

fine range (PM_{2.5}), the unique composition of Ghee (proven by TGA) suggests these particles are not condensed, toxic carbon. Furthermore, the single, large 1000 nm peak of Kerosene may represent highly agglomerated, toxic carbon structures (as suggested by its high TGA stability). Although both Kerosene and Ghee PM are in the inhalable range, the DLS data supports the TGA findings that the two are fundamentally different. Kerosene forms a unique, coarser, highly agglomerated particulate that is distinct from the general lipid combustion products. The ghee PM, while small, is thermally volatile and less condensed (TGA), making it less deleterious than the stable, highly condensed, and large Kerosene PM (TGA and DLS).

Conclusion

This study utilized an integrated analytical approach to perform a detailed comparative physicochemical characterization of PM generated from kerosene and animal ghee combustion, with vegetable oils included for context. The study successfully established a clear structural divergence between the PM derived from the highly saturated fat (ghee) and the petroleum distillate (kerosene), providing evidence to support the finding that PM from ghee possesses a more favorable physicochemical profile than PM from kerosene. The integrated evidence conclusively demonstrates that the physicochemical characteristics of Kerosene PM are aligned with highly matured, highly condensed carbonaceous aerosols. Specifically, Kerosene PM exhibited maximum overall absorption in the UV-Visible spectrum. This is the definitive electronic signature for HMW-PAHs - the key carcinogenic agents-confirming the highest degree of aromatic condensation. This high structural maturity is corroborated by TGA, which showed maximum thermal stability across the entire temperature range, signifying a robust Elemental Carbon matrix necessary for sequestering stable HMW-PAHs. Furthermore, DLS revealed that Kerosene PM forms large, highly aggregated soot clusters (1000 nm), distinguishing it physically from the other lipid combustion products. In sharp contrast, the PM generated by Ghee samples consistently demonstrated characteristics indicative of low carbon maturity and high volatility. Ghee PM showed significantly lower thermal stability in the TGA profile, suggesting a structure dominated by thermally degradable organic carbon and lacking the condensed graphitic structure found in kerosene soot. This minimal structural condensation correlates with the reduced overall UV-Visible absorption compared to kerosene, indicating a lower content of condensed aromatic species. In sum-

mary, the substantial differences in chemical structure, thermal stability, and aggregation state between the fuels lead to distinct PM profiles. Kerosene combustion yields highly condensed, chemically stabilized particulates associated with maximized aromatic hydrocarbon condensation, while ghee combustion yields PM that is thermally volatile and less condensed. Therefore, the findings of this detailed comparative analysis suggest that the PM generated from ghee samples exhibits a lower potential for adverse health effects than the PM generated from kerosene samples. While these physicochemical signatures provide a foundation for understanding fuel-specific emissions, they remain indicative rather than conclusive of biological toxicity. Future work should focus on quantifying the specific HMW-PAH species concentration in the PM extracts, including their time-dependent evolution during the combustion process, to provide a quantitative toxicological profile that directly builds upon these physicochemical distinctions. Additionally, conducting formal in vitro biological assays is essential to transition from these structural indicators to a definitive assessment of the actual health risks posed by these particles.

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