

Article

Seasonal Dynamics, Size Distribution, and Coastal Atmospheric Processing of Biomass-Derived Polycyclic Aromatic Hydrocarbons from Ribbed Smoked Sheet Production in Southern Thailand

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Abstract

Ribbed Smoked Sheet (RSS) rubber production in southern Thailand relies extensively on rubber-wood combustion, potentially generating substantial emissions of fine particulate matter and polycyclic aromatic hydrocarbons (PAHs). Despite the economic importance of this sector, systematic characterization of biomass-derived PAHs under tropical monsoonal and coastal conditions remains limited. This study investigates the particle size distribution, concentration levels, seasonal variability, and atmospheric dynamics of PAHs associated with RSS production in Chumphon Province, Thailand. Size-segregated particulate matter was collected using an eight-stage Andersen cascade impactor at two contrasting sites during a seven-month monitoring period from March to September 2025, covering the transition from the late dry/summer season to the rainy season in southern Thailand. Fifteen priority PAHs were quantified by high-performance liquid chromatography with fluorescence detection. Results indicate that emissions from rubber-wood combustion inside smokehouses exhibit a unimodal distribution dominated by submicron particles (MMAD = 0.85 μm ; GSD = 2.71). Ambient aerosols displayed a bimodal structure, with an accumulation-mode peak ($\sim 0.6 \mu\text{m}$) associated with combustion processes and a coarse-mode peak ($\sim 4 \mu\text{m}$) linked to mechanical and marine aerosol sources. Particle-bound PAHs were predominantly associated with fine particles ($\sim 0.59 \mu\text{m}$), although seasonal hygroscopic growth under high humidity shifted modal diameters toward $\sim 1.8 \mu\text{m}$ during the rainy season. PAH profiles were dominated by 3–4 ring compounds characteristic of biomass combustion. Total PAH concentrations exhibited a strong positive correlation with monthly RSS production, while precipitation demonstrated an exponential scavenging effect. Monsoonal circulation and sea spray aerosol (SSA) interactions were identified as key regulators of gas–particle partitioning, transport pathways, and removal efficiency. The findings reveal that the coastal atmosphere of southern Thailand functions as a dynamic multiphase system in which emission intensity, hygroscopic particle growth, monsoonal transport, and wet deposition collectively govern PAH behavior. This study provides the first integrated assessment linking rubber-sheet production dynamics to size-resolved PAH distributions under tropical coastal conditions and offers a scientific foundation for emission mitigation strategies in biomass-dependent agro-industrial regions.



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Keywords: ribbed smoked sheet (RSS); polycyclic aromatic hydrocarbons (PAHs); high-performance liquid chromatography (HPLC); sea spray aerosol (SSA); particulate sampling

1. Introduction

Thailand is one of the world's leading producers and exporters of natural rubber derived from *Hevea brasiliensis*. The natural rubber industry plays a strategic role in the national economy, contributing substantially to export revenues, rural employment, and the development of downstream manufacturing sectors. Major importing countries include China, Japan, and the United States, where natural rubber is an essential raw material for tire manufacturing and engineered rubber products [1,2]. Among the key processed products is Ribbed Smoked Sheet (RSS), which undergoes drying and smoking in curing chambers over several days. Thermal energy for this process is primarily generated through the combustion of firewood, particularly rubber-wood and other biomass residues from rubber plantations [3–5]. Although biomass utilization aligns, to some extent, with circular economy principles, suboptimal control of combustion temperature and air–fuel ratios often leads to incomplete combustion, a major source of air pollutants, especially polycyclic aromatic hydrocarbons (PAHs) [3,6–9].

Typical anthropogenic sources of PAHs include petrogenic emissions, industrial processes, and biomass combustion. In biomass combustion systems, PAHs are primarily generated through the thermal cracking (pyrolysis) of the major structural components of biomass, including cellulose, hemicellulose, and lignin, at temperatures typically ranging from 300 to 700 °C. The formation and emission profiles of PAHs depend strongly on combustion conditions, such as temperature, oxygen availability, residence time, and fuel composition. In the rubber sheet smoking process, incomplete combustion of rubber-wood under controlled smoking conditions may promote the formation of particle-bound PAHs, which can subsequently be released into the ambient atmosphere together with fine particulate matter. Aromatic precursors generated during pyrolysis undergo radical reactions and pyrosynthesis, forming multi-ring structures containing two to six fused aromatic rings. High-molecular-weight PAHs (≥ 4 rings), such as benzo[a]pyrene, are chemically stable and persistent in the environment, and many high-molecular-weight PAHs exhibit strong carcinogenic potential [7,10,11]. The International Agency for Research on Cancer (IARC) has classified benzo[a]pyrene as a Group 1 human carcinogen and several other PAHs as probable or possible carcinogens [10,12]. Environmentally, PAHs are categorized as semi-volatile organic compounds (SVOCs) that partition between the gas and particulate phases, with a strong tendency to adsorb onto fine particulate matter, particularly PM_{2.5} and submicron particles ($< 1 \mu\text{m}$). These particles possess high specific surface areas, enhancing sorption capacity, and can remain suspended in the atmosphere for extended periods, facilitating long-range transport and regional dispersion [13–15]. In southern Thailand, seasonal monsoonal wind systems may further influence the transport pathways and spatial distribution of smoke plumes originating from rubber-smoking facilities. The adverse health effects of PAHs have been extensively documented. Their carcinogenicity is associated with metabolic activation via cytochrome P450 enzymes, producing reactive epoxide intermediates capable of forming DNA adducts, thereby initiating mutagenesis at the cellular level [13,16–18]. In addition to carcinogenic outcomes, exposure to PAHs bound to PM_{2.5} has been linked to oxidative stress, respiratory inflammation, and elevated risks of cardiovascular disease [17,18]. In occupational settings such as RSS smoking facilities, workers may experience substantially higher PAH exposure levels than ambient background concentrations, particularly in semi-enclosed environments with limited ventilation. Beyond occupational risks, emissions from biomass combustion may also degrade ambient air quality at the community and regional scales.

Source apportionment techniques, including diagnostic ratios and multivariate statistical models such as principal component analysis (PCA) and positive matrix factorization (PMF), have been widely applied to distinguish PAH sources, including biomass burning, vehicular emissions, and fossil fuel combustion [17,19–21]. These approaches enable the identification of chemical fingerprints that link ambient PAH profiles to specific emission sources. Although both biomass fuels (e.g., firewood) and fossil fuels are carbon-based energy sources, they differ substantially in their chemical composition, formation history, and combustion characteristics. Firewood and other lignocellulosic biomass materials primarily consist of cellulose, hemicellulose, and lignin, whereas fossil fuels are composed of geologically transformed hydrocarbons with higher carbonization levels and more condensed aromatic structures. Consequently, the combustion of these fuels can generate distinct PAH emission profiles due to differences in fuel composition, combustion conditions, and the mechanisms of thermal degradation. However, empirical data characterizing PAHs associated specifically with rubber-wood combustion in Thailand's RSS production sector remain limited, particularly in the southern region where rubber-processing and palm oil industries are densely concentrated and biomass is extensively used as a primary fuel.

Pathio District, Chumphon Province (Figure 1), is centrally located within a cluster of rubber and palm oil processing facilities, including cooperative RSS smoking plants that rely heavily on wood-based fuels. Local topography and meteorological factors—such as wind speed and direction, atmospheric stability, and precipitation—are likely to influence the concentration levels, accumulation patterns, and dispersion dynamics of PAHs in the ambient atmosphere. Within this context, the present study aims to characterize the chemical composition of particle-bound PAHs in the ambient atmosphere of Pathio, southern Thailand, and to investigate their association with rubber-wood combustion from RSS production activities. Specifically, this study evaluates spatial and seasonal variations in PAH concentrations, applies diagnostic ratios and multivariate statistical analyses to identify dominant emission sources, and assesses the environmental health implications of community-level and occupational exposure. The findings are expected to address critical knowledge gaps regarding the air quality impacts of rubber sheet smoking operations in southern Thailand and to provide scientific evidence supporting improved combustion management, emission control strategies, and sustainable industrial development.



Figure 1. Map of southern Thailand showing the sampling location in Pathio District, Chumphon Province.

2. Seasonal Dynamics of RSS Production, Biomass Fuel Use, and Climate in Chumphon, Thailand

The production of RSS in southern Thailand is closely linked to the availability of local biomass resources and regional weather conditions, particularly in Chumphon Province, one of the country's major natural rubber-producing areas. Weather factors, including rainfall, ambient temperature, and relative humidity, influence the drying efficiency and moisture control of rubber sheets during the smoking process, thereby affecting the operational requirements and energy consumption of RSS production facilities. Moreover, seasonal variations in weather conditions can influence biomass fuel consumption, combustion behavior, and atmospheric dispersion of smoke emissions, thereby affecting the temporal variability of particulate matter and PAHs released from RSS production processes [22,23]. Traditional RSS processing relies primarily on rubber-wood as the main fuel for drying and smoking. Owing to the extensive plantation area in southern Thailand, rubber-wood derived from the replanting of senescent trees—typically after 25–30 years of latex production—is sufficiently available to serve as an industrial-scale biomass energy source [22,24]. However, the fuelwood used in conventional smokehouses is often freshly cut and stored outdoors, resulting in high moisture content under the region's humid tropical climate and abundant rainfall [24,25]. The combustion of high-moisture wood promotes incomplete combustion and the release of dense smoke. Previous studies have demonstrated that total particulate emissions increase significantly with increasing fuel moisture content [25–27]. Moreover, particulate emission rates are strongly influenced by combustion conditions, smoking duration, and furnace management practices in traditional RSS processing, all of which directly affect ambient concentrations of particulate matter and associated air pollutants [24,27].

At the national scale, Thailand remains one of the world's leading producers of natural rubber, accounting for approximately one-third of global production in recent years [24]. Southern Thailand constitutes the principal production region, and Chumphon Province is characterized by extensive plantation areas and relatively high yield per hectare compared with many other provinces [22,27]. Nevertheless, rubber production is highly sensitive to meteorological variability at both monthly and seasonal scales [23]. Accordingly, the present analysis considers the average monthly RSS production over a one-year period in Chumphon Province to capture seasonal variability, rather than relying on data from a single calendar year.

Chumphon exhibits a tropical monsoon climate, with a mean annual temperature of approximately 27–29 °C and average annual precipitation exceeding 2200 mm. The province is influenced by the southwest monsoon from May to October and by the northeast monsoon during the late-year transition period [28]. Persistently high relative humidity and seasonally shifting wind patterns play critical roles in the dispersion, accumulation, and transport of airborne particulates from local emission sources [7,28]. When average monthly RSS production is examined in conjunction with monthly rainfall (Figure 2), an inverse relationship is observed during several periods of the year. During the monsoon season, continuous rainfall restricts latex tapping activities and may lead to rainwater contamination of fresh latex, thereby reducing product quality and causing defects in dried sheets. Consequently, average monthly RSS production declines markedly [3,4]. Conversely, although the dry season is generally more favorable for tapping, the hot period from March to May coincides with leaf shedding and thermal stress in rubber trees, which reduces latex yield and limits sheet production despite low rainfall [4,7]. These patterns indicate that production variability is not governed solely by precipitation but also by rubber tree physiology and temperature-related stress.

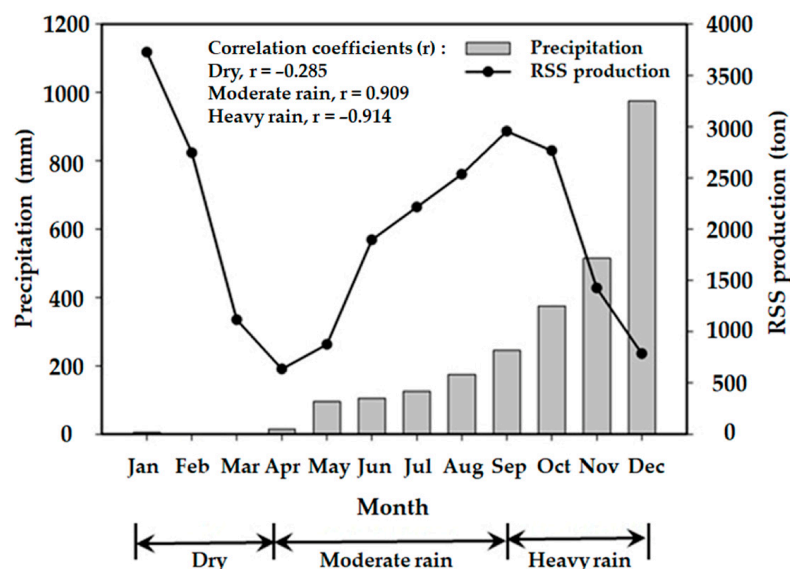


Figure 2. Precipitation and RSS production in Chumphon province.

Seasonal fluctuations in RSS output are directly associated with fuelwood demand in smokehouse operations, as fuel consumption scales proportionally with production volume. Periods of higher average monthly production correspond to increased rubberwood combustion and, consequently, greater potential emissions of biomass-derived air pollutants [3,4,7]. Notably, during the rainy season, even when production decreases, elevated fuel moisture content may reduce combustion efficiency and increase particulate emissions per unit of product [29]. In summary, fuel properties, combustion conditions, and the climatic characteristics of Chumphon Province—including temperature, humidity, wind regime, and precipitation—collectively determine the emission patterns of particulate matter and hazardous pollutants, such as polycyclic aromatic hydrocarbons (PAHs), from RSS production [29,30]. A comprehensive understanding of the linkage between seasonal production dynamics and local climatic context is therefore essential for air quality assessment, health risk evaluation, and the development of region-specific emission control strategies for southern Thailand.

3. Materials and Methods

3.1. Study Objective and Context

This study aimed to evaluate the impact of smoke emissions from wood combustion used as the primary fuel in community-level rubber smoking cooperatives on ambient air quality. Thailand is one of the world's leading producers and exporters of natural rubber, with approximately 700 community-based rubber smoking cooperatives, the majority of which are located in the southern region—the country's principal rubber-producing area [4,7]. Between 2020 and 2024, Thailand's natural rubber production remained above 4 million tons annually, with fluctuations influenced by seasonal and climatic variability [1].

The primary product of these cooperatives is RSS. The production process requires continuous drying and smoking through biomass combustion, particularly rubberwood and locally sourced firewood, as thermal energy sources [2,7]. During the traditional RSS production process, the raw rubber sheets are exposed to smoke and heat generated from biomass combustion, with the smoking chamber temperature typically maintained at approximately 40–60 °C to promote moisture removal, color development, and preservation of the rubber sheets. At this temperature range, thermal degradation of the natural rubber matrix is limited; therefore, particulate matter and PAH emissions are expected

to originate predominantly from incomplete combustion of biomass fuels rather than from direct decomposition of the heated rubber substrate. However, interactions between smoke constituents and the rubber surface during the smoking process may influence the adsorption and retention of certain organic compounds, including PAHs, within the final RSS products. Biomass combustion is widely recognized as a significant source of fine particulate matter ($PM_{2.5}$ and PM_{10}) and semi-volatile organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), which can accumulate in the atmosphere and pose long-term health risks [7,16,18]. Recent studies indicate that community-scale biomass burning can substantially contribute to local $PM_{2.5}$ concentrations, particularly in regions with limited atmospheric ventilation under tropical monsoon conditions [16,31].

3.2. Study Area

Air sampling was conducted in Chumphon Province, one of Thailand's major rubber-producing regions [32,33]. The province is influenced by both the northeast and southwest monsoon systems, which play a crucial role in governing atmospheric circulation, pollutant dispersion, and accumulation patterns [32]. To assess spatial variability in pollutant concentrations, two monitoring sites with contrasting environmental characteristics were selected. The first site was located along Phetkasem Road in Pathio District, a traffic-influenced area characterized by relatively high vehicle density and potential exposure to multiple emission sources, as shown in Figure 3. The second site was situated at King Mongkut's Institute of Technology Ladkrabang, Prince of Chumphon Campus (KMITL–Prince of Chumphon), a coastal location near the Gulf of Thailand with minimal traffic influence; this site was therefore considered a semi-background location. Both monitoring sites are located in close proximity to rubber processing factories, palm oil mills, and several rubber smoking cooperatives. This spatial configuration provides an appropriate setting for investigating pollutant dispersion associated with Ribbed Smoked Sheet (RSS) production within a semi-rural, agro-industrial environment representative of southern Thailand.



Figure 3. Monitoring sites (Phetkasem Road; KMITL–Prince of Chumphon) and wind direction in Chumphon Province during dry and rainy seasons.

3.3. Size-Segregated Particulate Sampling

Size-segregated particulate sampling was conducted simultaneously at both stations using an Andersen cascade impactor (AN-200, Tokyo Dylec Co., Ltd., Tokyo, Japan), a widely applied technique for classifying particles based on aerodynamic diameter in air quality studies [34,35]. The cut-off diameters for the eight stages were 0.43, 0.65, 1.1, 2.1, 3.3, 4.7, 7.0, and 11.0 μm , covering fine to coarse particle fractions. This configuration enabled detailed characterization of PAH distribution across particle sizes, which is critical for health risk assessment since fine particles can penetrate deeply into the respiratory system [35]. Quartz fiber filters (Advantec QR-100, Toyo Roshi Kaisha, Ltd., Tokyo, Japan; 80 mm) were pre-conditioned for 72 h under controlled temperature and 50% relative humidity, following established quality control procedures for particulate analysis [35,36]. Sampling was conducted at a flow rate of 28.3 L min^{-1} , with each sample collected over a three-week period to obtain sufficient mass for trace-level organic analysis. The monitoring campaign was conducted over a total duration of 12 months to characterize the seasonal variability of particulate-bound organic pollutants under different meteorological conditions.

3.4. Total Suspended Particulate (TSP) Measurement

Total Suspended Particulate (TSP) concentrations were measured using a high-volume air sampler (Shibata HV-500F, Sibata Scientific Technology Ltd., Saitama, Japan.) operated at a constant flow rate of 500 L min^{-1} for 24 h, in accordance with standard high-volume air sampling methods [34,35]. Quartz fiber filters (110 mm) were used for collection. Sampling was conducted over several consecutive months to capture seasonal variability, which is particularly important in monsoon-influenced regions [34,36]. One PAH sample per month was selected for chemical analysis to enable consistent monthly trend comparisons.

3.5. Sample Preparation and Extraction

After sampling, filters were reconditioned for 72 h prior to analysis. Fifteen PAH compounds were quantified, as these are widely used indicators of combustion-related pollution in contemporary environmental research [3,4,7,35]. Extraction was performed using ultrasonic agitation in two cycles with an ethanol:benzene solvent mixture (1:3, *v/v*), following modified procedures from established PAH analytical methods further refined in recent studies [7,35]. Extracts were concentrated using a rotary evaporator and re-dissolved in acetonitrile prior to storage at $-20\text{ }^{\circ}\text{C}$ until analysis.

3.6. HPLC Analysis and Quality Assurance/Quality Control (QA/QC)

Quantitative analysis was conducted using high-performance liquid chromatography (HPLC) equipped with a fluorescence detector, Model RF-20Axs (Shimadzu, Kyoto, Japan) and an ODS C18 column (5 μm , 4.6 mm ID $\times$ 150 mm) (GL Sciences, Tokyo, Japan). A gradient elution program of acetonitrile/water was applied at a flow rate of 1 mL min^{-1} and a column temperature of $20\text{ }^{\circ}\text{C}$. This method has been validated for sensitivity and reliability in environmental PAH analysis [7,35]. The reported PAH concentrations were corrected using the average analytical recovery determined from laboratory-spiked blank filters. Travel blank values were subtracted from all measured concentrations to account for background contamination as part of the QA/QC procedure [37,38]. The methodology was adapted from internationally recognized standard protocols and the relevant recent literature and optimized for the specific context of emissions from rubber smoking operations in southern Thailand [7,34]. This approach ensures analytical accuracy, precision, reproducibility, and scientific robustness, thereby supporting the reliability and academic credibility of the findings.

4. Results and Discussion

4.1. Particle Size Distribution of Smoke Emissions from the Rubber Sheet Smoking Process

The particle size distribution of smoke emitted from rubber-wood combustion inside the smoking chamber was determined using an eight-stage Andersen cascade impactor. The results revealed a clearly unimodal distribution pattern, as illustrated in Figure 4, with the majority of particles concentrated in the accumulation mode ($<1\ \mu\text{m}$). The statistical analysis showed a Mass Median Aerodynamic Diameter (MMAD) of $0.85\ \mu\text{m}$ and a Geometric Standard Deviation (GSD) of 2.71. The MMAD value below $1\ \mu\text{m}$ confirms the dominance of fine particles in the emitted aerosol. Meanwhile, the GSD value greater than 2 indicates relatively broad particle size dispersion, despite the presence of a single predominant mode. These findings are consistent with previous investigations by Kalasee et al., 2003 [39], Furuuchi et al. 2006 [40], and Chomanee et al., 2009 [41], which examined particulate emissions from biomass combustion and rubber sheet smoking operations. Similar to the present study, those works reported that most emitted particles were distributed within the accumulation mode, with MMAD values generally below $1\ \mu\text{m}$. This consistency reflects the characteristic formation mechanisms of biomass combustion aerosols, including nucleation, condensation of semi-volatile organic vapors, and subsequent coagulation of primary particles under high-temperature combustion conditions.

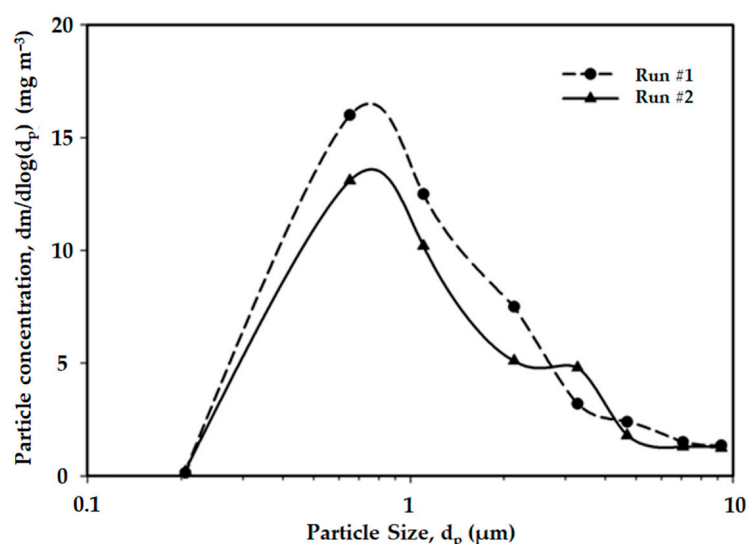


Figure 4. Size distribution of smoke particles from rubber-wood combustion.

To facilitate a more comprehensive assessment of the environmental impact of RSS production, particulate emissions should also be normalized according to the amount of biomass fuel consumed and the quantity of rubber sheets produced. The emission factor expressed per unit mass of biomass burned (e.g., g PM kg^{-1} biomass) can represent the intrinsic emission characteristics of the combustion process, whereas the emission rate per unit of rubber production (e.g., g PM ton^{-1} RSS produced) provides a practical indicator for estimating emission burdens associated with different production capacities. Such parameters can support the development of local emission inventories and provide valuable information for assessing potential exposure risks in communities surrounding rubber smoking facilities. In particular, production scale, biomass consumption rate, and local atmospheric dispersion conditions should be considered together to estimate the potential affected area and to design appropriate emission mitigation strategies for community-level RSS production systems.

From an environmental and health perspective, the predominance of submicron particles is of particular concern. Fine particles in the accumulation mode have high atmospheric

residence times and can be transported over long distances. Moreover, particles in this size range are capable of penetrating deep into the human respiratory tract and depositing in the alveolar region, thereby posing potential health risks to workers and nearby communities. Overall, the size distribution pattern presented in Figure 4 confirms that the rubber sheet smoking process is a significant source of fine particulate matter. These results emphasize the need for effective emission mitigation strategies, particularly for small- and community-scale rubber smoking facilities operating in close proximity to residential areas.

4.2. Particle Size Distribution in the Atmosphere and Total Suspended Particulates (TSP)

The mass size distribution of ambient particles collected along Phetkasem Road, Pathio District, Chumphon Province, during March–September 2025 is presented in Figure 5a. The monitoring duration differed between the two sampling locations because each site was established with different monitoring objectives. Site (a), located along Phetkasem Road in Pathio District, was selected as the primary monitoring site and was monitored from March to September 2025 to characterize the seasonal variation in ambient particulate matter size distributions. In Chumphon Province, southern Thailand, March represents the late summer/dry season, which is generally characterized by higher temperature, lower precipitation, and more stable atmospheric conditions, whereas September represents the rainy season under the influence of the southwest monsoon, with increased rainfall, relative humidity, and altered atmospheric dispersion conditions. Therefore, measurements conducted during these two periods provide representative information on particle size distributions under contrasting seasonal meteorological conditions. The extended monitoring period at Site (a) was designed to capture the transition between dry and wet seasons and to provide a more comprehensive understanding of seasonal aerosol behavior. In contrast, Site (b), located at the KMITL–Prince of Chumphon campus, was established as a comparative monitoring location to investigate the spatial consistency of aerosol characteristics rather than seasonal variability. Therefore, a shorter monitoring period was applied at this site, and the collected data were used primarily to confirm whether similar particle size distribution patterns existed between the two locations. Although the monitoring durations were different, both sites were evaluated using the same particle measurement approach, allowing reliable comparison of the dominant aerosol modes and their potential emission characteristics.

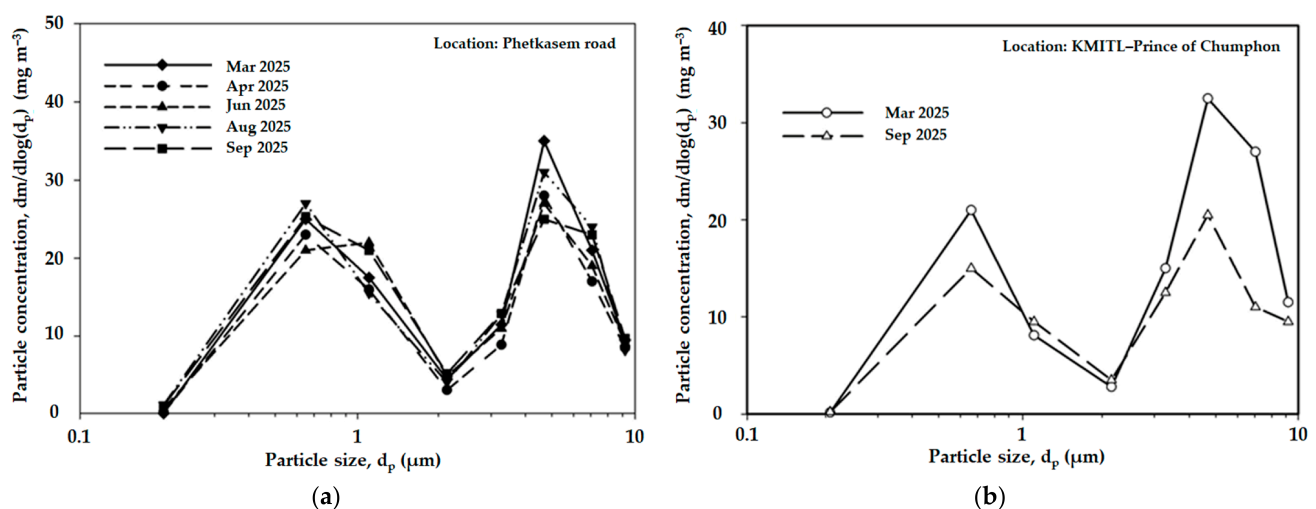


Figure 5. Size distribution of particulate matters. (a) Phetkasem road site. (b) KMITL–Prince of Chumphon site.

The results demonstrate a clearly bimodal distribution pattern, with a dominant peak in the accumulation mode at approximately $0.54\text{--}0.67\text{ }\mu\text{m}$ and a second peak in the coarse mode at approximately $4.0\text{--}4.3\text{ }\mu\text{m}$, as shown in Figure 5a. A comparable bimodal structure was also observed at the KMITL–Prince of Chumphon site, as shown in Figure 5b, confirming the spatial consistency of aerosol characteristics across the study area. This bimodal structure is consistent with the classical aerosol size distribution framework, which distinguishes particles generated by combustion and secondary atmospheric processes from those produced by mechanical mechanisms. Particles smaller than $1\text{ }\mu\text{m}$ are typically associated with primary combustion emissions and secondary aerosol formation through gas-to-particle conversion, whereas particles larger than $2\text{--}3\text{ }\mu\text{m}$ are predominantly linked to mechanical processes such as road dust resuspension, soil particle entrainment, and sea spray aerosol generation [42–44]. From a theoretical perspective, the accumulation mode can be explained by aerosol dynamic processes, particularly condensation of low-volatility vapors and coagulation of ultrafine particles. These mechanisms promote the growth of particles derived from biomass burning or fossil fuel combustion, resulting in a characteristic size range of approximately $0.1\text{--}1\text{ }\mu\text{m}$ [43,44]. In contrast, the coarse mode arises primarily from mechanical generation processes, including wind-driven resuspension of surface materials and the bubble bursting mechanism at the ocean surface, which represents the principal source of sea salt aerosols in coastal environments [44–46]. The prominence of the coarse-mode peak at approximately $4\text{ }\mu\text{m}$ in both monitoring sites (Figure 5) further supports the influence of mechanically generated particles in the study area.

The Total Suspended Particulate (TSP) concentrations measured using high-volume air samplers at Phetkasem Road and the KMITL–Prince of Chumphon site are presented in Figure 6, together with the average monthly rainfall data for Chumphon Province. The missing TSP data for January, May, and July 2025 were primarily due to limitations associated with field sampling operations and instrument availability. Sampling campaigns were conducted according to the availability of the monitoring equipment and field accessibility, and only valid samples passing quality assurance and quality control criteria were included in the final analysis. Therefore, these months were excluded rather than estimated to avoid introducing uncertainty or bias into the dataset. The available TSP measurements represent the periods with successful quality-controlled sampling and are considered sufficient to evaluate the general temporal variation and relationship with meteorological factors and rubber smoking activities in the study area.

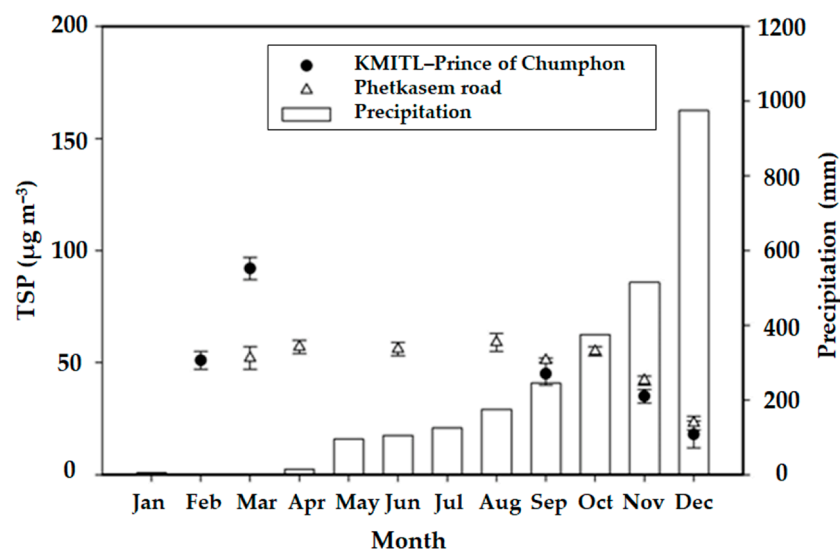


Figure 6. TSP and precipitation in 2025.

The annual mean TSP concentrations at the two sites were approximately 51–52 $\mu\text{g m}^{-3}$, indicating similar levels across locations and remaining below Thailand’s national ambient air quality standards. Although these concentrations comply with regulatory limits, their temporal variation suggests the influence of both emission sources and meteorological factors. The relationship between TSP concentration and rainfall is illustrated in Figure 7. In general, TSP levels decreased with increasing precipitation, demonstrating an inverse relationship that becomes more evident during periods of high rainfall. This pattern is consistent with the theory of wet deposition (wet scavenging), whereby rainfall efficiently removes suspended particles—particularly those in the coarse mode—through impaction and interception processes [45,46]. A slight increase in TSP during low-rainfall months (<200 mm) may be associated with reduced atmospheric cleansing and potential regional transport of smoke from biomass burning. Furthermore, the relationship between TSP concentrations and the total production of ribbed smoked sheet (RSS) rubber from cooperatives across Chumphon Province is shown in Figure 8. The data reveal a nearly linear increase in TSP concentrations with increasing rubber sheet production at both monitoring sites. This finding strongly indicates that smoke emissions from rubber-wood combustion during the rubber smoking process contribute significantly to ambient suspended particulate levels.

Overall, the combined interpretation of Figures 5–8 demonstrates that ambient aerosol characteristics in the study area are governed by a mixed-source system involving combustion-related fine particles, mechanically generated coarse particles, and meteorological modulation. The bimodal size distribution (Figure 5), the temporal variation in TSP and rainfall (Figure 6), the inverse TSP–precipitation relationship (Figure 7), and the positive association between TSP and rubber production (Figure 8) collectively confirm that both anthropogenic activities and environmental factors control particulate matter dynamics in this coastal region. These findings are consistent with established aerosol dynamics theory and recent empirical studies, underscoring the importance of differentiating between natural and anthropogenic contributions in comprehensive air quality assessment and management strategies.

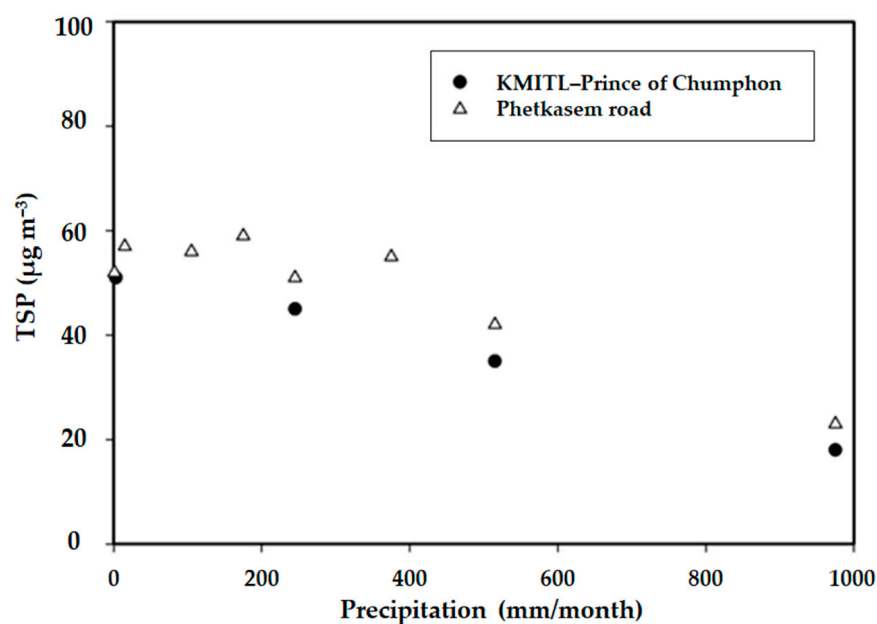


Figure 7. Relationship between TSP and precipitation.

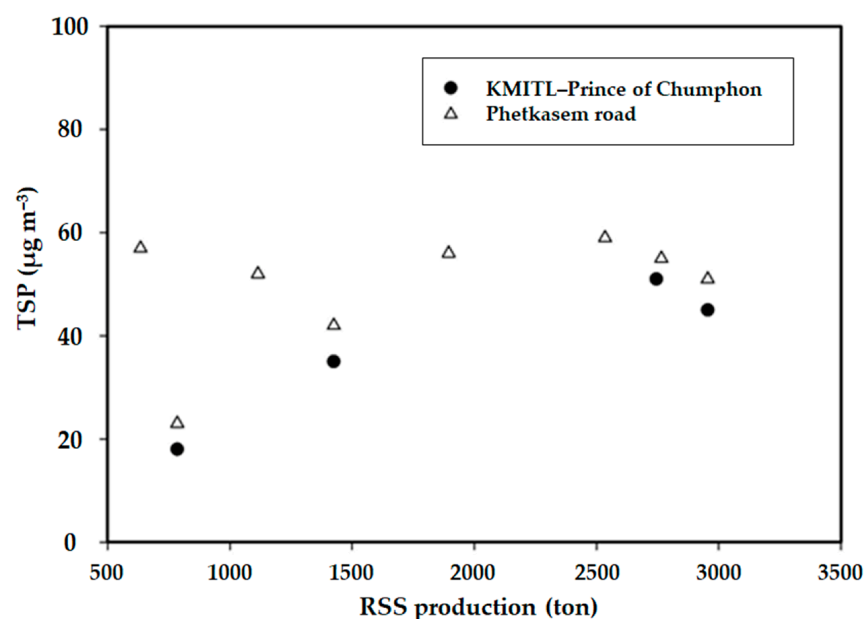


Figure 8. Relationship between TSP and RSS production.

4.3. Distribution, Concentration, and Atmospheric Dynamics of PAHs in a Coastal Environment

The size distribution, concentration, and atmospheric dynamics of polycyclic aromatic hydrocarbons (PAHs) in the coastal atmosphere of Chumphon Province reveal a complex multiphase system governed by biomass combustion sources, meteorological conditions, monsoonal circulation, sea spray aerosol (SSA) influence, and precipitation-driven removal processes, consistent with recent advances in coastal aerosol research [47,48]. Analysis based on Andersen sampler measurements and HPLC quantification (Figure 9) indicates that the mass size distribution of PAHs is predominantly unimodal, with a pronounced peak in the fine particle mode at approximately $0.59\ \mu\text{m}$ at Phetkasem Road, Pathio District. At KMITL–Prince of Chumphon, the dominant peak occurred at $0.59\ \mu\text{m}$ in March but shifted to approximately $1.8\ \mu\text{m}$ in September. This seasonal shift reflects the dynamic equilibrium among gas–particle partitioning, surface adsorption, and hygroscopic particle growth under high relative humidity conditions typical of coastal environments [47]. The compositional profiles of PAHs (Figure 10) are dominated by 3–4 ring compounds, including Phenanthrene (Phe), Fluoranthene (Flu), and Pyrene (Pyr), which are well-established tracers of biomass combustion [48–50], particularly wood burning associated with rubber sheet production. In contrast, higher molecular weight PAHs (5–6 rings) were present at relatively low fractions, suggesting comparatively moderate combustion temperatures relative to fossil fuel combustion or diesel engine emissions [49]. Total PAH concentrations (Figure 11) exhibited a clear relationship with rubber sheet production volume. During the dry season (January–April), when production declined, PAH concentrations remained relatively low. From May to December, concentrations increased in accordance with intensified production activities. Notably, an exponential relationship was observed between the concentration or mass fraction of 4–6 ring PAHs and production volume, indicating that emission source strength is a primary determinant of the system’s mass balance, in agreement with source-driven mass balance frameworks reported [48,50–52].

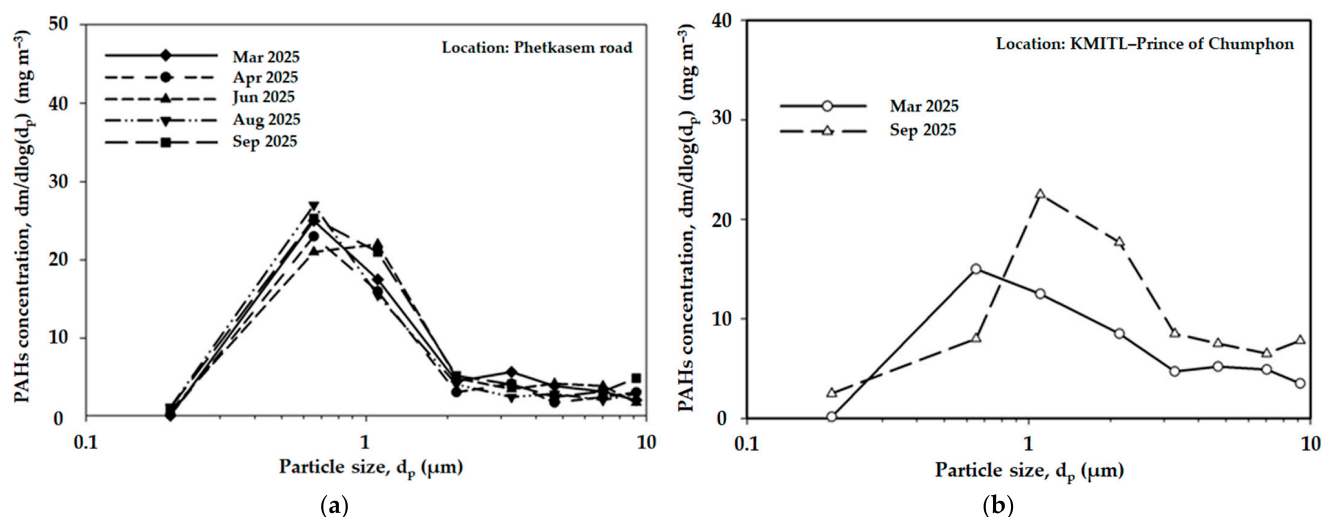


Figure 9. Mass size distribution of atmospheric PAHs. (a) Phetkasem road site. (b) KMITL–Prince of Chumphon site.

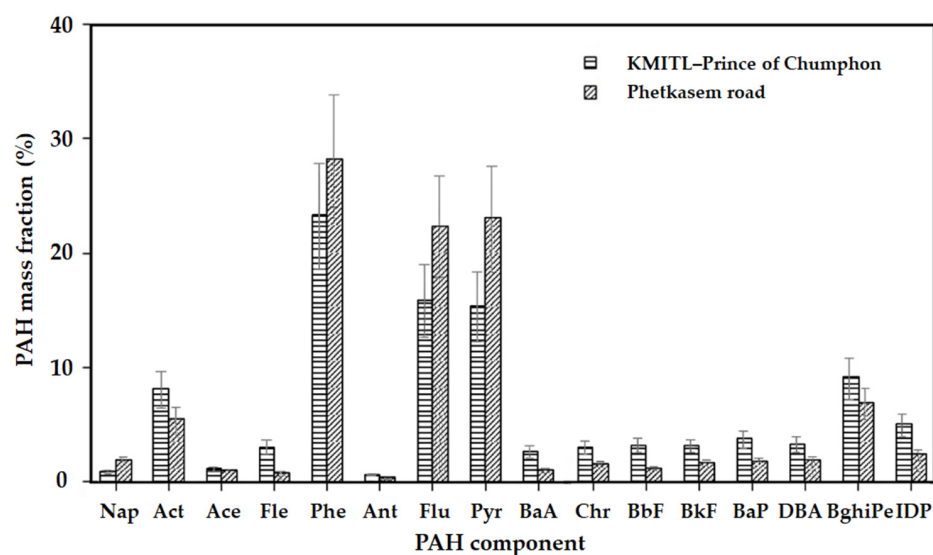


Figure 10. Mass fraction of PAH components measured by high-volume sampling.

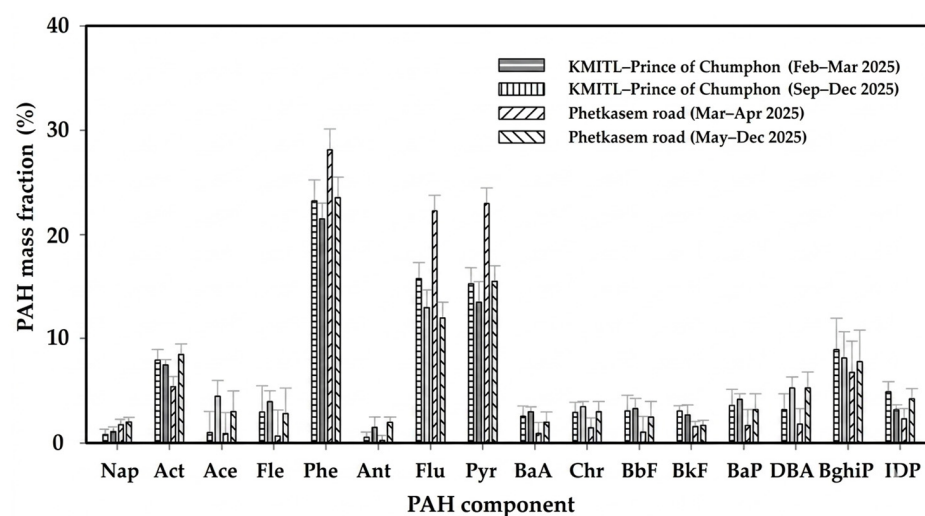


Figure 11. Mass fraction of PAH components measured by high-volume sampling during the dry and rainy seasons.

Given the proximity of the study area to the Gulf of Thailand, sea spray aerosol plays a critical role in modulating PAH dynamics. Sea salt particles are highly hygroscopic and readily absorb atmospheric moisture, leading to hygroscopic growth and an increase in particle size and surface area [52,53]. This enhanced surface area facilitates the adsorption or condensation of semi-volatile PAHs from the gas phase onto particle surfaces, a process widely documented in coastal atmospheric chemistry studies [53–55]. Such mechanisms plausibly explain the observed shift in the modal diameter to 1.8 μm in September (Figure 9), a period characterized by elevated relative humidity and rainfall. Thus, SSA not only enhances phase partitioning but also modifies the structural characteristics of the particle size distribution in the coastal atmosphere. Monsoonal wind patterns (Figure 3) exert a significant influence on PAH transport and spatial distribution, as demonstrated in recent regional transport studies in Southeast Asia [54,55]. During the dry season, northeasterly winds originating from the Gulf of Thailand transport marine air masses inland, promoting mixing between biomass combustion emissions and sea salt aerosols. In contrast, during the rainy season, southwesterly winds direct air masses seaward, resulting in more comparable PAH concentrations between the two monitoring sites. Additionally, the foothill topography surrounding KMITL–Prince of Chumphon may locally influence airflow patterns and pollutant accumulation under specific meteorological conditions, consistent with terrain–circulation interaction mechanisms described by recent modeling studies [35,41].

Precipitation represents the most critical removal mechanism for atmospheric PAHs. Although the inverse relationship between precipitation and atmospheric PAH concentrations has been widely recognized, the novelty of this study lies in the identification of the coupled influence of rainfall, coastal atmospheric processes, and biomass combustion sources on PAH behavior in a tropical monsoonal environment. Unlike previous studies that primarily evaluated rainfall as a simple scavenging factor, this study provides insight into how precipitation interacts with particle-bound PAHs originating from rubber-wood combustion during ribbed smoked sheet (RSS) production, while simultaneously being affected by sea spray aerosol (SSA), atmospheric humidity, and seasonal monsoon circulation. These interactions determine not only the removal efficiency of PAHs but also their particle-phase distribution, atmospheric persistence, and transport characteristics in the coastal environment of southern Thailand. As shown in Figure 12, PAH concentrations decreased exponentially with increasing rainfall, particularly during the May–December period. The primary mechanisms include in-cloud scavenging (rainout), whereby PAH-associated particles act as cloud condensation nuclei and are incorporated into cloud droplets, and below-cloud scavenging (washout), in which falling raindrops intercept and capture suspended particles [3,7,35,41]. The efficiency of these processes depends on particle size, rainfall intensity, and raindrop terminal velocity. Particles that have undergone hygroscopic growth due to SSA influence become larger and are more readily removed by wet deposition [55–57]. Therefore, precipitation not only reduces ambient PAH concentrations but also alters the particle size distribution within the atmospheric system. In addition to physical removal, PAHs undergo chemical transformation through photodegradation under ultraviolet radiation and oxidation reactions involving atmospheric radicals such as $\text{OH}\bullet$, O_3 , and $\text{NO}_3\bullet$ [56,58,59]. Reaction rates depend on temperature, solar radiation intensity, and atmospheric chemical composition. During the hot season, elevated temperatures may enhance volatilization of low-molecular-weight PAHs and accelerate chemical aging processes [50,51]. Conversely, during the rainy season, wet deposition becomes the dominant controlling mechanism. Taken together (Figures 9–12), the coastal atmosphere of Chumphon Province can be characterized as a highly dynamic multiphase system. The integrated analysis presented in this study provides new evidence that rainfall-driven PAH reduction cannot be interpreted solely as a precipitation effect, but

rather as the outcome of interactions among emission intensity, aerosol physicochemical evolution, coastal meteorology, and seasonal atmospheric cleansing processes. Biomass combustion associated with rubber sheet production serves as the primary emission source. Most PAHs are initially associated with fine particles ($\sim 0.59 \mu\text{m}$), but their size distribution can shift toward larger diameters ($\sim 1.8 \mu\text{m}$) under the combined influence of sea spray aerosol and high humidity. Monsoonal circulation governs pollutant transport and spatial variability, while precipitation acts as the principal removal mechanism and a key regulator of atmospheric mass balance. Consequently, the atmospheric behavior of PAHs in this coastal environment arises from the integrated interaction among emission sources, physicochemical transformation, particle growth processes, wind-driven transport, and rainfall-induced removal, all of which exhibit pronounced seasonal variability, consistent with findings reported in coastal and monsoonal regions worldwide.

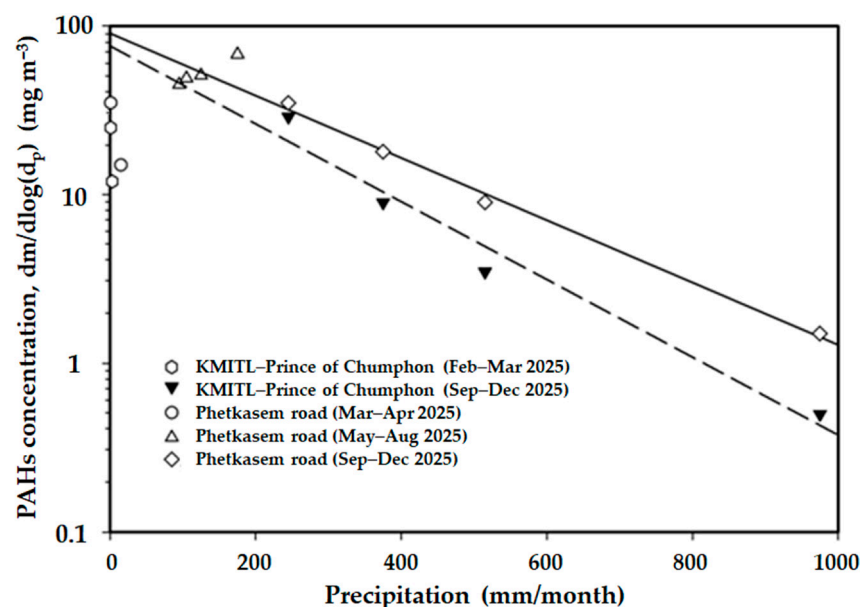


Figure 12. Relationship between precipitation and atmospheric PAH concentrations.

Future research should further advance both mechanistic and quantitative understanding of this system. Priority areas include: (1) real-time measurements of gas–particle partitioning to resolve dynamic phase equilibrium under varying humidity and temperature conditions; (2) isotopic analyses or molecular diagnostic ratios to apportion contributions from biomass combustion and other potential sources; (3) investigation of secondary transformation products such as oxy-PAHs and nitro-PAHs, which may exhibit enhanced toxicity; (4) application of chemical transport modeling to evaluate the combined effects of monsoonal circulation and complex topography on regional dispersion; (5) assessment of PAH deposition in rainwater, soils, and sediments to quantify atmospheric-to-ecosystem mass transfer; and (6) integrated health risk assessment incorporating concentration levels, particle size distribution, and compound-specific toxic equivalency factors. Advancing research along these directions will strengthen the system-level understanding of PAH dynamics in tropical coastal atmospheres and support the development of effective and sustainable air quality management strategies tailored to humid, near-marine environments.

5. Conclusions

This study provides a comprehensive evaluation of particle size distribution, concentration variability, and atmospheric processing of PAHs associated with rubber-wood combustion from Ribbed Smoked Sheet production in southern Thailand. The monitoring

durations for mass size distribution differed between Phetkasem Road in Pathio District and KMITL–Prince of Chumphon campus. The extended monitoring at Phetkasem Road, conducted from March to September 2025, captured the transition between dry and wet seasons to provide a comprehensive understanding of seasonal aerosol behavior. In contrast, the shorter monitoring period at the KMITL campus served as a comparative baseline to investigate spatial consistency rather than seasonal variability. Furthermore, the lack of TSP data for January, May, and July 2025 stemmed chiefly from operational constraints in field sampling and limited equipment availability. The results indicate that rubber-wood combustion in RSS smokehouses is an important contributor to submicron particulate matter and biomass-related PAHs in the study area. However, contributions from other local emission sources, particularly traffic-related emissions at the roadside monitoring site, cannot be excluded. The direct measurements obtained inside the RSS smokehouse, together with the observed ambient particle characteristics, suggest that biomass combustion plays a major role in shaping the atmospheric aerosol profile in this rubber-producing region. Emissions were initially dominated by fine-mode particles, whereas atmospheric transformation processes—including hygroscopic growth induced by sea spray aerosol and high relative humidity—modified particle size distributions under coastal conditions. Ambient aerosol dynamics were governed by a mixed-source system comprising combustion-derived fine particles and mechanically generated coarse particles. PAH concentrations exhibited clear seasonal dependence, strongly linked to rubber production volume and inversely correlated with precipitation. Monsoonal wind systems regulated spatial dispersion and site-to-site variability, whereas wet deposition served as the primary removal mechanism controlling atmospheric mass balance. The coastal monsoon environment of Chumphon Province represents a highly dynamic multiphase atmospheric system in which emission strength, particle microphysics, meteorological forcing, and physicochemical transformation interact to determine PAH fate and transport. These findings contribute new empirical evidence from Southeast Asia, a region where biomass combustion remains a major energy source but size-resolved PAH data are scarce. From a policy perspective, improving combustion efficiency, reducing fuel moisture content, and implementing emission control technologies in community-scale smokehouses could significantly mitigate fine particle and PAH emissions. Future research integrating real-time gas–particle partitioning measurements, source apportionment modeling, secondary PAH derivatives, and quantitative health risk assessment will further enhance system-level understanding and support sustainable air quality management in tropical coastal regions.

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