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Polychlorinated biphenyls (PCBs) accumulation in street urban soil in Novi Sad (Serbia)

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Abstract: Ratio and accumulation of polychlorinated biphenyls (PCBs) in urban soils from three sites across street in Novi Sad (Serbia) were analyzed. Ten PCBs (PCB 8, 20, 28, 35, 52, 101, 118, 138, 153, and 180) were extracted using microwave-assisted extraction (MAE), solid-phase extraction (SPE) clean-up, and quantified by GC/MS technique. Since PCBs remain persistent and toxic for all living organisms, the main aim of this study is to emphasize the importance of ongoing monitoring, even more than three decades after their industrial ban on the middle-sized sites with 'light' industry in their surroundings. The results indicate that higher molecular weight compounds, such as PCB 138, PCB 153, and PCB 180, exhibited the highest mean concentrations (108–121 ng g^{-1} dry weight (DW)), whereas low weight compounds (PCB 20, PCB 28, and PCB 101) were accumulated at lower levels (84–101 ng g^{-1} DW). Variability among soil samples was statistically significant, particularly for PCB 35 and PCB 118, following ANOVA, that reflecting localized heterogeneity likely influenced by proximity to pollution emission sources, soil composition, and specific surrounded environmental drivers. The predominance of high weight PCBs aligns with their environmental persistence, bioaccumulative potential, and association with the most common PCB mixtures, while low weight compounds due to their faster volatilization and degradation into the soil. These findings underscore the importance of compound-specific assessments in urban soil pollution monitoring, as well as the ecological and human health risks posed by persistent PCBs, including endocrine disruption and neurotoxicity. Likewise, this study provides a baseline for targeted monitoring, risk assessment, and remediation strategies in urban environments, emphasizing the need for ongoing and long-term surveillance to track PCB fate and transport.

Keywords: Organic pollutants, Micropollutants, PCB, Environmental pollution, Soil, Urban forestry.

1. Introduction

Soil in urban areas are strongly influenced by anthropogenic activities. Opposite of soils in natural ecosystems, they often contain mixtures of mineral fractions, construction debris, organic residues, and industrial waste, resulting in complex structures for living organisms (Morel et al. 2005,

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Kostić et al. 2022). Likewise, urban environments are highly exposed to contamination, particularly by heavy metals, microplastics, organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), etc. (Wei and Yang, 2010; Lu et al. 2019, Kostić et al. 2024, Nikolić Jokanović et al. 2024). Organic pollutants enter soils through industrial emissions, vehicular exhaust, atmospheric deposition, and improper waste disposal (Madrid et al., 2008). Their persistence has effect on soil quality, contributes to bioaccumulation in foods, and poses direct risks to human health (Rodríguez Eugenio et al. 2018).

Polychlorinated biphenyls (PCBs) are synthetic organochlorine compounds formerly used in electrical equipment, hydraulic fluids, and construction materials owing to their thermal stability and insulating capacity (Breivik et al. 2002; Erickson and Kaley, 2011). Chemically they are in group of organic pollutants. Despite production bans since the late 20th century, PCBs remain ubiquitous environmental contaminants due to their persistence and resistance to degradation.

In urban environments, contamination arises from legacy sources such as obsolete capacitors and transformers, building materials, and industrial residues, as well as from secondary emissions during demolition or waste mismanagement (Hu and Hornbuckle, 2010; Gasic et al. 2021). Human exposure occurs primarily through dietary intake of contaminated food but also via inhalation and dust ingestion in urban settings (Lauby-Secretan et al. 2013). Likewise, chronic PCB exposure has been associated with carcinogenicity, endocrine disruption, reproductive toxicity, and neurodevelopmental disorders (Carpenter, 2006; Mitro et al. 2016). Vulnerable groups, including children and pregnant women, are at heightened risk due to transplacental transfer and lactational exposure (Lyall et al. 2017).

Urban soils act as long-term reservoirs for PCBs. Their hydrophobic and lipophilic characteristics facilitate strong sorption to organic matter, reducing mobility but promoting persistence (Cousins et al. 1997; Krogh et al. 2013). The extent of accumulation depends on soil composition, climatic conditions, and land use intensity (Guo et al. 2020). In densely populated areas, reduced vegetation cover and high levels of impervious surfaces limit natural degradation processes and intensify atmospheric deposition (Huang et al. 2014; Kostić et al. 2019). Likewise, pollutants in soil significantly affect plant stress, e.g. in poplar (Kebert et al. 2017, 2022) and horse chestnut (Čukanović et al. 2020). It is well known that soil type affects biomass production and its sensitivity to drought (Kostić et al. 2021). Additionally, soils may function as secondary sources, releasing PCBs back into the atmosphere through volatilization and resuspension, thereby prolonging their environmental lifetime (Meijer et al. 2003).

Phytoremediation has emerged as a cost-effective and environmentally sustainable strategy for the remediation of PCB-contaminated soils (Salt et al. 1998; Kalozi et al. 2025). This approach exploits the capacity of specific plant species to extract, stabilize, or metabolize pollutants, while simultaneously stimulating rhizosphere microbial activity that contributes to degradation (Burken et al. 2011).

Woody species such as willows (*Salix* spp.) and poplars (*Populus* spp.) have demonstrated high efficiency in PCB uptake and transformation, facilitated by their extensive root systems (Vouillamoz and Milke, 2009; Zhang et al. 2019; Kalozi et al. 2025). The effectiveness of phytoremediation in urban street soils, however, is influenced by contaminant concentration, soil characteristics, plant physiology, and long-term management practices (Cameselle et al. 2013). Integrating phytoremediation into urban greening initiatives could therefore enhance soil quality and contribute to the reduction of human exposure to PCBs.

The aim of this study is to examine the potential of urban soils as a pools of PCBs, with a particular focus on their sources, persistence, and potential risks to human health. Furthermore, this study evaluates the potential of phytoremediation as a sustainable and 'green' strategy for mitigating PCBs contamination in urban environments. Therefore, the main research questions addressed in this study are what the PCB concentration in street urban areas are, and what their profile in topsoil areas are. Finally, at the end human health risks in high PCB contaminated urban environments are discussed and emphasized.

2. Material and methods

2.1. Study area and site descriptions

This study was conducted at three urban sites in Novi Sad, Serbia at Cara Lazara Boulevard close to the petrol station. The city lies in the Pannonian Plain along the Danube River at 76–82 m above sea level, with shallow groundwater levels between 0.5 and 4 m (JP "Urbanizam", 2024). Novi Sad has a moderate continental climate with warm summers following Köppen–Geiger classification (Beck et al., 2018). According to 30-year records (1991–2020), the mean annual temperature is 12.2 °C and average precipitation is 675.8 mm. August is the warmest month (16.1–29.2 °C), while January is the coldest (–2.5–4.3 °C). Dry summers often intensify urban heat islands, particularly in densely built areas. Street soils, classified as urbisols, show strong anthropogenic influence.

2.2. Data collection and preparation

Soil samples were collected in July 2024 during sunny and dry weather conditions. Three mixed samples were collected at Cara Lazara Boulevard. At the site, approximately 200 g of surface soil (0–30 cm depth) were collected using a stainless-steel trowel from three representative locations. Care was taken to avoid visible debris, stones, and organic litter. The collected soil was placed in paper bags and transported to the laboratory. Upon arrival, soil samples were air-dried at room temperature, sieved through a 2 mm stainless-steel mesh to remove coarse particles. Subsequently, a portion of the soil was homogenized using a Retsch MM 400 ball mill to obtain a fine, uniform powder. The homogenized soil samples were stored in a dark area at room temperature until extraction.

2.3. Standards and reagents

All solvents used for extraction, including hexane (HEX), dichloromethane (DCM), acetonitrile, 2-propanol, and methanol, were GC grade and supplied by J.T. Baker (Phillipsburg, NJ, USA). External standards for 10 PCBs (PCB 8, 20, 28, 35, 52, 101, 118, 138, 153, 180) as well as five PAH surrogate standards, were purchased from Supelco (Bellefonte, PA, USA) with purities >99%. The PAH surrogates (d_8-naphthalene, d_{10}-acenaphthene, d_{10}-phenanthrene, d_{12}-chrysene, d_{12}-perylene) were supplied in DCM at 1 ng μL^{-1}. Solid-phase extraction (SPE) C_{18} cartridges were obtained from Macherey-Nagel (Düren, Germany).

2.4. PCBs quantification: extraction, clean-up, and GC/MS analysis

Per each sample, tree replications were analyzed. The soil samples (10 g, air-dried and sieved) were spiked with 100 μL of isotopically labeled surrogate standards (100 μg L^{-1}) prior to extraction. PAHs and PCBs were extracted using a Microwave Assisted Extraction system (Ethos X, Milestone, Italy) with 40 mL DCM in 100 mL PTFE vessels. The extraction protocol included a temperature ramp from 40 °C to 120 °C over 20 min, followed by 30 min at 120 °C (total 50 min).

A 25 mL aliquot of the extract was filtered through 0.22 μm PTFE syringe filters and purified using preconditioned C_{18} SPE cartridges (6 mL, 500 mg). Polar compounds were removed with methanol and 2-propanol washes, and nonpolar analytes were eluted with DCM, DCM:HEX (1:1), and HEX. The eluates were evaporated to dryness, resuspended in DCM, and transferred to GC vials (200 μL inserts).

Analyses were performed on an Agilent 7890 GC coupled with a 5975C MS using an HP-5MS column (30 m × 0.25 mm × 0.25 μm). One microliter of sample was injected in splitless mode, with a temperature program ramping 20 °C min^{-1} to 230 °C, then 10 °C min^{-1} to 315 °C, held for 5 min (total run 25.25 min) (Feng and Hom, 2013). Detailed GC/MS conditions, quality control procedures, and

compound-specific data including retention times, target ions, LOD, and LOQ are reported in Kostić et al. (2024). The used GC/MS method setup is enlisted in Table 1.

Table 1. PCB compounds, retention time, quantifier, qualifier ions, Limit of Detection (LOD) and Limit of Quantification (LOQ) values.

Compound	Retention time (min.)	Quantifier/ Qualifier ions	LOD (ng g^{-1})	LOQ (ng g^{-1})	Linearity (r^2)
PCB 8	9.401	221/223, 186	0.02	0.14	>0.99
PCB 20	10.456	255/257, 186	0.04	0.22	>0.99
PCB 28	10.601	256/258, 186	0.05	0.19	>0.99
PCB 52	10.886	292/290, 222	0.02	0.13	>0.99
PCB 35	11.136	257/259, 186	0.04	0.21	>0.99
PCB 101	12.221	326/328, 254	0.03	0.31	>0.99
PCB 118	13.434	326/328, 254	0.08	0.24	>0.99
PCB 153	13.998	308/310	0.05	0.30	>0.98
PCB 138	14.406	360/362, 290	0.04	0.28	>0.99
PCB 180	15.903	394/396, 324	0.11	0.74	>0.98
Intern standards (IS)					
Naphthalene-d_8	6.115	136/134, 108	0.02	0.79	>0.99
Acenaphthene-d_{10}	8.157	164/162, 160	0.18	0.43	>0.99
Phenanthrene-d_{10}	9.950	188/189	0.05	0.22	>0.99
Chrysene-d_{12}	15.300	240/236, 241	0.12	0.33	>0.99

2.5. Statistical analyses

Descriptive statistics are presented as mean ± standard deviation (SD). All analyses were conducted in R (R Core Team, 2013) using the '*ggplot2'* (Wickham, 2011), '*ggfortify'* (Tang et al., 2020), and '*rstatix'* (Kassambara, 2021) packages.

3. Results

The concentrations of the ten analyzed PCBs in urban soil samples from Novi Sad showed considerable variation both among compounds and between sites (Table 2). PCB 138 and PCB 153 exhibited the highest mean concentrations, with average values of 120.92 ng g^{-1} and 115.19 ng g^{-1}, respectively, whereas PCB 101 displayed the lowest mean concentration at 83.87 ng g^{-1}. Other congeners, including PCB 118, PCB 180, and PCB 35, presented intermediate average concentrations ranging from 100.75 to 118.65 ng g^{-1}.

Variability among the three replicate samples was moderate to high for most congeners. PCB 118 and PCB 35 demonstrated the greatest standard deviations, 17.30 ng g^{-1} and 16.43 ng g^{-1}, respectively, reflecting substantial heterogeneity in their distribution within the sampled soils. In contrast, PCB 101 and PCB 180 exhibited lower variability, with standard deviations of 7.83 ng g^{-1} and 7.12 ng g^{-1}, respectively, suggesting a more homogeneous distribution of these congeners. The relative variability indicates potential differences in the sources, deposition patterns, or environmental behavior of the different PCB congeners in street urban soils.

Spatial patterns inferred from replicate comparisons reveal that some congeners, notably PCB 138, PCB 153, and PCB 118, consistently displayed higher concentrations across all replicates, indicating that these congeners may dominate the PCB profile in the urban soils studied. Conversely, lower-chlorinated congeners such as PCB 20, PCB 28, and PCB 52, while still present in measurable

concentrations, were generally found at lower mean concentrations, suggesting either lower historical emissions or higher environmental mobility and degradation.

Table 2. PCBs concentration and their standard deviations (SD) in street soils of Novi Sad.

Compound (ng g^{-1} DW)	Average	SD
PCB 20	92.109	13.725
PCB 28	90.464	13.864
PCB 52	95.819	15.420
PCB 35	100.750	16.431
PCB 101	83.872	7.833
PCB 118	118.649	17.299
PCB 153	115.195	14.006
PCB 138	120.92	14.384
PCB 180	108.078	7.122

The average concentrations of PCBs followed a roughly increasing trend with chlorination level, although exceptions were observed. For instance, PCB 180, a highly chlorinated congener, presented a mean concentration of 108.08 ng g^{-1}, slightly lower than that of PCB 138, which may reflect differences in deposition patterns or physicochemical interactions with soil organic matter. These differences highlight the heterogeneous nature of PCB contamination in urban environments and underscore the need for PCBs specific assessments in environmental monitoring programs.

Overall, the data indicates that urban soils in Novi Sad are contaminated with a mixture of PCB compounds, with higher-chlorinated PCBs generally more abundant. The variability observed among replicate samples suggests localized heterogeneity, which could be influenced by factors such as proximity to emission sources, soil composition, and specific microclimate conditions. These results provide a valuable background for evaluating the potential human and ecological risks associated with PCB contamination in street urban soils and can help during selection of appropriate remediation or mitigation strategies in Novi Sad.

4. Discussion

PCB concentrations across three soil samples revealed significant variability in the levels of individual concentrations. Compounds such as PCB 138, PCB 153, and PCB 180 exhibited higher mean concentrations, while PCB 20, PCB 28, and PCB 101 showed relatively lower levels. This distribution aligns with previous studies reporting that higher-chlorinated PCBs are more persistent in the environment due to their lower volatility and resistance to degradation (Safe, 1994; Erickson, 1997; Hansen, 1999).

The observed variability in PCB concentrations, particularly for PCB 35 (SD 16.43) and PCB 118 (SD 17.30), may reflect differences in environmental matrices, sampling locations, or localized contamination sources (Jones and de Voogt, 1999; Melymuk et al. 2022). Lower variability in PCB 180 (SD 7.12) suggests a more uniform environmental presence, consistent with its high stability and bioaccumulative potential (Breivik et al., 2002). This pattern is typical for higher-chlorinated PCBs, which are frequently found in sediments and biota due to their hydrophobic nature (Ross, 2004; Avila et al. 2025).

The higher concentrations of PCB 138 and PCB 153 are more consistent with their predominance in commercial PCB mixtures such as Aroclor 1254 and 1260 (Hansen, 1999). Meanwhile, lower-chlorinated compounds, such as PCB 20 and PCB 28, are more volatile and susceptible to long-range atmospheric transport, which may explain their presence even in relatively uncontaminated areas (Othman et al. 2022; Schulz et al. 2024).

The persistence and bioaccumulation of PCBs raise concerns for both ecological and human health. Higher-chlorinated congeners, including PCB 153 and PCB 180, are known to bioaccumulate in fatty tissues and biomagnify through food webs, posing risks such as endocrine disruption, neurotoxicity, and reproductive effects (Ross, 2004; Norström et al. 2009). Understanding specific PCB distribution is therefore essential for environmental risk assessment and for designing remediation strategies. Comparative studies indicate that PCB concentrations observed in this study are consistent with urban sediment and soil samples reported globally, though regional variations occur due to historical PCB usage, industrial activity, and environmental transport mechanisms (Weber et al. 2002; Bennett, 2011). The results highlight the importance of continuous monitoring and targeted sampling to track PCB trends and identify potential hotspots of contamination.

5. Conclusions

This study highlights PCB accumulation in soils across street in Novi Sad, showing that higher-chlorinated congeners, such as PCB 138, PCB 153, and PCB 180, dominate in both concentration and persistence. Lower-chlorinated congeners, like PCB 20, PCB 28, and PCB 101, were detected at lower levels, likely due to higher volatility and faster environmental degradation. Variability among samples, particularly for PCB 35 and PCB 118, reflects localized contamination and differences in environmental matrices, emphasizing the importance of targeted monitoring. Higher-chlorinated PCBs are persistent, bioaccumulative, and toxic, posing ecological and human health risks, including endocrine disruption and neurotoxicity. In conclusion, PCB contamination is dominated by persistent, higher-chlorinated congeners, reinforcing the need for ongoing monitoring, risk assessment, and mitigation strategies. Future studies should include seasonal sampling and long-term monitoring to better understand PCB fate and transport in the environment.

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