

Article

Urban Air Pollution and Food Safety: A Comparative Study of PAH Contamination in Fruits Sold Outdoors and Indoors

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Abstract

Urban air pollution is a major public health concern, especially in densely populated cities. This problem also includes food safety issues in outdoor retail environments, where fresh products may be exposed to airborne pollutants. This study examines the presence of polycyclic aromatic hydrocarbons (PAHs) on fruits sold at indoor and outdoor locations across Budapest and several Hungarian cities. Results showed higher PAH concentrations on fruit sold outdoors, with benzo[a]pyrene (BAP) exceeding 2 µg/kg in 62% of outdoor samples and in 22% of indoor ones. Washing with water reduced contamination by 40–50% on average, with some samples showing over 65% reduction for BAP. Differences across fruit types were limited overall, though statistically significant for BAP in certain cases, highlighting compound-specific variability. Correlation analysis revealed weak but interpretable associations between PAH levels and ambient air quality indicators, with a moderate correlation for fine particulate matter ≤ 2.5 µm (PM_{2.5}) ($r = 0.4355$) and a weaker one for the calculated Air Quality Index (AQI) ($r = 0.2148$). These findings suggest that while urban microenvironments influence contamination, the general air quality indices may not predict surface PAH burden reliably. The study highlights the role of public wells in enabling citizen-level mitigation through rinsing and calls for integrated urban health strategies considering food exposure alongside infrastructural access.

Keywords: airborne PAH contaminants; street selling locations; fruit surface contamination; environmental exposure; risk mitigation and resilience

1. Introduction

Urban environments are increasingly recognized as complex ecosystems, where human activity, infrastructure, and environmental factors intersect. Among the many challenges posed by urbanization, air pollution remains one of the most persistent threats to public health and urban sustainability [1,2]. In Hungary, cities such as Budapest face recurring air quality issues, particularly during colder months, when heating and traffic emissions intensify, resulting in elevated fine particulate matter ≤ 2.5 µm (PM_{2.5}) concentrations linked to outdated heating systems and dense traffic [1,3,4]. These environmental stressors are not only health hazards but also indicators of infrastructural imbalance and urban planning inefficiencies [5,6].

Concerns about urban air quality are not new. As early as the 19th century, industrial cities like London, Manchester, and Pittsburgh were plagued by coal smoke, prompting early air quality regulations. At the same time, urban food systems evolved: open-air markets became central to daily life, often located near transport hubs and busy roads,



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exposing food to the pollutants that accompanied industrialization [7,8]. While indoor retail spaces emerged in the 20th century, open-air markets remain popular in many European cities due to their cultural and economic significance [9,10].

Polycyclic aromatic hydrocarbons (PAHs) are organic pollutants formed primarily through incomplete combustion of fossil fuels, biomass, and other carbon-based materials [11,12]. They are ubiquitous in urban air and pose a double risk: they adhere to surfaces and infiltrate biological systems via inhalation, ingestion, or dermal contact [13,14]. Several PAHs—such as benzo[a]pyrene (BAP) and benz[a]anthracene (BAA)—are classified as carcinogenic or mutagenic [15–17]. These compounds tend to accumulate in fine particulate matter (PM_{2.5}) being prevalent in densely built environments with limited green infrastructure [18,19]. Urban land-use patterns, including proximity to traffic corridors and heating-intensive zones, significantly influence PAH distribution [20–22].

While the health effects of airborne PAHs are well documented, less attention has been given to their deposition onto food items sold or stored in urban environments [23,24]. Fruits and vegetables displayed outdoors may be particularly vulnerable to surface contamination, especially in areas with poor air quality and high pedestrian traffic. [25,26] Atmospheric fallout has been shown to transfer PAHs onto plant surfaces, raising concerns about dietary exposure [27–29]. Seasonal variation complicates further this issue, with winter months often showing elevated PAH levels due to heating emissions [30,31].

As emphasized by the World Health Organization and recent urban health reviews, over 4.2 billion people live in cities that are becoming epicentres of environmental health challenges, where air pollution, poor infrastructure, and inadequate food environments converge to shape population health outcomes [29,32–34]. A 2025 UN-Habitat report emphasizes that well-designed public spaces and infrastructure—including food environments and water access—can reduce spatial and environmental inequalities, promoting both physical and mental health. Meanwhile, research from the Global Cities Hub highlights that over 1.1 billion people live in informal settlements, where exposure to environmental contaminants—including airborne pollutants and contaminated food—is exacerbated by infrastructural gaps and limited access to healthcare [6,35–39].

Urban retail environments play a critical role in mediating environmental exposure, positioning food points of sale as part of the broader urban infrastructure that shapes contamination pathways. Open-air stalls located near busy roads or transit hubs may inadvertently serve as hotspots for pollutant deposition, while enclosed supermarkets and shopping malls with air filtration systems offer partial protection. The WHO and urban health researchers have increasingly called for integrated urban planning approaches that consider food safety, air quality, and public health as interconnected domains [6]. As cities grow and densify, the spatial organization of food retail environments becomes a key determinant of exposure pathways—especially for vulnerable populations such as children, the elderly, and those with respiratory conditions [5].

In this context, public wells and other water access points may offer a subtle but meaningful mitigation pathway. Recent studies suggest that such infrastructure serves not only hydration and cooling functions but also supports food safety by enabling citizens to rinse products purchased at street selling locations [40,41]. Beyond technical availability and water quality, their effective role depends on regulatory frameworks and local customs: if local regulations or social norms discourage rinsing fruit at public wells, the potential benefit is lost. In cities with polluted air, the acceptance of such practices—both legally and socially—becomes an important dimension of urban resilience.

Although numerous studies have examined PAH accumulation in crops grown in polluted environments, agricultural soils, or processed foods [12,27–29], much less attention has been given to contamination occurring at the point of sale. Existing research has

predominantly focused on production-side exposure pathways, leaving a notable gap regarding how urban microenvironments—such as open-air markets, shopfront displays, or semi-enclosed transport hubs—shape the surface PAH burden of ready-to-eat fruits [20–22]. Moreover, few studies have compared indoor and outdoor retail settings within the same urban context, and even fewer have evaluated simple consumer-level mitigation practices such as rinsing. To address these gaps, we examine point-of-sale contamination across diverse urban environments, assess the effectiveness of washing, and explore how ambient air quality indicators relate to surface PAH levels.

This study investigates the presence and concentration of PAHs on the surface of fruits sold in various urban environments across Hungary, with a focus on point-of-sale exposure, washing efficiency, and the relations to ambient air quality parameters. By comparing samples from the different locations and conditions, we aim to assess the extent to which urban air pollution contributes to surface contamination of fresh products—a concern that remains underexplored in urban health discourse—and how citizens may reduce these risks through simple, accessible practices. The findings of our research may contribute to a broader understanding of urban environmental health. They offer insights for public health policy, food system resilience, and urban planning strategies that integrate food safety into city planning.

Most previous studies on PAHs have focused on agricultural exposure pathways—such as uptake from polluted soils, atmospheric deposition during cultivation, or formation during food processing. To our knowledge, no studies have examined PAH contamination at the point of sale in urban environments, nor compared indoor and outdoor retail settings within the same cities. Research on simple consumer-level mitigation, such as rinsing fresh fruits immediately after purchase, is also largely absent. This study addresses these gaps by analysing surface PAH levels on fruits sold in different urban microenvironments and evaluating the effectiveness of washing.

2. Materials and Methods

2.1. Sampling Locations and Strategy

Fruit samples were collected during the winter and summer seasons from eight different cities: Budapest, Debrecen, Miskolc, Győr, Szeged, Békéscsaba, Kecskemét, and Schladming (Austria). The selection aimed to capture a range of urban air pollution exposure scenarios, particularly in areas with high vehicular traffic and residential heating activity. At each site, commercially available fruits—apples, peaches, and nectarines—were purchased directly from vendors. Care was taken to ensure that the fruits had been displayed in their respective environments (indoor or outdoor) for several hours prior to sampling.

Samples were categorized into three groups of selling location: sold outdoors (e.g., open-air stalls and shopfront displays), sold indoors (e.g., supermarkets and enclosed shops), and “special.” The latter referred to fruit obtained from a greengrocer located inside of Keleti Railway Station, Budapest. Although physically it is an indoor location, the station’s open architecture and the frequent nearby diesel engine activity—trucks and lorries transporting passengers and goods to be forwarded by railway—lead to a pollution load comparable to outdoor environments. This unique setting justified its classification as “special.”

In total 30 fruit samples were collected (see Supplementary Table S1), with balanced representation across fruit types and selling categories. Upon collecting, samples were transported to the laboratory in sealed containers to prevent further contamination.

2.2. Sample Preparation and Washing Procedure

Upon arrival at the laboratory, fruit samples were processed with care to preserve surface integrity prior to analysis. In selected cases, a washing procedure was applied: fruits were rinsed under cold running tap water for approximately 20 s. This step was performed immediately upon receipt, before any further handling, and was intended to simulate typical consumer behaviour.

Washing was applied to those samples for which the point of purchase was located near a public drinking fountain or other water access point, reflecting situations where consumers could realistically rinse fresh produce immediately after purchase. To maintain consistency, all washing was performed in the laboratory under controlled conditions. As a result, the washing subset (see Supplementary Table S3) represents a targeted but non-systematic portion of the full sample pool, enabling exploratory comparison of washed and unwashed conditions. Accordingly, washing results are interpreted as indicative of potential consumer-level mitigation rather than as generalisable estimates across all fruit types and sites.

Following washing (where applicable), all fruits were stoned/cored and homogenized using a stainless-steel blender. From each homogenized sample, three subsamples of 15 g were prepared to ensure triplicate analysis. Subsamples were stored at -20°C until extraction.

2.3. PAH Extraction and Analysis

PAHs were extracted using a liquid–liquid extraction method with organic solvents. A surrogate standard (100 μL of 30 mg/mL triphenyl phosphate, TPP) was added to each sample, followed by extraction with 20 mL of a toluene/acetone (2:1) mixture. Sodium chloride was added to enhance phase separation, and samples were centrifuged at $8000\times g$ for 10 min at room temperature. The upper organic layer was collected, evaporated under nitrogen at 55°C , reconstituted in 500 μL acetonitrile, and filtered through a 0.22 μm membrane prior to analysis.

Quantification of PAHs was performed using high-performance liquid chromatography with fluorescence detection (FL-HPLC), employing a Shimadzu 10A series system (Shimadzu Corporation, Kyoto, Japan). Separation was achieved on a Phenomenex Kinetex[®] C18 column (150 $\times$ 4.6 mm, 2.6 μm particle size; Phenomenex, Torrance, LA, USA) under isocratic conditions with 85% acetonitrile at a flow rate of 0.3 mL/min. The column oven was maintained at 35°C , and injection volume was 20 μL . Each sample was injected three times.

Fluorescence detection was wavelength-programmed to optimize sensitivity for six target PAHs: fluoranthene (FLU), benzo[a]anthracene (BAA), chrysene (CHR), benzo[b]fluoranthene (BBF), benzo[a]pyrene (BAP), and dibenzo[a,h]anthracene (DAHA). TPP was detected via UV at 267 nm. Calibration curves were constructed using certified PAH standards (Sigma-Aldrich; Merck Group, St. Louis, MO, USA), and quality control included procedural blanks and triplicate analyses.

2.4. Air Quality Data and Proxy Alignment

To contextualize ambient exposure, air-pollution data were retrieved from the European City Air Quality Viewer and the Hungarian National Air Quality Monitoring Network [42–44]. For each sampling site, concentrations of fine particulate matter $\leq 2.5\ \mu\text{m}$ and $10\ \mu\text{m}$ ($\text{PM}_{2.5}$ and PM_{10}), carbon monoxide (CO), and benzene (BE) were obtained for the sampling day and the three preceding days. These values were averaged to generate a location-specific four-day pollution profile.

PM_{2.5} was used as a proxy for airborne PAH exposure, based on its established role in transporting particle-bound organic pollutants. Numerous studies have demonstrated that PAHs, particularly those with higher molecular weight, preferentially adsorb to fine particulate matter such as PM_{2.5}, which facilitates their atmospheric persistence and deposition onto surfaces including plant tissues and food items. This relationship has been documented in both urban and agricultural contexts [10,45].

In addition to PM_{2.5} concentrations, we also constructed a composite air quality index (AQI) to capture a broader set of combustion-related pollutants. The index incorporated four-day average concentrations of PM_{2.5}, PM₁₀, carbon monoxide, and benzene, selected for their documented relevance to incomplete combustion processes and their established associations with atmospheric PAH levels. Because these pollutants differ by one to two orders of magnitude in their raw concentration ranges (with CO typically higher and benzene lower than particulate fractions), CO values were divided by 10 and benzene values multiplied by 10 to harmonise scales and prevent any single component from dominating the index.

$$AQI = \frac{PM_{2.5(av)} + PM_{10(av)} + \frac{CO_{(av)}}{10} + (BE_{(av)} \cdot 10)}{10}$$

where AQI means the derived air quality index, PM_{2.5(av)} and PM_{10(av)} are the four-day averages of concentrations of 2.5 micron and 10 micron size dust particles, respectively, expressed in µg/m³, CO_(av) is the four-day average of concentration of carbon-monoxide (CO), expressed in µg/m³, and BE_(av) is the four-day average of concentration of benzene, expressed in µg/m³.

The weighting scheme represents a simple linear rescaling intended to harmonize pollutant magnitudes rather than to construct a formalized exposure model. As the index relies on basic additive and multiplicative transformations, its qualitative behaviour is expected to remain stable under reasonable scaling choices, making it suitable for exploratory contextualization. The AQI is therefore a non-standardized, study-specific proxy intended to support interpretation of potential links between ambient air quality and surface PAH contamination.

2.5. Statistical Analysis

Data processing and statistical analysis were performed using Microsoft Excel. Descriptive statistics were calculated for each sampling group. For correlation analyses, samples collected at the Keleti Railway Station were included within the Budapest group, as no statistical procedure required treating this location separately. Removal efficiency was determined for each sample pair using the formula:

$$Efficiency (\%) = \frac{Unwashed - Washed}{Unwashed} \cdot 100$$

Comparative analyses across fruit types and selling categories were conducted using *t*-tests and ANOVA (*p* < 0.05). Parametric tests were selected for their robustness to moderate deviations from normality and their suitability for identifying broad patterns in small, heterogeneous environmental datasets. Non-parametric alternatives (e.g., Mann–Whitney U, Kruskal–Wallis) were considered, but the study's exploratory aim and limited subgroup sizes made parametric methods the most practical choice. Washing comparisons were based on the available paired samples and were therefore analysed in an exploratory manner. The overall sample size (*n* = 30) reflects the monitoring-oriented design of the study, which prioritised coverage of diverse urban microenvironments over

formal power calculations. Consequently, all inferential statistics are interpreted cautiously and serve to highlight indicative trends rather than confirmatory effects.

2.6. Declaration of Generative AI Use

Generative AI (Microsoft Copilot, Smart mode using GPT-5.1, used between November 2025 and January 2026) was employed to assist in refining phrasing of methodological descriptions and clarifying the presentation of correlation results. Its role was limited to improving readability and consistency of the manuscript text. No AI tools were used to generate data, perform analyses, or create figures; all scientific content and interpretation were carried out by the authors.

3. Results

3.1. Measured PAH Levels

Prior to the measurement of the fruit samples, method validation was performed to assess the overall reliability of the analytical procedure. Spike-recovery experiments yielded mean recoveries of 88–108% with RSD values below 5.5%. Quality control samples analysed on three separate days showed intra- and inter-day precision consistently below 7% RSD. The agreement of recoveries and QC results across matrices indicates no substantial matrix effects. External calibration was linear ($R^2 > 0.999$), and limits of quantification were 0.25 ng/mL for PAHs and 0.15 ng/mL for TPP.

In total, 30 fruit samples were analysed for polycyclic aromatic hydrocarbon (PAH) contamination, including apples, peaches and nectarines collected from eight cities. Each sample was categorised by fruit type, point of sale (outdoors, indoors or special), and city of selling. The concentrations of six PAHs were measured (see Section 2.3 for details), and the sum of BAA, CHR, BBF and BAP concentrations was calculated as EU PAH4, following the definition used in Commission Regulation (EU) No 835/2011 amending Regulation (EC) No 1881/2006.

Figure 1 shows average concentrations of individual PAH compounds, while Figure 2 shows aggregated EU PAH4 values across fruit types and selling location. To preserve scale sensitivity, EU PAH4 is shown separately due to its markedly higher values. These visualizations highlight fruit-specific and location-dependent contamination patterns, with outdoor nectarines showing the highest average EU PAH4 levels. For detailed numerical values and deviations, see Supplementary Table S1.

Individual sample-level data and corresponding visualizations are provided in Supplementary Figures S1 and S2, including the highest EU PAH4 value (14.60 µg/kg) detected in an outdoor sold nectarine sample from Budapest (sample N02), followed by an apple from Miskolc (A10, 12.89 µg/kg) and another apple from Budapest, Keleti railway station (A18, 11.97 µg/kg). All of these fruits were displayed and sold outdoors.

Benzo[a]pyrene (BAP), the most toxic and carcinogenic PAH in the group, showed similar trends. Approximately half of the samples remained below the EU threshold for baby food (2 µg/kg), while the other half exceeded it. The highest BAP level was measured on the A18 apple from the Keleti Railway Station, Budapest (3.93 µg/kg), followed by N02 and N03 nectarines (3.88 and 3.82 µg/kg, respectively). Notably, all three nectarine samples (N01–N03) surpassed the BAP threshold, suggesting a potential fruit-specific vulnerability. At the same time, it is worth noting that this pattern should be interpreted with caution, as the limited sample size precludes any firm conclusion about whether this reflects characteristics of nectarines or simply sample-level variation.

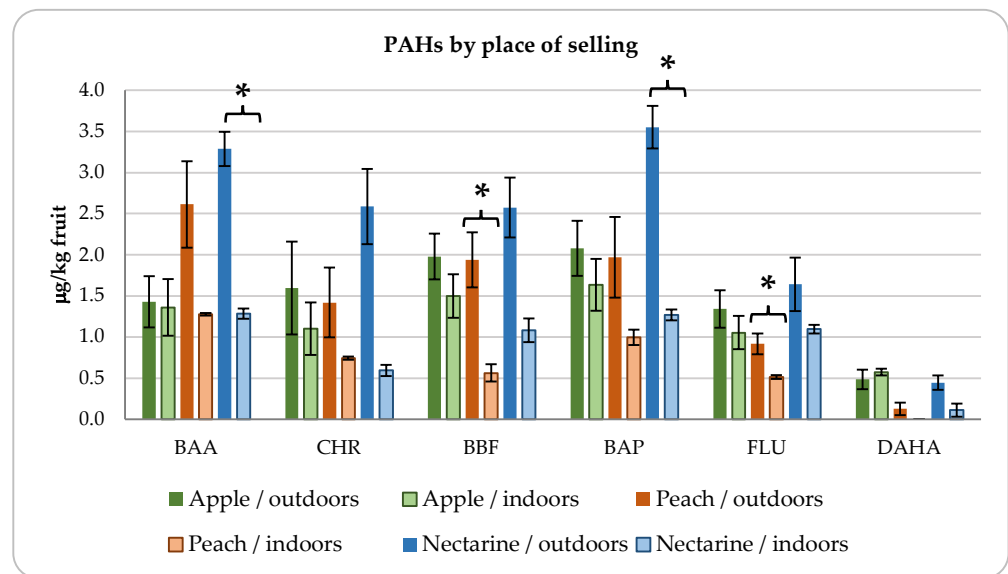


Figure 1. Average concentrations of the measured PAH compounds on the studied fruits sold at outdoor or indoor locations. Asterisks indicate statistically significant differences between outdoor and indoor samples for specific compounds and fruits.

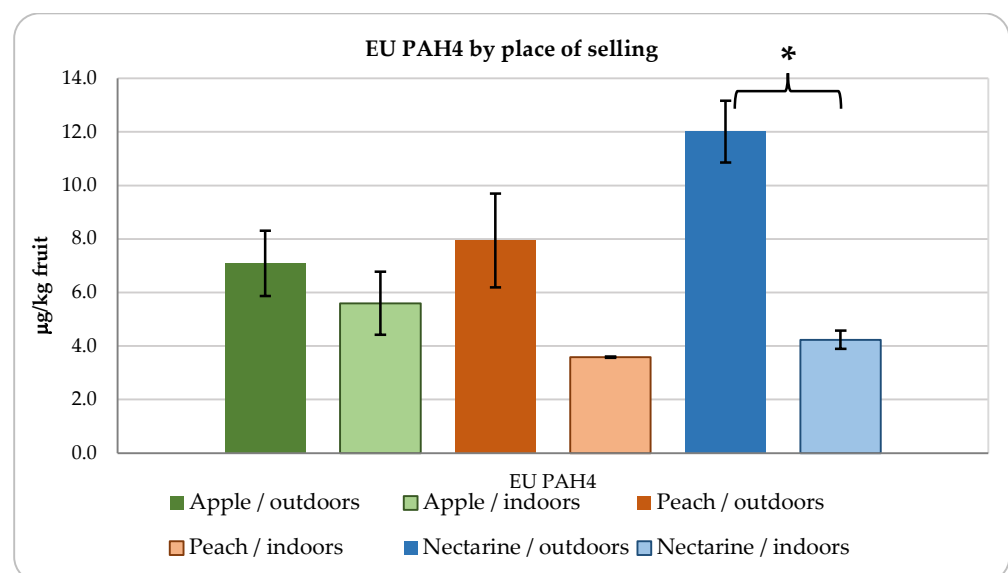


Figure 2. Average concentrations of the EU PAH4 values for the studied fruit sold at outdoor or indoor locations. Asterisks indicate statistically significant differences between outdoor and indoor samples for specific fruits.

Overall, fruits sold outdoors tended to show higher PAH concentrations than the ones sold indoors, although exceptions were observed. The “special” samples from the Keleti Railway Station (A18–A19) reflected this variability: one ranked among the highest for both EU PAH4 and BAP, while the other fell into the mid-range but still showed a BAP concentration close to the $2 \mu\text{g/kg}$ threshold. Peach samples generally exhibited lower PAH levels than nectarines, consistent with previous findings on fruit skin structure and wax composition [46].

For detailed numerical values, see Supplementary Table S2 for average concentrations with *p*-values.

3.2. Effects of Washing

To assess the impact of surface rinsing on PAH contamination, a subset of fruit samples underwent a standardized washing protocol prior to analysis. Figure 3 illustrates the concentration differences between washed and unwashed samples for EU PAH4, while Figure 4 focuses on BAP specifically. In most cases, washing resulted in a measurable reduction in PAH levels, although the magnitude of this effect varied considerably across samples. For example, apple sample A05 showed a decrease in EU PAH4 concentration from 8.60 $\mu\text{g}/\text{kg}$ (unwashed) to 5.21 $\mu\text{g}/\text{kg}$ (washed), corresponding to a 39.4% reduction. Similarly, peach sample P02 dropped from 11.65 $\mu\text{g}/\text{kg}$ to 6.55 $\mu\text{g}/\text{kg}$ (−43.8%), and nectarine sample N01 from 10.15 $\mu\text{g}/\text{kg}$ to 5.83 $\mu\text{g}/\text{kg}$ (−42.6%). Detailed concentration values for washed and unwashed samples are provided in Supplementary Table S3.

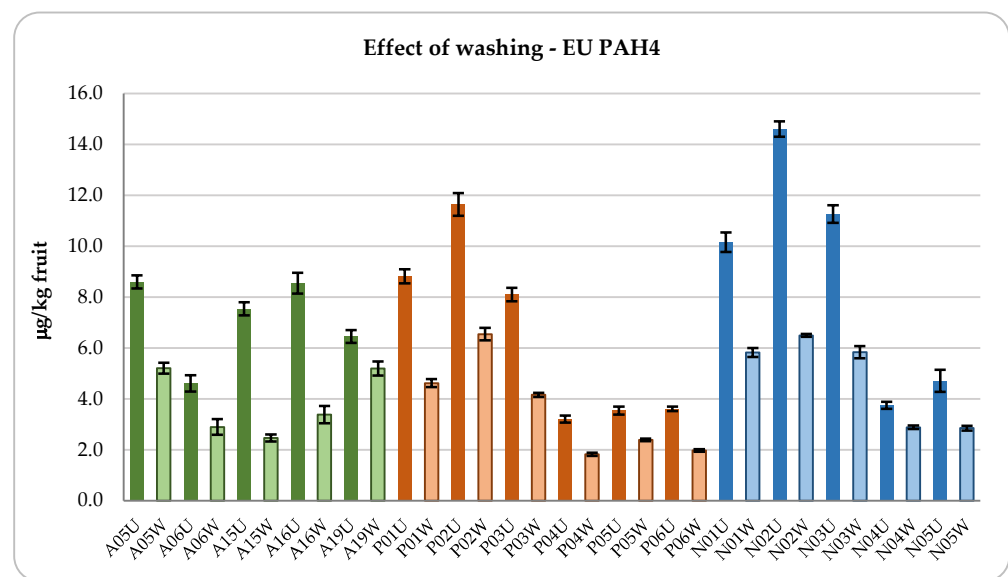


Figure 3. Effects of washing on the EU PAH4 concentrations. Legend: A: apples, P: peaches, N: nectarines; U: unwashed, W: washed. Colours: green—apples, orange—peaches, blue—nectarines; shades: dark—unwashed, light—washed.

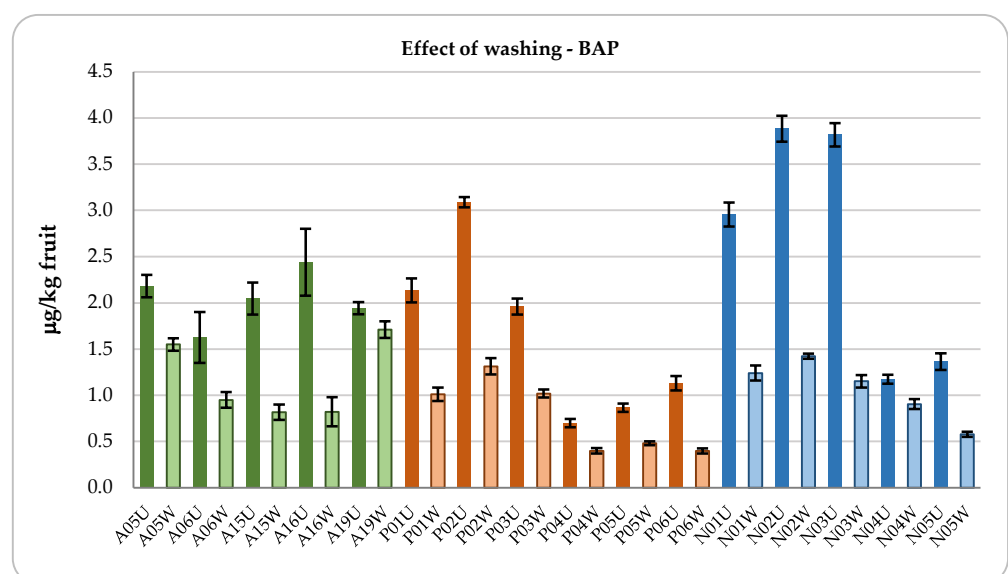


Figure 4. Effects of washing on the benzo[a]pyrene concentrations. Legend: A: apples, P: peaches, N: nectarines; U: unwashed, W: washed. Colours: green—apples, orange—peaches, blue—nectarines; shades: dark—unwashed, light—washed.

The effect was particularly pronounced for BAP, the most toxic compound in the group. In sample P06 (peach), BAP concentration decreased from 1.13 µg/kg to 0.40 µg/kg (−65.8%) after washing, while in sample N03 (nectarine), the reduction was even more substantial: from 3.82 µg/kg to 1.15 µg/kg (−69.8%).

Figure 5 summarizes the calculated removal efficiency for each sample, expressed as a percentage reduction relative to the unwashed condition. On average, BAP showed higher removal rates than the broader EU PAH4 group, with several samples exceeding 50% efficiency. However, the variability across fruits and locations suggests that washing is not uniformly effective indicating that washing effectiveness depends on fruit type, skin structure, and local exposure conditions.

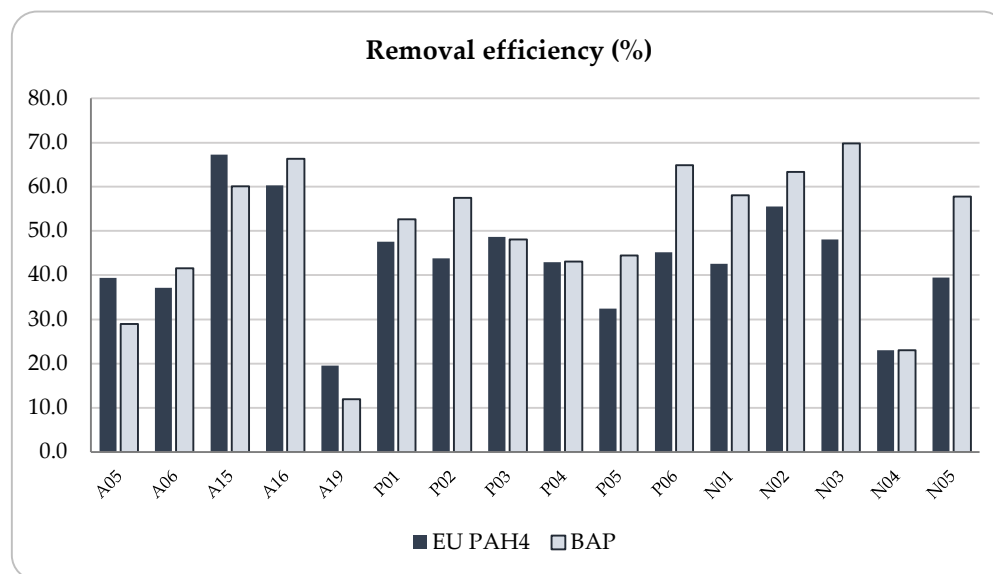


Figure 5. Removal efficiency of PAH compounds from fruits. Legend: A: apples, P: peaches, N: nectarines.

The reduction was particularly pronounced in certain apple and nectarine samples, with some washed fruits showing up to 60–70% lower concentrations compared to their unwashed counterparts. For example, sample A15 exhibited a marked decrease in both EU PAH4 and BAP levels following washing, while sample A19 showed minimal change, suggesting that surface adherence and removal efficiency may depend on fruit type, skin structure, or environmental exposure.

Detailed numerical values are provided in Supplementary Table S3, while removal efficiencies by sample and their statistical parameters (deviation, RSD%, *t*-test results) are summarized in Supplementary Table S4A,B.

4. Discussion

This study suggests that fruits sold in outdoor urban places may be more susceptible to contamination by polycyclic aromatic hydrocarbons (PAHs) than those sold indoors, although the magnitude of this effect varied by fruit type and compound. Statistically significant differences were observed in benzo[a]pyrene (BAP) and EU PAH4 concentrations for certain fruits, underscoring the role of ambient urban air pollution in surface deposition of these hazardous compounds. This pattern aligns with the broader mechanisms summarized by Liu et al. [12], who highlight atmospheric deposition as a major pathway for PAH accumulation on plant surfaces, particularly in urban environments.

Our results indicate that simple, citizen-level practices—most notably rinsing—may help to reduce PAH contamination, though effectiveness varies by fruit type and local exposure conditions.

Four PAHs from the analysed ones—chrysene, benzo[a]pyrene, benz[a]anthracene, and benzo[b]fluoranthene—are regulated under Commission Regulation (EU) No 835/2011 amending Regulation (EC) No 1881/2006 [47]. Although fresh fruits are not currently regulated for PAH content, the concentrations observed in some outdoor samples approached thresholds established for processed foods such as smoked meats and oils [15].

Recent studies support the plausibility of such contamination pathways. Sauret et al. mapped PAH deposition in urban gardens in Nice, France, while Di Fiore et al. reported detectable levels of PAHs in apples and grapes exposed to urban air. Liu et al. reviewed detection methods and sources of PAHs in food, emphasizing the role of surface accumulation on produce [12,46,48].

The spatial distribution of PAH contamination in fruit samples reflects not only chemical and biological factors, but also the urban environments in which the produce was sold. While the origin of the fruits remains unknown, the point of sale serves as a proxy for ambient exposure, shaped by traffic density, architectural enclosure, and socio-economic conditions.

Beyond urban context, variability was also evident across fruit types and even within single categories. Statistically significant differences emerged for benzo[a]pyrene (BAP) in certain fruits, while wide dispersions within the same fruit type highlighted the influence of local selling conditions and microenvironmental factors, consistent with earlier observations of urban PAH variability [49]. These observations caution against overgeneralization and suggest that fruit-specific characteristics may modulate contamination patterns. Comparable baseline heterogeneity has also been reported by Di Fiore et al. [46], who found that PAH concentrations can differ markedly among fruit species even under similar environmental conditions. This supports the interpretation that intrinsic fruit traits contribute to variability, while in our dataset the dominant drivers were the point-of-sale microenvironment and the mitigating effect of washing.

Taken together, these findings illustrate how food safety outcomes are influenced by urban environmental conditions, linking contamination risks to factors such as traffic emissions, architectural enclosure, and local selling settings.

4.1. Effects of Urban Environments and Selling Locations

Budapest, as the capital and the largest urban agglomeration in Hungary, presents a complex air pollution profile. Although district-level variation exists, the city functions as a single atmospheric basin, especially for pollutants like PM_{2.5} and PAHs. According to the European Environment Agency, Budapest consistently ranks among Europe's more polluted cities, with traffic-related emissions as a dominant source [1]. Districts VII and VIII, where several samples were collected, are densely built, historically underprivileged areas undergoing partial rehabilitation. Despite improvements, these zones remain exposed to high vehicular flow and limited green buffering. It is consistent with the higher EU PAH4 and BAP concentrations measured in several Budapest samples in our dataset.

Keleti Railway Station, where “special” samples were obtained, is a terminal station, the busiest public transport hub in Hungary. Although the produce was sold under the station's roof, it remained outside the shop, exposed to ambient air. The elevated contamination levels in such semi-enclosed transport environments are well documented internationally. Studies from London, Birmingham, and Paris show that PAH and particulate concentrations inside railway stations often exceed outdoor levels due to poor ventilation and nearby traffic emissions [50–52]. The semi enclosed architecture of Keleti Railway

Station—and its proximity to high-density traffic—buses, delivery vans, and taxis—likely contributed to the observed contamination, even in the absence of diesel locomotives inside the hall.

In contrast, Békéscsaba, a mid-sized agrarian city, showed consistently low PAH levels. Although occasionally it experiences elevated particulate matter due to seasonal heating and dust mostly of agricultural origin, its overall air quality remains moderate. Similarly, Győr and Szeged, both regional centres with mixed industrial-agricultural profiles, presented intermediate contamination levels. Notably, Debrecen, despite its agrarian and market town origin, has developed into a major industrial and logistical node, with significant truck traffic and an operational international airport [53]. This transformation is reflected in higher PAH concentrations observed in its fruit samples.

Miskolc, once a heavy industrial centre, now faces compounded challenges: economic decline, social vulnerability, and persistent air pollution. Its location in a valley within the Northern Hungarian Mountains exacerbates pollutant accumulation, making it one of the most polluted regions in the country. The elevated PAH levels in samples from Miskolc align with this environmental burden.

These findings suggest that point-of-sale location is a meaningful proxy for ambient exposure, particularly in urban environments where traffic density, architectural enclosure, and socio-economic factors converge. The contamination patterns observed at the moment of selling reflect the urban microenvironment in which consumers interact with food, highlighting how food safety outcomes can intersect with urban environmental conditions. Broader assessments of air quality and food safety support this interpretation: Veskovíc Moracanic et al. [19] emphasize that ambient pollution can directly influence contamination levels in foods exposed to urban environments. Mechanistic parallels were also documented in megacities, where Yin et al. [22] found that PAH accumulation on plant surfaces varies strongly with land-use type, with higher levels in traffic-dominated and densely built areas. Evidence from urban agriculture further reinforces this pattern, as Amato-Lourenço et al. [23] reported elevated PAH levels in vegetables grown in traffic-influenced areas of São Paulo. A similar spatial signal was observed by Sauret et al. [48], who mapped PAH concentrations across the urban area of Nice and showed that crops grown in traffic-influenced microenvironments accumulated substantially higher levels than those in less exposed locations. Taken together, these studies mirror the location-dependent differences observed in our fruit samples.

4.2. Washing as a Citizen-Level Mitigation

Because washing was applied only to a subset of samples, the observed reductions are interpreted as indicative of potential consumer-level mitigation rather than as generalisable estimates across all fruit types and selling environments.

The washing experiments highlight the potential of everyday urban practices to reduce PAH exposure. Although individual samples showed substantial variability, the overall trend was consistent: rinsing fruits lowered contamination levels, particularly for benzo[a]pyrene (BAP). In several cases, reductions exceeded 40–50%.

When averaged by fruit type, the removal efficiency was remarkably similar: 44.7% for apples, 43.4% for peaches, and 41.7% for nectarines (EU PAH4), with slightly higher values for BAP, except for apples. Statistical analysis revealed no significant differences between fruit types, suggesting that the variability was driven more by environmental exposure than by morphological differences. It suggests that washing can be effective across fruit categories, despite individual fluctuations.

From an urban planning perspective, these findings suggest that accessible public water infrastructure may support citizen-level mitigation. Public wells and drinking

fountains, often installed for hydration and heat relief, may also play a supportive role in enabling safer fruit consumption in outdoor settings. In urban areas with high traffic, where ambient contamination is elevated, the possibility to rinse produce before eating may contribute to reducing exposure to harmful compounds. This dual function—hydration and decontamination—positions public water access as a subtle but meaningful contributor to urban health resilience.

However, the persistence of contamination even after washing highlights the limits of individual action. While citizens may have some limited possibility to reduce contamination on produce through practices such as washing, systemic improvements in urban air quality remain essential for broader public health. In environments such as railway stations or traffic-heavy districts, where deposition rates are high, washing may offer partial mitigation for food but cannot substitute for cleaner air, and its effectiveness ultimately depends on local conditions and individual behaviour.

4.3. Air Quality Correlations: Weak but Instructive

To explore potential links between ambient air pollution and fruit surface contamination, EU PAH4 concentrations were compared with two indicators: the general Air Quality Index (AQI) and fine particulate matter (PM_{2.5}). AQI was used solely to contextualize ambient pollution levels across sampling sites and was therefore not included as a predictive variable in the correlation analysis. The results revealed only weak associations (Supplementary Table S5).

AQI showed minimal predictive power ($R^2 = 0.034$), suggesting that aggregated air quality scores are not reliable indicators of PAH deposition on fruit surfaces. In contrast, PM_{2.5} exhibited a slightly stronger correlation ($R^2 = 0.206$), indicating that fine particles may play a more direct role in transporting and depositing PAHs. It aligns with previous findings that PAHs often adhere to airborne particulates, especially those in the submicron range [54,55].

While the correlation remains weak, the relative improvement with PM_{2.5} suggests that targeted air quality metrics may be more informative than composite indices when assessing environmental contamination risks. For urban policy, it implies that monitoring specific pollutants—rather than relying solely on general AQI scores—could help improve the contextual interpretation of food safety assessments in outdoor selling locations and public spaces, even if the correlations remain weak, as they still point to instructive pathways of exposure.

4.4. Patterns and Limits in Correlation

To further explore the relationship between ambient air pollution and fruit surface contamination, a full correlation matrix was constructed using both chemical and environmental variables. It included daily and averaged air quality metrics (PM_{2.5}, PM₁₀, CO, benzene), fruit characteristics, and the variability of measured PAH concentrations across replicates.

The results confirmed the earlier observations: PM_{2.5} showed the strongest positive correlation with EU PAH4 levels, with a coefficient of $r = 0.3956$ for daily values and $r = 0.4355$ for the four-day average. In contrast, the general Air Quality Index (AQI) showed a much weaker association ($r = 0.2148$), and other pollutants such as PM_{10(av)} ($r = -0.0084$), CO_(av) ($r = 0.0574$), and benzene (BE_(av): $r = 0.0984$) exhibited negligible or inconsistent relationships (see Table 1). These findings suggest that fine particulate matter (PM_{2.5}) plays a more direct role in transporting and depositing PAHs onto fruit surfaces than composite air quality scores or other gaseous pollutants.

Table 1. Correlation factors between the most important study parameters determined.

	PM _{2.5} (act)	PM _{2.5} (av)	PM ₁₀ (act)	PM ₁₀ (av)	CO _(act)	CO _(av)	BE _(act)	BE _(av)	AQI
FLU	0.40	0.50	0.03	0.10	0.27	0.20	0.13	0.29	0.34
BAA	0.18	0.11	−0.08	−0.22	−0.17	−0.24	−0.43	−0.43	−0.13
CHR	0.38	0.51	−0.11	−0.06	0.10	0.06	−0.03	0.23	0.25
BBF	0.41	0.43	0.17	0.23	0.32	0.28	0.23	0.31	0.37
BAP	0.41	0.44	0.03	0.06	0.22	0.12	0.10	0.23	0.27
DAHA	0.35	0.33	0.00	0.00	0.16	−0.02	0.28	0.28	0.14
EU PAH4	0.40	0.44	−0.01	−0.01	0.13	0.06	−0.05	0.10	0.21
D/FLU	0.32	0.34	0.15	0.11	0.28	0.23	0.07	0.13	0.24
D/BAA	0.25	0.22	0.12	0.02	0.08	0.03	−0.16	−0.19	0.09
D/CHR	0.58	0.60	0.20	0.23	0.45	0.23	0.37	0.35	0.40
D/BBF	0.37	0.53	−0.06	0.05	0.26	0.21	0.18	0.40	0.34
D/BAP	0.45	0.54	−0.04	0.10	0.30	0.19	0.30	0.44	0.33
D/DAHA	−0.07	0.06	−0.04	−0.02	0.01	−0.09	0.14	0.19	−0.03

Legend: BE: benzene; act: on the actual day; av: average of the actual day and the three preceding days; AQI: air quality index (calculated, see details in Section 2.4); D/BAP, BAA, CHR. . . : deviation of the given measured parameter. Colour shading indicates relative magnitude. Darker red meaning stronger positive correlation, lighter meaning weaker ones; lighter blue meaning weaker negative correlation, darker meaning stronger ones).

Notably, the averaged PM_{2.5} values correlated more strongly than single-day measurements, indicating that PAH deposition reflects cumulative exposure rather than momentary conditions. This temporal dimension may be particularly relevant in urban settings, where pollution levels fluctuate but deposition effects persist.

The analysis also considered the variability of PAH measurements, expressed as standard deviations across replicates (e.g., D/FLU, D/CHR), to assess whether measurement heterogeneity was influenced by air quality. Notably, PM_{2.5} concentrations showed consistent moderate correlations with the dispersion of several PAH compounds, suggesting that higher levels of fine particulate matter may not only elevate PAH concentrations but also amplify their variability. This pattern may reflect the heterogeneous nature of urban dust and its variable PAH-adsorbing capacity, potentially influenced by particle composition, source diversity, and microenvironmental dynamics [56].

Correlation analysis revealed no strong association between fruit type and overall PAH contamination (e.g., fruit type vs. EU PAH4: $r = 0.0251$). However, moderate correlations were observed between fruit type and specific compounds, such as benzo[a]anthracene (BAA: $r = 0.4367$), suggesting that certain fruit characteristics may influence compound-specific accumulation. Similarly, the indoors/outdoors selling classification showed modest correlations with several PAHs (e.g., BAA: $r = 0.3680$; BBF: $r = 0.2322$), indicating that selling context may play a role in surface contamination. These findings support the view that while biological and logistical factors contribute to variability, urban microenvironment and ambient particulate exposure remain dominant drivers.

While these correlations are modest and exploratory, they offer valuable clues. They suggest that targeted air quality indicators, such as PM_{2.5}, may be more informative than composite indices when assessing environmental contamination risks. At the same time, the limits of correlation analysis remind us that urban contamination is a multifactorial phenomenon, shaped by spatial, temporal, and infrastructural complexity, suggesting that urban food safety assessments may benefit from considering heterogeneous and context-specific exposure pathways.

5. Conclusions

The investigation focused on the presence of polycyclic aromatic hydrocarbons (PAHs) on fruit surfaces sold in various urban environments, examining spatial patterns, washing efficiency, and correlations with ambient air pollution. The findings highlight that PAH contamination of ready-to-eat fruits can arise at the point of sale, shaped by microenvironmental conditions rather than production-side factors. The results revealed that:

- PAH contamination levels varied significantly by point of sale, with higher concentrations observed in high-traffic urban areas, particularly the inner districts of Budapest and the Keleti Railway Station.
- Fruits sold in outdoor urban locations contained significantly higher concentrations of PAHs than those sold indoors.
- Fine particulate matter (PM_{2.5}) showed a weak but measurable correlation with PAH concentrations ($r \approx 0.4355$), while general air quality indices and other pollutants exhibited no consistent association.
- Washing fruits with clean water reduced PAH levels by an average of 40–50%, with no significant difference between fruit types, suggesting that rinsing can be effective across categories.
- As a consequence, urban infrastructure, such as public wells, may play a subtle but meaningful role in enabling safer fruit consumption in outdoor urban environments.

From an urban policy perspective, these findings suggest that food safety considerations may have relevance within broader environmental health planning. While citizens can mitigate some risks through washing, systemic improvements in air quality and thoughtful placement of public amenities remain essential.

Our results resonate with earlier studies. Font and her co-workers [52] demonstrated that PAHs in enclosed urban transport environments are primarily associated with fine particulate matter (PM_{2.5}), supporting our interpretation that PM_{2.5} is a more relevant indicator for surface contamination risk than composite indices. Similarly, Stevanović [41] emphasized the role of public fountains as climate adaptation and public health infrastructure, aligning with our suggestion that accessible water points can also enhance food safety in certain outdoor points of sale, such as markets and public transport hubs. Finally, the European Environment Agency's city-level air quality data underline the complexity of urban pollution patterns, reinforcing our observation that aggregated indices (AQI) may obscure pollutant-specific risks relevant to contamination.

Limitations and Scope

The study's findings are exploratory and context-specific. The sample size, while diverse, is limited, and the origin of the fruits is unknown, making it impossible to distinguish between contamination during transport, storage, or selling. Although the Keleti Railway Station exhibited higher concentrations, its inclusion within the Budapest group in the correlation analysis does not affect the study's main conclusions, as no statistical comparison relied on city-level means. Air quality data were matched to sampling locations and dates, but spatial resolution and pollutant coverage varied. The correlation analyses, while informative, do not imply causation and are constrained by the complexity of urban microenvironments.

Moreover, the study focused on surface contamination only, without assessing internal uptake or long-term exposure risks. The washing protocol was standardized but may not reflect the full range of citizen practices. Finally, while the results suggest policy relevance, they do not constitute a comprehensive risk assessment.

A detailed toxicological risk assessment was outside the scope of this work, as such analyses require integration of concentration data with consumption patterns, body-weight

assumptions and toxicological benchmarks. Our findings should therefore be interpreted as indicators of relative exposure potential across urban settings rather than as direct estimates of health risk. Future studies combining surface contamination data with dietary intake information and established risk-assessment frameworks could help clarify the health relevance of these patterns.

Despite these limitations, the study offers valuable insights into the intersection of urban infrastructure, environmental exposure, and everyday food practices. It illustrates how small-scale measurements can inform broader urban health strategies, and how citizen-level actions interact with structural conditions. Future work may benefit from several directions that naturally follow from our findings: (i) more detailed characterization of point-of-sale settings, including local air quality, architectural enclosure, and airflow patterns; (ii) experimental exploration of fruit-surface properties that could influence PAH deposition and removal; (iii) systematic assessment of washing protocols to clarify compound-specific removal mechanisms; and (iv) analysis of how the spatial distribution and accessibility of public water points shape real-world washing practices at outdoor points of sale. Such targeted analyses could clarify to what extent infrastructure placement influences exposure mitigation opportunities across different urban contexts.

Urban fruit contamination by PAHs is not random: it reflects the conditions of sale, the role of fine particulates in deposition, and the limits of citizen-level mitigation. Washing can reduce exposure by nearly half, and public water infrastructure may amplify this benefit, but systemic air-quality management remains essential. Importantly, variability across and within fruit types cautions against overgeneralization, reminding future studies that contamination patterns may differ substantially even among similar produce. The study demonstrates how small, everyday practices intersect with broader urban policy, underscoring that safeguarding health in cities requires both individual resilience and collective structural change.

Supplementary Materials: Detailed basic data tables and correlation factors can be downloaded at <https://www.mdpi.com/article/10.3390/urbansci10020076/s1>. The Supplementary Materials include raw PAH concentration data for unwashed fruits (Table S1), averages with *p*-values (Table S2), washed vs. unwashed concentrations (Table S3), removal efficiencies and statistical parameters (Table S4A,B), and ambient air quality data (Table S5). Figures S1 and S2 visualize EU PAH4 and benzo[a]pyrene concentrations across samples.

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Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of variance
AQI	Air Quality Index (composite index of PM _{2.5} , PM ₁₀ , CO and benzene)
BAA	Benz[a]anthracene
BAP	Benzo[a]pyrene
BBF	Benzo[b]fluoranthene
Be	Benzene
CHR	Chrysene
CO	Molecular formula of carbon monoxide
DAHA	Dibenzo[a,h]anthracene
EU PAH 4	Sum of BAA, CHR, BBF and BAP concentrations
FL-HPLC	High-performance liquid chromatography with fluorescence detection
FLU	Fluoranthene
MOE	Margin of Exposure
N.A.	Not available information
N.D.	Non-detectable (concentration below 0.05 µg/kg)
OD/ID/Spec	Outdoors/Indoors/Special selling location
PAH(s)	Polycyclic Aromatic Hydrocarbons
PM (2.5 or 10)	Particulate matter with aerodynamic diameter ≤ 2.5 µm/≤10 µm
RSD%	Relative standard deviation
TPP	Triphenyl phosphate (used as surrogate standard)
UV	Ultraviolet (detection)

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