Sustainable
Food Technology

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Sustainability Spotlight Statement

View Article Online
DOI: 10.1039/D5FB00592B

This work demonstrates that the incidental use of plastics as smoking fuels—through packaging waste or contaminated scrap wood—substantially elevates persistent organic pollutants in smoked beef. By establishing clear fuel-dependent contaminant profiles, our study identifies the elimination of plastic-derived fuels as an actionable strategy to improve food safety while reducing hazardous emissions. Promoting clean biomass fuels aligns with the United Nations Sustainable Development Goals, particularly SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). The findings provide evidence-based guidance for sustainable post-harvest food processing, supporting both safer nutrition and environmentally responsible practices across the food supply chain.

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DOI: 10.1039/D5FB00592B

ARTICLE

Impact of Plastic-Contaminated Fuels on Persistent Organic Pollutants in Smoked Beef: Implications for Sustainable Food Processing

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

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This study compared polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs) in beef smoked with four fuels: clean wood (W), wood plus polyethylene (PE), wood plus polyvinyl chloride (PVC), and wood plus both plastics (PE+PVC). For PCBs, totals increased progressively from W to PE, further in PE+PVC, and peaked in PVC. Meanwhile, totals of PCDDs/Fs were near zero in W, increased with PE, were substantially higher in PVC, and were greatest in PE+PVC (all $p < 0.05$). Multivariate analysis confirmed distinct fuel-specific congener patterns, with PVC driving broad enrichment in higher-chlorinated PCBs and the emergence of PCDDs/Fs, whereas PE affected a narrower PCB subset. For PAHs, totals were lowest in W, intermediate and statistically indistinguishable between PE and PVC, and highest in PE+PVC ($p < 0.05$ for all contrasts involving W or PE+PVC). Compositionally, PE was marked by a Phenanthrene-centered shift; PVC showed higher contributions of Fluoranthene, Pyrene, Benzo[a]anthracene, Chrysene, Benzo[b]fluoranthene, and Benzo[k]fluoranthene; and PE+PVC promoted Naphthalene, Acenaphthylene, Acenaphthene, Fluorene, Benzo[e]pyrene, Benzo[a]pyrene, and Indeno[1,2,3-cd]pyrene. Overall, plastic contamination—especially PVC and mixed plastics—not only increases contaminant burdens and reshapes profiles relative to clean wood, but also highlights a critical sustainability concern. Avoiding plastic-derived fuels in smoking is essential to safeguard food safety and to support environmentally responsible, sustainable meat processing practices.

Introduction

Smoking is a traditional preservation and flavoring method that remains widely practiced across cultures, but it is also a significant source of chemical contaminants in food. Incomplete combustion of biomass generates polycyclic aromatic hydrocarbons (PAHs), which readily deposit on smoked products and are well recognized as hazardous to human health [1-4]. In addition, combustion conditions and fuel composition influence the formation of polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs), compounds that are toxic, persistent, and bioaccumulative [5-9]. These pollutants represent a dual challenge: they compromise food safety and increase the environmental footprint of traditional processing systems.

Polychlorinated biphenyls (PCBs) are chlorinated biphenyls classified as persistent, bioaccumulative, and carcinogenic contaminants [10]. Their toxicological behavior depends on the substitution pattern: congeners are broadly divided into coplanar (non-ortho) and non-coplanar types. A subset of PCB congeners possess coplanar structures similar to PCDD/Fs, which allows them to bind to the aryl hydrocarbon receptor and elicit similar toxic effects, even though they are classified in a distinct pollutant group [11]. Because both PCBs and PCDD/Fs activate the aryl hydrocarbon receptor (AHR)—albeit with markedly different binding affinities and potencies—co-planar and mono-ortho PCBs are treated as contributors to dioxin-related toxicity and grouped with PCDD/Fs as dioxin-related compounds (DRCs) [12]. PCDD/Fs themselves comprise two benzene rings linked by oxygen bridges: dioxins (PCDDs) contain two bridging oxygens, whereas furans (PCDFs) contain one; in both series, one to eight chlorine atoms may be substituted on the rings, yielding families of congeners with diverse properties [4, 13-15].

Meanwhile, polycyclic aromatic hydrocarbons (PAHs) are a broad class of food- and environment-related contaminants composed of two or more fused aromatic rings [16]. In foods, PAHs arise predominantly from high-temperature processing—such as smoking, grilling, and smoke-drying—where thermal degradation and partial oxidation of lignocellulosic biomass generate radical fragments that cyclize and condense into aromatic rings under conditions of incomplete combustion rather than being fully oxidized to CO_2 and H_2O [13, 17, 18]. Given their toxicological relevance and regulatory attention, profiling PAHs provides a complementary lens to chlorinated POPs when evaluating smoke-derived contamination.

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Additional supporting information can be found online in the Supplemental section. See DOI: 10.1039/x0xx00000x

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DOI: 10.1039/D5FB00592B

From a regulatory perspective, the presence of smoke-derived contaminants in food is subject to strict control in many jurisdictions. In the European Union, maximum limits have been established for the sum of four marker PAHs (PAH4: benzo[a]pyrene, benzo[a]anthracene, benzo[b]fluoranthene, and chrysene), with limits of 12 ppb for smoked meat products under Regulation (EU) No 835/2011. For chlorinated pollutants, food safety assessment is based on toxicity equivalency (TEQ), with maximum levels defined for the sum of dioxins and dioxin-like compounds in foods of animal origin, underscoring the importance of controlling both aromatic and chlorinated POPs formed during smoking[1-4].

While clean lignocellulosic biomass such as wood is generally regarded as the appropriate fuel for smoking, in many settings plastics are inadvertently or deliberately introduced into the combustion process. Common pathways include the burning of household packaging waste, the use of scrap wood contaminated with paint or polymer coatings, or the inclusion of plastic bindings and wrappings that are not removed prior to burning. These practices are often driven by convenience, lack of awareness, or fuel shortages, but they introduce substantial sustainability concerns. Plastics are chlorine-containing or hydrocarbon-rich materials that, when burned, favor the generation of toxicants well beyond the levels associated with clean wood [10, 19, 20]. Thus, plastic contamination of smoking fuels is both a food safety hazard and a contributor to unsustainable processing.

Previous studies have documented the presence of PAHs in smoked meats, with concentrations varying widely depending on fuel type and smoking conditions. For instance, surveys of smoked beef and pork ham reported PAH levels on the order of a few micrograms per kilogram, often higher in traditional smokehouses compared to industrial systems [21, 22]. Certain PAHs such as benzo[a]pyrene are regulated due to their carcinogenic potential, and market surveillance has revealed high burdens in oily smoked fish products [23]. Beyond PAHs, chlorinated POPs have also been detected in animal products, though direct data linking their formation to smoking fuel composition are limited [10]. This knowledge gap is especially relevant given the widespread use of plastic packaging and the potential for its uncontrolled burning during food processing.

Addressing this issue is essential not only for food safety but also for the sustainability of post-harvest food processing. This study tests the hypothesis that plastic-contaminated smoking fuels significantly increase the burden of persistent organic pollutants in smoked beef. Through quantitative analysis of PAHs, PCBs, and PCDD/Fs formed under different fuel conditions, the study seeks to clarify the role of fuel composition in chemical hazard formation and to support the transition toward cleaner and more sustainable smoking practices.

Experimental

Samples

A total of fifteen beef samples were collected from local markets, thoroughly washed with water, and allowed to drain. Each sample was then divided into five equal portions of approximately 500 g. These portions were subsequently smoked using different smoking materials: pure wood without impurities (W), wood mixed with polyethylene (PE) pellets at a ratio of 99/1 (w/w), wood mixed with polyvinyl chloride (PVC) pellets at a ratio of 99/1 (w/w), and wood mixed with both PE and PVC pellets at a ratio of 99/0.5/0.5 (w/w/w). The smoking process was carried out for five consecutive days, with 8 hours of smoking per day. Before use, the wood was thoroughly washed and air-dried.

The remaining portion of each sample (not subjected to smoking) was oven-dried at 90 °C until a constant weight was reached and subsequently freeze-dried, ground, and stored at −20 °C. These un-smoked controls were analyzed in parallel to verify that the target pollutants were not generated by thermal treatment alone in the absence of smoke exposure.

Procedure

The samples were processed and analyzed following the same procedure as described in our previous publication [19, 20]. Briefly, the samples were freeze-dried, and the fat content was determined. After extraction and cleanup, PAHs and PCBs were quantified using GC–EI–MS/MS in selected reaction monitoring mode, whereas PCDD/Fs were analyzed using high-resolution GC-HRMS. All POP concentrations were determined from three technical replicate injections of each five biological replicates (n = 5), and are reported as mean ± standard deviation (SD) on a ppb lipid weight basis. Data were processed and extracted with XCalibur 4.2 software (Thermo Scientific, USA), and subsequent statistical analyses were performed using R software (R Foundation for Statistical Computing, Vienna, Austria). The entire protocol from sample pretreatment through extraction, purification, and GC-MS/GC-HRMS analysis was shown in Figure 1. A detailed description of the procedure is provided in the Supplemental section.

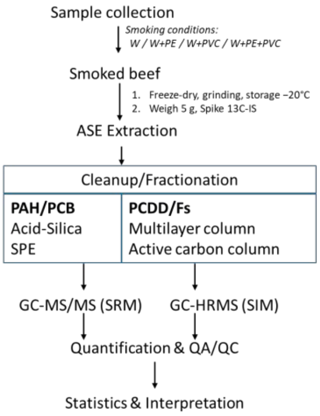

Figure 1. Workflow of sample preparation, extraction, cleanup, and instrumental analysis for POP determination in smoked beef.

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Results and discussion

PCDD/Fs and PCBs contents in the samples

Polychlorinated biphenyls (PCBs) are chlorinated biphenyls classified as persistent, bioaccumulative, and carcinogenic contaminants [10]. Their toxicological behavior depends on the substitution pattern: congeners are broadly divided into coplanar (non-ortho) and non-coplanar types. A subset of PCB congeners possess coplanar structures similar to PCDD/Fs, which allows them to bind to the aryl hydrocarbon receptor and elicit similar toxic effects, even though they are classified in a distinct pollutant group [11]. Because both PCBs and PCDD/Fs activate the aryl hydrocarbon receptor (AHR)—albeit with markedly different binding affinities and potencies—co-planar and mono-ortho PCBs are treated as contributors to dioxin-related toxicity and grouped with PCDD/Fs as dioxin-related compounds (DRCs) [12]. PCDD/Fs themselves comprise two benzene rings linked by oxygen bridges: dioxins (PCDDs) contain two bridging oxygens, whereas furans (PCDFs) contain one; in both series, one to eight chlorine atoms may be substituted on the rings, yielding families of congeners with diverse properties [4, 13-15]. In this study, we detected 24 PCB congeners and six PCDD/F congeners in smoked meat produced with wood fuels adulterated by plastics, enabling an integrated assessment of DRC burdens alongside the PAH patterns reported in the preceding sections.

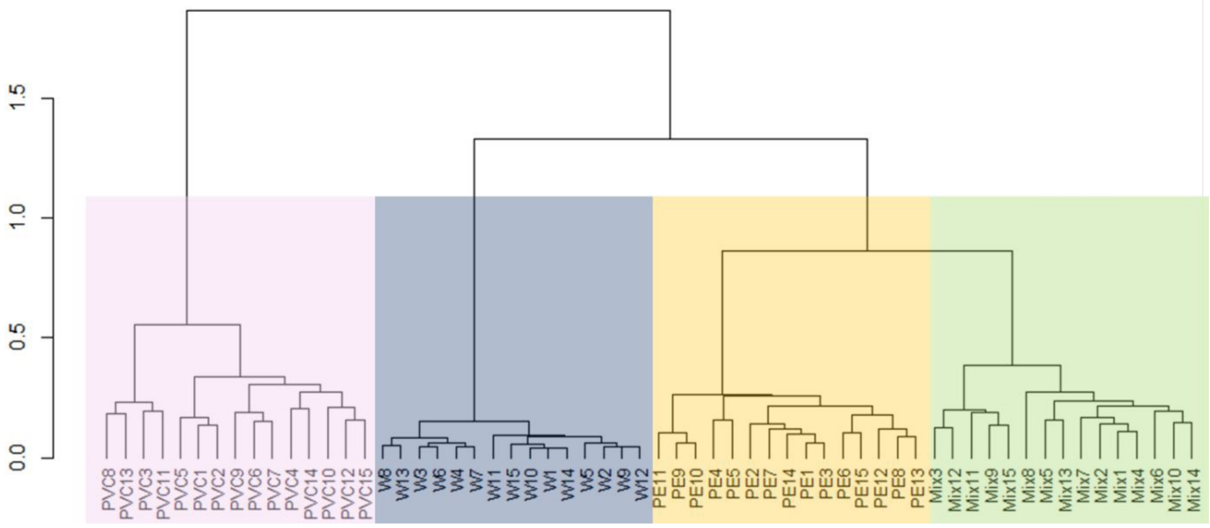

Figure 2. Hierarchical cluster analysis dendrogram of the PCDDs/Fs and PCBs in smoked beef samples

The contents of PCDDs/Fs and PCBs in smoked meat samples are presented in Table S1. The dataset presented the concentrations of polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins/furans (PCDDs/Fs), expressed in ppb, across four groups of smoked beef samples: clean wood (W), wood mixed with polyethylene (PE), wood mixed with polyvinyl chloride (PVC), and wood mixed with both plastics (PE+PVC). Overall, the clean wood group showed comparatively low PCB levels, with values remaining consistent across congeners and limited or undetectable amounts of PCDDs/Fs. In contrast, the groups involving plastic admixtures exhibit higher and more variable concentrations. Samples smoked with PVC or with the combined PE+PVC mixtures tend to accumulate greater quantities of higher-chlorinated PCBs and detectable PCDDs/Fs, reflecting the influence of chlorine-containing materials during combustion. The PE group shows intermediate levels, with increases in several PCB congeners relative to clean wood but generally lower PCDD/F occurrence compared with the PVC group. These differences highlight the significant impact of fuel composition on contaminant formation and deposition in smoked meat.

The hierarchical cluster analysis – HCA (Figure 2) further illustrates the differences among the four treatment groups. The dendrogram reveals a clear separation of samples according to fuel type, indicating consistent compositional patterns within each group. Clean wood (W) samples form a compact cluster, reflecting their relatively low and homogeneous contaminant levels. The PE group also clusters distinctly, positioned closer to the W group, which is consistent with their intermediate PCB concentrations and limited PCDD/F occurrence. In contrast, the PVC samples are grouped together and clearly separated from the other categories, highlighting their higher and more diverse contaminant profiles. The mixed PE+PVC group (Mix) occupies an intermediate position between the PE and PVC clusters, showing partial overlap but generally closer proximity to PVC, suggesting that the presence of PVC strongly influences the contaminant burden. Overall, the HCA results corroborate the chemical analyses, emphasizing the dominant role of chlorine-containing plastics, particularly PVC, in driving elevated PCB and PCDD/F formation in smoked meat.

Principal component analysis (PCA) reveals that group separation is primarily determined by the first two components: PC1 accounts for 74.3 percent of the variance, and PC2 accounts for 14.1 percent, resulting in a combined 88.4 percent. Because only the first three components have eigenvalues greater than one, using the first two—at most the first three—components is sufficient for representation and discrimination. On the PC1–PC2 score map (Figure 3), wood occupies the low end of PC1 with a compact profile, PE remains on the low side of PC1 but

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shifts upward on PC2, and both PVC and the PE+PVC mix move to high PC1; PVC tends to sit higher on PC2 than the mix, which is consistent with a stronger dioxin/furan signature in the mix. PC1 behaves as a total-burden axis and aligns with the totals shown in the boxplots: totals rise stepwise from wood to PE to mix to PVC for PCBs, and from wood to PE to PVC to mix for PCDDs/Fs. Two additional observations support the overall interpretation. First, group centroids on the PC1–PC2 plane are well separated with little overlap, in agreement with the hierarchical clustering, which found tight and fuel-specific clusters. Second, variability increases from wood to plastics, as seen in the rising standard deviation of total PCBs from wood through PE and mix to PVC, consistent with more heterogeneous formation conditions under plastic combustion.

On the PC1–PC2 score plot (Figure 3b), the wood group sits at low PC1 and slightly negative PC2, reflecting low totals and a compact, homogeneous profile. The PE group remains on the low side of PC1 but shifts upward on PC2, which matches its selective enrichment in a few congeners rather than a broad increase. The PVC and the PE+PVC mix groups move to high PC1, signaling high overall contamination; PVC tends to occupy moderately high PC2, whereas the mix group is lower on PC2, consistent with stronger contributions from dioxins and furans. Quantitatively, PC1 correlated strongly with total PCB concentration and also strongly with total PCDD/F concentration. These relationships are consistent with the group means of total PCBs —wood 1.55 ppb, PE 3.21 ppb, mix 5.00 ppb, and PVC 6.67 ppb—and with the totals of PCDDs/Fs—wood approximately zero, PE 0.0022 ppb, PVC 0.048, and mix 0.0518 ppb.

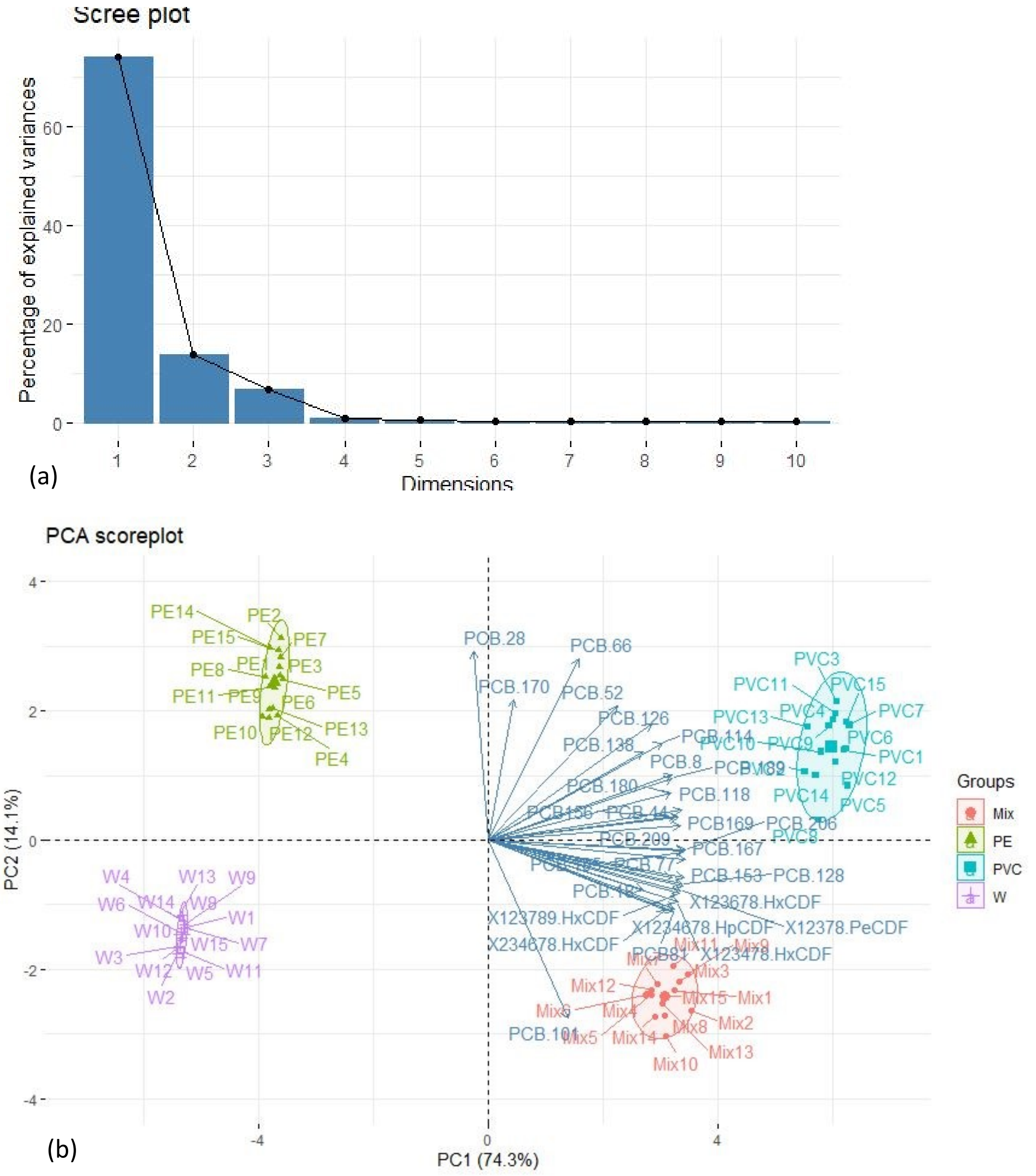

Figure 3. The PCA (a) scree plot and (b) biplot of PCBs and PCDDs/Fs contents of the samples

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Loadings clarify the chemistry behind these statistical results. PC1 is driven by higher-chlorinated PCBs together with multiple PCDD/F variables, so movement to the right on PC1 reflects simultaneous increases across those species and matches the higher totals in the PVC and mix groups. PC2 captures differences in pattern: PCB 28, 66, 52, and 170 load positively and describe the PE-like signature, whereas PCB 101 and several PCDD/Fs pull in the opposite direction. Congener-level nonparametric tests agree with this interpretation without requiring individual values: relative to wood, PE shows significantly higher levels of PCB 28, PCB 52, PCB 66, and PCB 170 ($p < 0.05$); relative to PE, PVC is significantly higher across a broader chlorine-rich suite, including PCB 118, PCB 114, PCB 8, PCB 44, PCB 180, PCB 189, PCB 126, and PCB 138, and it also exhibits the emergence of PCB 156 and PCB 169 ($p < 0.05$). These variables contribute positively to PC1 and help pull the mix group to high PC1 but lower PC2, which is consistent with the biplot and with the HCA dendrogram.

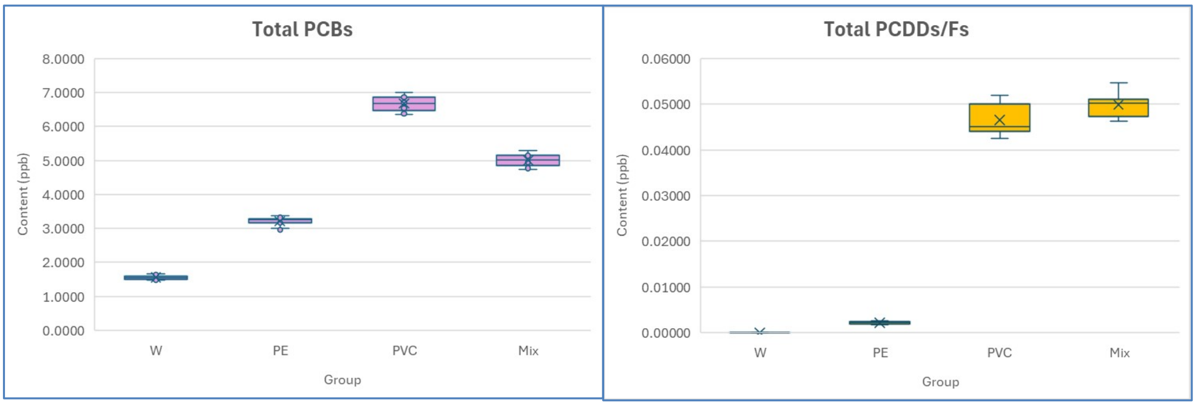

Figure 4. The boxplot of total PCBs (left) and total PCDDs/Fs (right) contents of the samples

The two boxplots (Figure 4) confirm these patterns formally. For total PCBs, a Kruskal–Wallis test indicates a significant overall difference among groups, and Benjamini–Hochberg–adjusted Mann–Whitney tests show a strict ordering in which PVC is significantly higher than the mix, the mix is significantly higher than PE, and PE is significantly higher than wood (all $p < 0.05$). For total PCDDs/Fs, the overall test is again significant, and every pairwise comparison is significant at $p < 0.05$; the ordering follows mix higher than PVC, PVC higher than PE, and PE higher than wood. The narrow boxes for wood, the modest spread for PE, and the larger spreads for PVC and mix in both plots are consistent with the increasing heterogeneity expected under plastic combustion.

Taken together, fuel composition governs both intensity and pattern: PE selectively elevates a small set of congeners and shifts samples along PC2; PVC causes a broad, statistically reliable escalation in higher-chlorinated PCBs and introduces dioxins and furans, pushing samples strongly along PC1; and combining PE with PVC yields the highest PCDD/F burden while maintaining a PCB pattern dominated by the PVC contribution. These conclusions are consistent across all three lines of evidence and are supported by significance at the $p < 0.05$ level.

PAHs contents in the samples

Polycyclic aromatic hydrocarbons (PAHs) are a broad class of food- and environment-related contaminants composed of two or more fused aromatic rings [16]. In foods, PAHs arise predominantly from high-temperature processing—such as

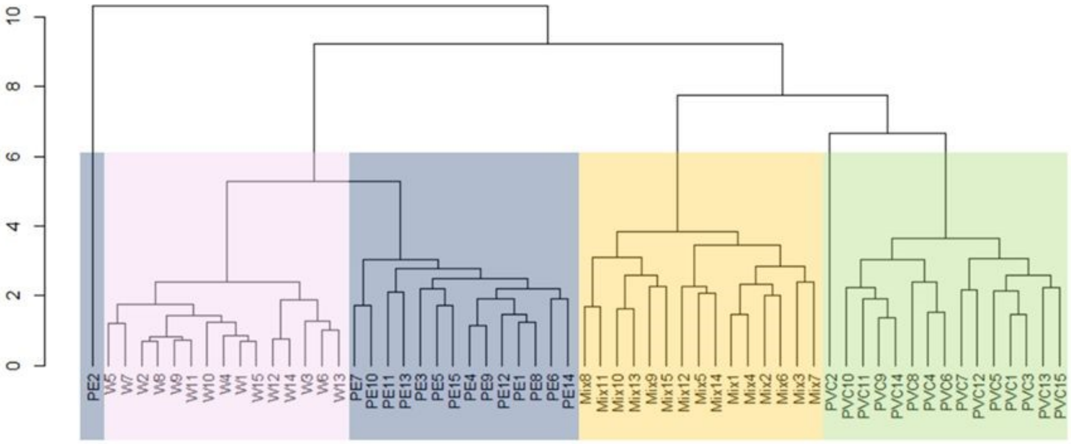

Figure 5. Hierarchical cluster analysis dendrogram of the PAHs in smoked beef samples

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smoking, grilling, and smoke-drying—where thermal degradation and partial oxidation of lignocellulosic biomass generate radical fragments that cyclize and condense into aromatic rings under conditions of incomplete combustion rather than being fully oxidized to CO_2 and H_2O [13, 17, 18]. Given their toxicological relevance and regulatory attention, profiling PAHs provides a complementary lens to chlorinated POPs when evaluating smoke-derived contamination.

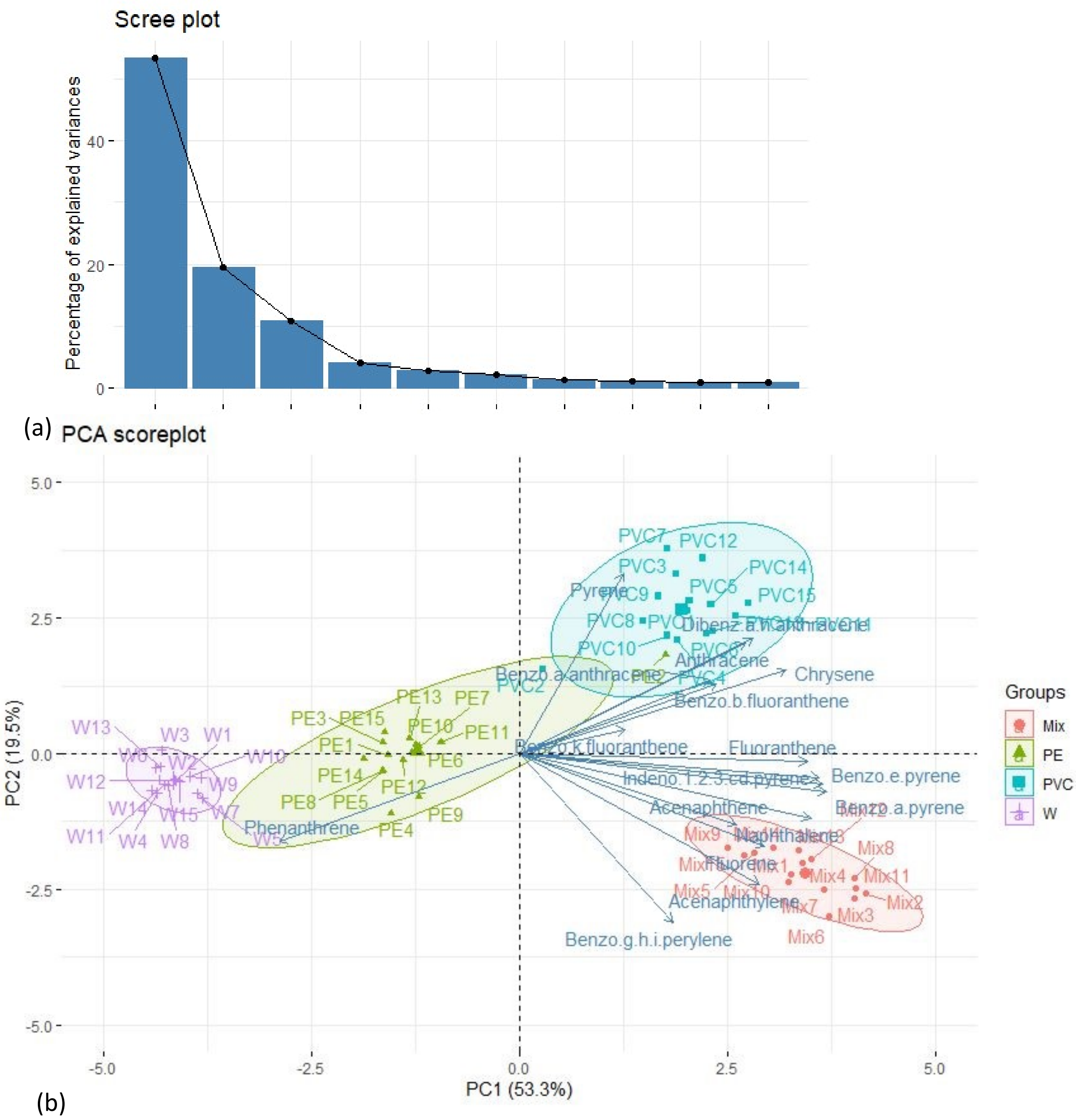

Figure 6. The PCA (a) scree plot and (b) biplot of PAHs contents of the samples

In this study, we quantified seventeen priority PAHs in smoked beef produced with four fuel conditions designed to isolate the impact of plastic adulteration of wood fuel: clean wood, wood with polyethylene (PE), wood with polyvinyl chloride (PVC), and wood with both plastics. This design allows direct comparison of PAH burdens and compositional shifts across fuels and provides a basis for interpreting multivariate patterns alongside the PCB/PCDD/F results reported earlier in the manuscript. The polycyclic aromatic hydrocarbon (PAH) profiles of beef smoked under the four fuel conditions display distinct compositional signatures (Table S2). Across all groups, two- to four-ring compounds—Naphthalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, and Pyrene—are consistently detected and constitute the core of the chromatographic fingerprint. Wood-fired samples show the most uniform composition within replicates and are characterized by a predominance of these lower-ring PAHs. Samples smoked with polyethylene (PE) remain broadly similar to wood yet exhibit a discernible shift toward mid-ring species, notably Fluoranthene and Pyrene. In contrast, combustion

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involving polyvinyl chloride (PVC) and, more markedly, the combined PE+PVC mixture yields a broader distribution that includes higher-molecular-weight, carcinogenic PAHs. These comprise Benzo[a]anthracene, Chrysene, Benzo[b]fluoranthene, Benzo[k]fluoranthene, Benzo[e]pyrene, Benzo[a]pyrene, Indeno[1,2,3-cd]pyrene, Dibenz[a,h]anthracene, and Benzo[g,h,i]perylene, which become more evident in the plastic-involved fuels. The PVC and PE+PVC groups also exhibit greater sample-to-sample heterogeneity, consistent with altered formation pathways and combustion microenvironments under plastic-containing conditions.

Hierarchical clustering of the PAH dataset (Figure 5) resolves the samples into four fuel-specific blocks that mirror the compositional tendencies described above. Wood forms a compact cluster with minimal within-group dispersion, consistent with a uniform profile dominated by two- to four-ring PAHs. The PE group forms a neighboring cluster on the same major branch, and one PE replicate merges with the wood block, indicating partial compositional overlap and a comparatively modest shift in PAH pattern under PE combustion. On the opposite branch, the mixture of PE+PVC constitutes a distinct cluster adjacent to the PVC block; their proximity reflects shared enrichment of higher-molecular-weight, carcinogenic PAHs, although the two groups remain separable, suggesting fuel-specific nuances in formation pathways. Compared with the HCA obtained for PCBs/PCDDs/Fs, the overall topology is similar—fuel composition is the primary driver—but the boundary between wood and PE is less pronounced for PAHs, whereas the wood and PE is less pronounced for PAHs, whereas the separation between plastic-involved fuels and wood/PE is strong in both chemistries. The PCB/PCDD/F dendrogram showed especially sharp divergence associated with chlorine-bearing species and the appearance of dioxins and furans; the PAH dendrogram instead emphasizes a gradient from wood to PE and from there to PE+PVC and PVC, with increasing heterogeneity within the plastic-involved clusters. This concordance across analyte classes supports a common combustion-driven ordering while highlighting that PAH profiles discriminate PE from wood more weakly than the PCB/PCDD/F profiles.

Consistent with the HCA topology described above, principal component analysis (PCA) of the PAH dataset yielded a compact and informative model in which most variance is concentrated in the first two to three components. PC1 has an eigenvalue of 9.068 and explains 53.3% of the variance; PC2 has an eigenvalue of 3.318 and explains 19.5%. Together, the first two components retain 72.9% of the total variance and are therefore adequate for discrimination and visualization on the PC1–PC2 plane. Adding PC3 (eigenvalue 1.846; 10.9%) raises the cumulative variance to 83.7%, but the marginal gain becomes modest thereafter. The scree plot (Figure 6a) shows a clear elbow after the second to third components, and the Kaiser criterion supports retaining the first three components only, since PC4 and PC5 have eigenvalues below one and captures mall, likely local variation. In practice, PC1 can be interpreted as the dominant gradient in the PAH profiles (a general intensity or co-varying mixture axis), PC2 adds a secondary compositional contrast that helps resolve fuel-related patterns, and PC3 contributes fine structure that may reflect within-group heterogeneity.

Thus, a two-component solution suffices for primary separation and reporting, while a three-component solution is appropriate if subtle distinctions need to be resolved. Interpretation of chemical drivers should be based on the loading matrix and biplot in the subsequent analysis. The PCA biplot (Figure 6b) yields a clear four-class separation. Along PC2, the wood (W) and polyethylene (PE) groups are well resolved from each other and from the plastic-involved groups: wood scores lie on the negative side of PC2 near the origin, whereas PE shifts to positive PC2. In contrast, the distinction between the two plastic conditions is captured primarily by PC1, with PVC and the PE+PVC mixture occupying separate, nonoverlapping regions on the positive side of that axis. Negative PC1 scores characterize the wood samples and indicate a lower overall PAH burden relative to the other groups, whereas PVC and the mixture display large positive scores on PC1 (and, respectively, high and low PC2), consistent with higher PAH accumulation. The loadings identify diagnostic compounds for each pattern. Phenanthrene projects toward the PE cluster and serves as a characteristic marker of combustion involving PE. Vectors pointing toward the PVC cluster include Pyrene, Dibenz[a,h]anthracene, Anthracene, Chrysene, Benzo[b]fluoranthene, and Benzo[k]fluoranthene, indicating their enhanced presence when wood is mixed with PVC. By contrast, the PE+PVC mixture aligns with Naphthalene, Acenaphthylene, Acenaphthene, Fluorene, Benzo[e]pyrene, Benzo[a]pyrene, and Indeno[1,2,3-cd]pyrene, suggesting a distinct co-promotion of these species when both plastics are present. Overall, PC2 resolves the W–PE contrast, PC1 separates PVC from the mixture, and the compound vectors explain the chemical basis for these score-space partitions.

Building on the boxplot interpretation, the distribution of total PAHs shows a clear fuel-dependent gradient (Figure 7). With fifteen samples per group, the median summaries indicate 940.6 ppb for wood, 1384.4 ppb for PE, 1397.7 ppb for PVC, and 2127.7 ppb for the PE+PVC mixture; corresponding means ±SD are 973.2 ± 100.8 ppb (wood), 1,371.0 ± 151.8 ppb (PE), 1,405.3 ± 171.0 ppb (PVC), and 2,129.6 ± 267.5 ppb (mixture). Thus, relative to wood, the mixture exhibits roughly a 2.3-fold increase in the median total PAH burden, while PE and PVC each show about a 1.5-fold increase. Variability follows the same ordering, with the smallest spread in wood (range 819–1,147 ppb), moderate spread in PE (1112–1,58 ppb) and PVC (1168–1685 ppb), and the largest spread in the mixture (1720–2459 ppb), consistent with more heterogeneous formation under plastic-containing combustion. A Kruskal–Wallis test confirms an overall difference among groups ($p < 0.001$). Pairwise Mann–Whitney comparisons with Benjamini–Hochberg adjustment indicate that wood is lower than every other group ($p < 0.001$) and that the mixture exceeds both PE and PVC ($p < 0.001$), whereas PE and PVC do not differ significantly in total PAHs (adjusted $p = 0.65$). These distributional results align with the PCA scores: negative PC1 values for wood reflect the lowest totals, the mixture and PVC map to large positive PC1 values, and PE is separated from wood along PC2 as described above.

Discussion

Incomplete combustion is the proximate source of PAHs in smoke and accounts for their deposition on smoked meats: thermal degradation and partial oxidation of lignocellulosic fuels generate reactive fragments that cyclize and condense into multi-ring aromatics rather than fully oxidizing to carbon dioxide and water. This mechanism is well documented for smoking and other high-temperature processes and underpins the PAH burdens observed in meat products[13, 17, 18]. Published measurements provide context for both magnitude and composition. In smoked beef and pork ham, surveillance of the 16 EU priority PAHs typically reports final concentrations on the order of a few micrograms per kilogram, with traditional smokehouses generally exceeding industrial systems (for example, total PAHs ≈3.9 ppb vs. 1.9 ppb for beef, and 4.9 ppb vs. 4.2 ppb for pork)[21, 22]. Benzo[c]fluorene is frequently among the most abundant during smoking; benzo[a]pyrene often tracks total PAHs and, under controlled conditions, remains below the 5 ppb regulatory limit. Market surveys show that oily matrices can accumulate substantially higher levels—canned smoked sprats in oil have been reported at 36.51 ppb benzo[a]pyrene and 73.01 ppb for the PAH4 sum—and thermal cooking contributes additional exposure, with grilled beef and chicken spanning roughly 0.29–21.95 ppb depending on product and preparation [23]. Outside smoked meats, high-fat foods such as butter may also carry measurable PAHs that evolve during storage[21, 24]. Against this background, our dataset shows a clear fuel-dependent gradient in total PAHs. With fifteen samples per group, the means (±SD) were 973.2 ± 100.8 for wood, 1371.0 ± 151.8 for PE, 1405.3 ± 171.0 for PVC, and 2,129.6 ± 267.5 for the PE+PVC mixture; the corresponding medians were 940.6, 1384.4, 1397.7, and 2127.7. Relative to wood, PE and PVC increased totals by about 40–50 percent, whereas the mixture produced a little more than a twofold rise (approximately 2.2-fold by the median). These magnitudes are consistent with the literature, well below the extreme burdens reported for oily smoked fish [22] yet clearly elevated when plastics contaminate the fuel—reinforcing the broader conclusion of this study: fuel composition, especially the presence of mixed plastics, is a primary driver of PAH accumulation in smoked meat and helps explain the multivariate patterns observed alongside the PCB/PCDD/F results. Nevertheless, the observed increments when plastics contaminate fuels reinforce the central sustainability concern of this study: fuel composition strongly determines the safety of smoked foods, and avoiding plastic-derived emissions is a prerequisite for both consumer health and environmentally responsible processing.

Consistently, fuel composition governed chlorinated POPs in smoked meat. In our experiment, clean wood produced the lowest and most uniform burdens (total PCBs about 1.6 ppb, PCDD/Fs essentially undetectable). Adding polyethylene raised only a limited subset of PCB congeners and left PCDD/Fs near background. Introducing polyvinyl chloride caused a broad escalation: total PCBs increased to approximately 6–7 ppb (PVC) and about 5 ppb (PE+PVC), while PCDD/Fs became clearly measurable (approximately 0.048–0.052 ppb). Multivariate analyses mapped these plastic-containing fuels to a high "burden" axis, consistent with chlorine-enabled formation during combustion and on cooling surfaces. The wet-weight PCB sums for PVC and PE+PVC fell in the same order of magnitude as marker-PCB levels reported for retail beef (typically a few ppb on a fat basis), whereas dioxin-like toxicity in meats was usually low but highly sensitive to chlorine sources and processing conditions. Direct, process-resolved benchmarks for PCB and PCDD/F formation during smoking were scarce relative to the PAH literature, and many surveys reported fat-normalized TEQs rather than wet-weight sums. Within these constraints, our results indicated that PE contamination modestly shifted PCB profiles with minimal dioxin signal, whereas PVC—alone or mixed with PE—produced the most consequential increases in both PCB loads and PCDD/F formation.

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DOI: 10.1039/D5FB00592B

From a sustainability perspective, these findings extend beyond food safety. They demonstrate that reliance on uncontrolled waste plastics as fuel is not only unsafe but also environmentally unsustainable, generating hazardous emissions that compromise product quality and increase downstream risks. By contrast, clean biomass fuels such as wood provide significantly safer profiles, reinforcing their suitability as a renewable and low-emission option. The differentiation between fuels underscores the need for sustainable smoking strategies, including stricter control of fuel sources, valorisation of clean agricultural by-products, and integration of emission-reducing technologies in traditional and industrial smokehouses. Such measures would not only protect consumer health but also align with broader goals of reducing chemical footprints and supporting a circular food economy.

Conclusions

Fuel composition is the principal determinant of POP contamination in smoked beef. Considering chlorinated POPs, clean wood yields the lowest levels; PE produces a modest rise with limited PCB congeners; PVC causes a broad escalation in higher-chlorinated PCBs and introduces PCDDs/Fs; and the combination of PE and PVC gives the strongest PCDD/F signal together with a PCB profile dominated by highly chlorinated congeners. For PAHs, wood again shows the lowest totals; PE and PVC are intermediate and similar in magnitude but differ in composition; and PE+PVC produces the highest totals and a distinct mixed-plastic signature. Overall, our findings consistently indicate that eliminating plastics—particularly PVC and mixtures of plastics—from smoking fuels is essential to minimize both the intensity and the toxicity profile of smoke-derived contaminants. Moreover, the work provides a sustainability framework by identifying fuel choices that reduce chemical hazards, supporting the transition toward safer, environmentally responsible food processing systems.

Author contributions

Do Hoang Giang processed the data and drafted the original manuscript. Nguyen Thi Luyen, Bui Thi Nhat Le, Luu Hai Nhi, and Hoang Thuy Duong collected the samples and performed the smoking experiment. Nguyen Thu Uyen and Nguyen Thu Minh prepared the samples for instrumental analysis. Hoang Le Tuan Anh and Nguyen Ngoc Tung carried out the GC–MS analysis. Nguyen Tien Dat reviewed and revised the manuscript.

Conflicts of interest

There are no conflicts to declare

Data availability

The data supporting this article have been included as part of the SI. See DOI: 10.1039/x0xx00000x.

Acknowledgements

This research was supported by the Vietnam Academy of Science and Technology (VAST) under grant number NCXS 01.02/23-25.

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DOI: 10.1039/D5FB00592B

Data availability

The data supporting this article have been included as part of the SI. See DOI: 10.1039/x0xx00000x.