Influence of former industrial waste landfill in central Poland on PCBs content in the environment

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Abstract: The aim of this study was to investigate the impact of industrial waste landfill on the release of polychlorinated biphenyls (PCBs) on the environment with reference to water flow directions. 10 study plots were designated around the landfill site. Soil samples were taken from different soil layers. Plants: *Solidago canadensis* (leaves, stem), *Quercus L.* (leaves), and Poaceae were tested on PCBs contents. Groundwater samples were taken from piezometers. PCBs in the samples were determined by gas chromatography with an electron capture detector (GC/ECD).The highest accumulation of PCBs congeners was observed in the topsoil layers and decreased with the sampling depth. The dominant PCBs congeners in soil were PCB 28 and PCB 138, in plants PCB 28 and PCB 52. The most significant PCBs accumulation in the topsoil layer occurred in the research area on which the largest amount of waste was deposited and was equal to 14.2 ng/g. The largest sum of determined PCBs congeners was found in *Solidago canadensis* leaves – 3.26 ng/g and *Quercus L.* leaves – 3.32 ng/g. PCB 28 and PCB 52 were capable of translocation from soil to plants. It was found that the water flow direction did not affect PCB content in soils.

Introduction

Polychlorinated biphenyls (PCBs) are contaminants, which are persistent, lipophilic and hydrophobic, with a high potential for bioaccumulation in living organisms (Kaya et al. 2018). PCBs were used in transformer cooling oils, dielectric fluids of capacitors, hydraulic and heat transfer fluids, pesticides, as lubricants in oils or greases, preservatives and impregnating agents (Kodavanti 2017). PCBs can be produced accidentally as impurities in chlorinated products or as by-products in solvent production (Liu et al. 2018) or during waste incineration (Gabryszewska and Gworek, 2020 a).

Low solubilities in water (ranging from 9.3 to $7.6*10^{-4}$ g m^{-3}) and high octanol-water partition coefficient (log K_{ow} ranging from 4.3 to 8.3) cause strong adsorption of PCBs by organic matter and clay minerals (Erickson 2001). As the number of chlorine atoms in the molecule increases, the octanol-water partition coefficient increases. PCBs move very slowly into the soil, for example, assuming soil homogeneity; it takes 825 years for 2.4-diCB to move in the soil at a distance of 10 m of soil (Hansen and Robertson 2001). PCBs can be transported in the air for long distances and spread almost all over the globe (Degrende et al., 2020). PCBs from the air are transferred to the ground surfaces via dry particulate deposition. PCBs, due to high octanol-water partition coefficients (ranging from 4.3

to 8.3), are effectively sorbed to soils and sediments (Erickson, 2001). PCBs can migrate in the soil to the depth about 30 cm (Gabryszewska and Gworek, 2020 b) nonetheless PCBs can be washed away from sandy soils that are poor in organic matter. The most susceptible to soil leaching are PCBs with a small number of chlorine atoms in the molecule. PCBs can also be transported bound to eroded soil or sediments. PCBs are hydrophobic, so they are transported together with a particulate material to the lower levels of the catchment (Dias-Ferreira et al., 2016). The most susceptible to soil leaching are PCBs with a small number of chlorine atoms in the molecule (ATSDR 2000). For other PCB homologues, this process may occur in the presence of organic solvents such as trichloroethylene (TCE) or Freon 113 (Norris et al. 1999). It is estimated that approximately 99% of PCBs in the environment are deposited in soil or sediment and 1% in air and water (Travis et al. 1991, Erickson 2001).

Plants can take PCBs from water or soil through the root system or from the air, as a result of dry or wet deposition to ground parts of plants (Bohme et al. 1999, ATSDR 2000). PCBs homologues with small amounts of chlorine atoms in the molecule, such as tri-chlorobiphenyls or tetra-chlorobiphenyls, can enter plants through their roots. For hepta- and octa--chlorobiphenyls the main source is dry deposition (Bohme et al 1999). With a high octanol-water partition coefficient,

PCBs tend to bind strongly to the organic phase, so in soils rich in organic matter the bioaccessibility of PCBs for plants is limited (Yu et al. 2018, Ti et al. 2018). The lower the amount of chlorine atoms in the PCB molecule, the more mobile it is and the more easily it is absorbed by plants.

At the landfill, organic waste is anaerobically decomposed with the production of CO_2 and CH_4. These gases can be a carrier of PCBs from landfill, and cause soil and water contamination by deposition in the surroundings of landfills (Murphy et al., 1985). In research on Polish municipal waste landfill impact on the environment it was shown that PCBs are present in soils around this landfill. The sum of PCBs contents in the topsoil was within the range of 2.0–24.5 µg/kg (Gabryszewska and Gworek, 2021). In Norwegian waste landfill, waste were tested for PCBs content. Sums of seven PCBs (PCB-28, -52, -101, -118, -138, -153 and -180) were found in plastic waste 3700 ±1800 µg/kg, in electrical waste and in electronic equipment 1300 ± 400 µg/kg (Arp et al., 2020). Iron-steel manufacturing and copper smelting processes comprise 94% of the PCB releases from stationary sources (Kuzu et al. 2013). In several provinces in Northern Vietnam, PCBs (including CB-28, 52, 101, 153, 138, 180) were tested in fly ash, bottom ash and soil from combustion processes of waste incineration, metallurgy (steel making and zinc production) and cement production. Total PCBs concentrations ranged from 18.0 to 8260 ng/g in the fly ash, from 1.0 to 10600 ng/g in bottom ash, and from 14.5 to 130 ng/g in soil (Hue et al., 2016).

In view of the above literature reports, an attempt was made to determine the impact of the former industrial waste landfill on PCBs contents in the environment. The sources of PCBs in soil, plants and water at the industrial waste landfill Warsaw Ironworks were road transport and stored waste such as:

– used oils and greases – in the past, to increase the durability of cooling and hydraulic oils, a mixture of PCB congeners were added to them, due to their long half-life and resistance to high temperatures,

– post-mining sludge – PCBs could be formed as a result of incomplete combustion of coal and be included in the sludge.

In the scientific literature, there is no available data on the impact of ground water flow direction on PCBs contents in soil or in water. Water has a significant impact on the transfer of pollutants. The purpose of the work was to examine the impact of the industrial waste landfill, as a source of PCBs release into the environment, on the PCBs contamination of soils, plants and water. The assessment was made based on profile PCBs distribution in soils and on PCBs contents in water and plants growing on the above soils. The impact of landfill on PCBs contents in the environment was shown through biological indices: Bioaccumulation Coefficient (BAC) and Mobility Ratio (MR).

Materials and methods

Features of the industrial landfill

The industrial waste landfill is located in Warsaw, Poland (52° 18′ 16″ N, 20° 54′ 42″ E). The total area of the landfill, together with technical facilities, covered an area of about 34 ha, and its active area (for waste disposal) was 26 ha. The area of the landfill belongs to the Vistula River catchment area, which is the main water receiver for water flowing from this area. Top layers of soils are built predominantly from loose sands and loamy sand.

The landfill was established in the early 1960s and operated until 2004. It was designed to deposit industrial waste produced at the Warsaw Ironworks and was used to store aggregate produced from slag and refractory materials produced at the Ironworks. By 2004, 353.2 thousand tons of waste was deposited. At the site of the landfill, remediation procedures were undertaken to manage the deposited waste, to organize the method of its storage and to avoid further contamination of the landfill ground and groundwater. The heap of post-mining waste has been liquidated and the landfill site is flat now.

Sampling

10 study plots of an area of 10 m^2 were designated around the landfill site. The study plots were selected according to the water flow, presence of piezometers and plants. Soil samples were taken from soil layers, the depth of soil layers was different depending on the research area. The depth of layers was given in Table 2. Each sample was an average of mixed 12 subsamples for the top layer and of 4 subsamples for the deeper layers. Research area number 7 was adopted as a low anthropopressure area. Soil surface layers up to 20 cm were taken up with Egner's stick. Deeper layers of soil were taken up with the auger in the form of soil cores.

The following plants were sampled for analyses from the designated study plots: *Solidago canadensis* (leaves, stem) – in the objects: 1, 2, 3, 4, 5, 6, 7, 8, 9; *Quercus L.* (leaves) – in the objects: 1, 2, 3, 4, 5, 6, 7, 8, 9; *Poaceae* (aboveground plant's parts) – in the objects: 1, 2, 3, 5, 6, 7, 8, 9. It was not possible to take plant samples in research area 10. Plants were not washed for testing to examine the total PCB content inside and outside the plant. Soil and plant samples were transported to the laboratory in paper bags at room temperature on the same day.

Groundwater samples were taken from piezometers, at the depth of 6.3 m, by means of a pump. Piezometers were located in research areas: 1, 2, 5, 7, 9 (Fig. 1). Water samples were transported to the laboratory in glass bottles of the volume of 1 L at room temperature on the same day.

Chemical analysis

The soils for analyses were air dried at a temperature of about 22°C, grounded in a mortar and sieved through 1 mm mesh sieves. The granulometric composition was determined by the aerometric method of Casagrande, modified by Prószyński, and soil pH – by potentiometric method in H_2O and 1N KCl. Organic carbon (OC) in the soil was determined on Shimadzu TOC-5000A apparatus at 680°C.

The air-dried soils were grounded in a mortar and sieved through 1 mm sieve. The plants' samples were air-dried then fragmented in the grinder. Contents of PCBs were determined in the above-ground parts and, in the case of *Solidago canadensis*, in stems and leaves, separately. Both soil and plant samples were stored in paper bags in room temperature until analysis.

About 15−20 g of dry soil or 5−10 g of dry plant material was extracted in n-hexane (95% pure) using a fast ASE 350 extractor for 20 min in elevated pressure and a temperature of 120°C. The extract was transferred to a flask and concentrated to 1 ml in a vacuum evaporator with a heated bath at 40°. The 5 ml of n-hexane was added to the concentrated extract. The solution was purified using column chromatography. The glass columns were filled with florosil (5 cm – bottom) and aluminium oxide (5 cm). Gradient washing out was applied, using 25 ml n-hexane and 10 ml mixture of n-hexane: acetone (max. 5% acetone in the mixture). The eluate was concentrated to dry form in a vacuum evaporator with a heated bath at 55°C. The remaining substance was dissolved in 1 ml n-hexane (GC 99% pure).

The water samples were stored in the refrigerator at 4°C until analysis. After the water samples reached room temperature 1000 ml of water were measured to glass separators at a capacity of 1 L, then 50 ml dichloromethane was added and extracted. The extract (bottom fraction) was then filtered through a funnel filled with anhydrous sodium sulphate into 100 ml flasks. The process was repeated twice. The extract (100 ml) was concentrated to dry form using a vacuum evaporator with a heated bath at 40°C. The remaining substance was dissolved in 1 ml n-hexane (GC 99% pure). Such prepared analyte was analyzed using gas chromatography with Varian electron capture detector (GC/ECD). The substances were separated using the VF-Xms column (30 m × 0.25 mm × 0.25 µm), helium was applied as the carrier gas (purity 5.0; flow 1 ml/min). The temperature sequence in the oven was as follows: 70°C for 3 min and 70–300°C at a rate of 5°C/min (Gabryszewska et al., 2018). Qualitative analysis of the studied compounds was based on signals (peak surface) using the calibration curve method. The limit of quantification (LOQ) was evaluated for all analyzed compounds. Indicative congeners with expanded uncertainties (U) were determined in the studied samples, their values are presented in per cents. The recoveries were calculated for each congener based on the testing of soil certified materials and on the basis spiked samples for plants. The final result for soils and plants was calculated taking into
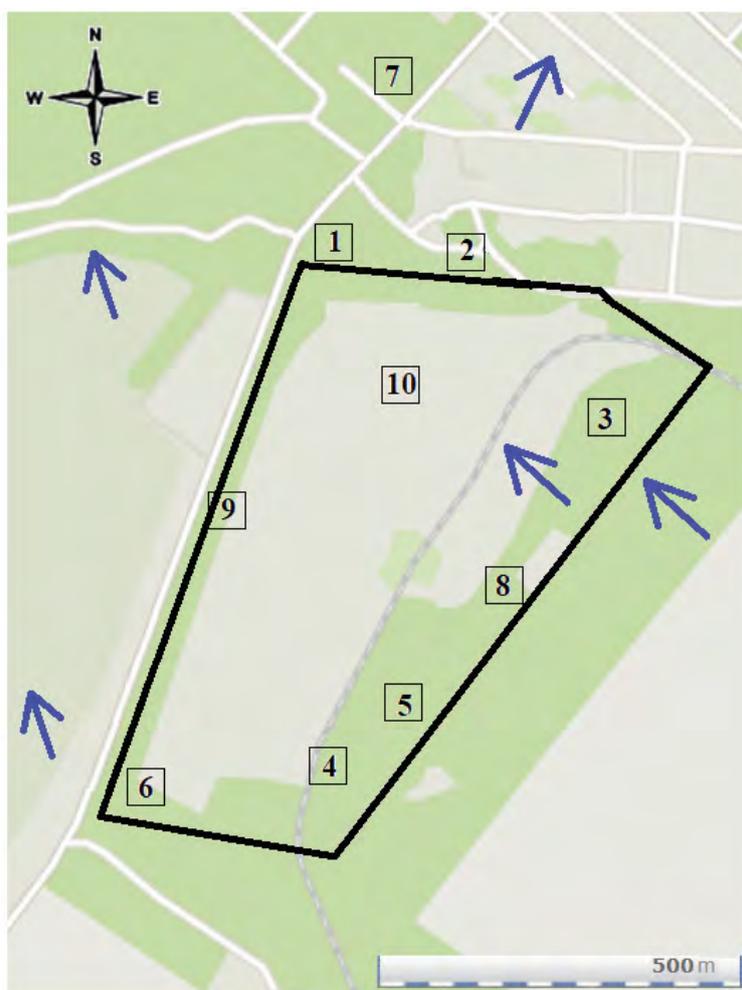
Fig. 1. Map of the sampling area at the former industrial landfill

account the recovery for each congener. Method validation parameters are presented in Table 1.

Biological indices

Biological indices were calculated to assess PCBs accumulation in the environment, as well as their mobility and translocation. The following indices were calculated (Gworek et al., 2016):

– Biological Accumulation Coefficient (BAC), which expresses the ratio of PCBs concentration in plants to its concentration in the topsoil:

$$BAC = PCB_{plant}/PCB_{soil}$$

The BAC indices show the substance ability to accumulate in plant. If values of BAC are high then this substance can accumulate in a plant.

– Mobility Ratio, which expresses the ratio of PCBs concentration in topsoil to its concentration in groundwater:

$$MR = PCB_{soil}/PCB_{groundwater.}$$

The MR indices indicate how much PCBs migrate from soil to groundwater. The high MR values point out to an insignificant impact of the PCBs contents in soils on water pollution.

Results and discussion

PCBs in soils

The texture of the soils examined is loose sands and weak loamy sands. The organic carbon contents in the upper soil levels ranged from 0.97 to 24.2% and decreased with the depth of soil profile, which may indicate the sorption of PCBs in the upper layers and their non-transfer into the soil. In most cases, pH of the soils examined was alkaline, the exception being soils taken from the areas: 2, 4, 6 and 7 whose top layers were slightly acidic. The contents of congeners determined in the soils are presented in Table 2.

The highest accumulation of PCBs congeners occurred in the topsoil layers and decreased with the sampling depth. Due to the high values of octanol-water partition coefficients, PCBs are strongly sorbed in the topsoil layers where there is most organic matter. Higher PCB content in litter than in topsoil was observed, which may indicate a significant impact of PCB deposition on plants. The highest accumulation in the topsoil layers was observed for PCB 28 and 138. The highest content of PCB 28, 5.51 ng/g, was determined in soils from the study area 8 and for congener 138–6.16 ng/g from area 6 (Table 2). The PCB 28 congener has 3 chlorine atoms, so it belongs to the tri-CB homologue.

These elevated contents of PCB 28 may be due to the fact that PCBs molecules with a larger number of chlorine atoms are possibly broken down to lower homologues by disconnecting chlorine atoms. In contrast, a high accumulation of PCB 138 is probably due to the fact that there was waste containing this congener in the landfill or that PCB 138 contaminated oils were used in the workshop on the landfill. Similar quantities of PCBs were marked in the topsoil (0–20 cm) around the Gdańsk landfill in Poland, the average PCBs content in the soil was 4.5 μg kg^{-1} (Melnyk et al. 2015).

The highest accumulation of PCBs in the topsoil layer, up to 20 cm, occurred in the research areas 8 and 10 (Fig. 2). This

Table 1. Validation parameters

PCB congener	PCB 28	PCB 52	PCB 101	PCB 118	PCB 138	PCB 153	PCB 180
Retention time min	30.3	31.6	34.8	37.2	39.5	38.1	42.5
Linearity: Correlation coefficient R^2	0.994	0.993	0.993	0.995	0.997	0.997	0.997
LOQ soils (corresponding to lowest level of calibration curve) (ng/g)	0.005	0.010	0.010	0.003	0.003	0.003	0.003
LOQ plants (corresponding to lowest level of calibration curve) (ng/g)	0.003	0.003	0.003	0.003	0.003	0.003	0.003
LOQ water (corresponding to lowest level of calibration curve) (ng/ml)	0.0001	0.0002	0.0002	0.0002	0.0002	0.0001	0.0003
Precision of certified material soils %RSD n=6	7.04	9.35	3.29	4.49	5.48	5.18	7.70
%Recovery of certified material soils n=6	67.2	67.80	75.50	74.80	76.00	68.50	66.10
Precision of spiked samples plant with 0.1 (ng/g) n=6	7.62	10.53	8.42	6.60	12.16	10.84	13.80
% Recovery of spiked samples plant with 0.1 (ng/g) n=6	102.1	72.2	74.50	75.2	66.90	71.50	63.90
Precision of spiked samples water with 0.1 (ng/ml) n=6	8.10	6.01	5.72	4.87	4.28	11.57	12.50
% Recovery of spiked samples water with 0.1 (ng/ml) n=6	98.5	85,7	86.30	81.40	79.80	78.2	70.30
Uncertainty k=2, p=0.05 (%)	30	23	35	33	27	36	30

Table 2. Contents of PCB homologues in the soil, organic carbon contents (%OC)

plot no.	depth (cm)	PCB content in soil (ng/g)							pH in H_2O	pH in KCl	OC (%)
		28	52	101	118	138	153	180			
1	0–25	0.029	0.135	< 0.003	< 0.003	1.211	0.035	0.010	8.51	8.48	0.97
	25–45	0.010	0.121	0.011	< 0.003	0.051	< 0.003	0.009	8.55	8.50	0.22
	45–60	0.062	0.179	< 0.003	< 0.003	0.127	< 0.003	< 0.003	7.92	7.22	0.20
	60–80	0.040	0.153	< 0.003	< 0.003	0.056	< 0.003	0.012	7.07	6.26	0.13
	80–100	< 0.005	0.020	< 0.003	< 0.003	< 0.003	0.023	0.017	9.07	8.23	0.08
2	Ol	0.208	0.267	0.125	0.042	0.408	0.018	0.031	5.09	4.52	38.6
	0–15	0.018	0.100	0.045	0.027	< 0.003	0.042	0.020	7.58	7.30	1.85
	15–25	0.010	0.044	< 0.003	< 0.003	0.267	< 0.003	0.009	5.74	4.63	0.39
	25–60	0.015	–	0.005	< 0.003	< 0.003	< 0.003	0.037	5.97	4.76	0.28
	60–90	0.034	–	0.012	< 0.003	< 0.003	< 0.003	0.005	6.84	6.16	0.12
3	litter	0.085	0.84	0.274	0.163	1.137	0.871	0.052	6.95	7.01	12.4
	0–5	0.125	0.773	0.246	0.077	1.730	1.008	0.042	7.45	7.46	3.60
	5–20	0.015	0.217	0.032	< 0.003	0.810	0.253	0.068	7.89	7.79	0.92
	50–100	< 0.005	< 0.003	< 0.003	< 0.030	0.032	< 0.003	0.042	7.83	7.25	0.08
4	litter	0.521	0.502	0.176	0.517	1.409	< 0.003	0.103	6.71	6.38	9.63
	5–20	0.010	0.115	< 0.003	0.031	1.036	< 0.003	0.052	7.00	6.89	1.64
	20–40	0.031	0.089	< 0.003	< 0.003	1.480	< 0.003	0.131	7.38	6.58	0.80
	40–50	0.018	0.050	< 0.003	< 0.003	< 0.003	< 0.003	0.037	6.74	4.83	0.43
	50–100	0.017	0.049	0.012	< 0.003	< 0.003	< 0.003	0.093	6.37	4.91	0.25
5	0–5	3.239	1.444	0.361	0.814	0.877	1.113	0.101	7.18	7.08	16.8
	5–10	0.321	0.261	0.057	0.124	0.373	< 0.003	0.066	7.38	7.45	2.80
	10–30	0.020	0.062	0.035	0.020	0.271	< 0.003	0.190	7.29	7.26	0.79
	30–60	0.022	0.046	0.026	< 0.003	0.086	< 0.003	0.070	7.48	6.58	0.40
	90–110	0.020	0.050	0.010	< 0.003	0.059	< 0.003	0.075	7.25	6.39	0.26
6	0–7	0.033	0.291	0.049	0.095	2.995	< 0.003	0.175	7.22	7.18	2.72
	7–40	0.019	0.330	0.019	< 0.003	6.160	< 0.003	0.084	6.70	6.15	1.29
	40–60	0.015	0.070	0.025	0.030	0.138	< 0.003	0.059	6.02	4.66	0.28
	60–80	0.025	0.017	< 0.003	< 0.003	0.023	< 0.003	0.045	6.00	4.62	0.08
	90–100	0.028	0.121	< 0.003	0.057	0.119	< 0.003	0.050	6.32	4.62	0.13
7	0–10	< 0.005	0.033	0.077	0.093	4.134	< 0.003	0.050	5.44	4.26	5.14
	10–30	0.016	0.053	< 0.003	< 0.003	0.029	< 0.003	0.037	4.92	4.22	1.64
	30–65	0.030	0.145	0.029	< 0.003	0.040	< 0.003	0.086	5.10	4.47	0.41
	65–90	0.017	0.038	< 0.003	< 0.003	0.028	< 0.003	0.042	5.31	4.42	0.22
8	0–6	5.510	2.187	0.542	1.181	2.293	1.617	0.128	7.34	7.27	24.2
	6–40	0.023	0.172	0.019	< 0.003	1.388	< 0.003	0.078	7.80	7.85	0.81
	40–90	0.020	0.134	0.028	< 0.003	0.064	< 0.003	0.032	7.64	7.18	0.25
	90–110	0.017	0.119	< 0.003	0.031	0.092	< 0.003	0.041	7.64	7.48	0.89
9	0–15	0.185	0.128	0.030	0.046	< 0.003	0.063	0.023	7.40	7.59	1.37
	15–30	0.042	0.106	0.019	0.020	< 0.003	0.024	0.029	7.33	6.88	0.48
	30–40	0.025	0.071	0.027	0.021	< 0.003	0.026	< 0.003	7.32	6.38	0.11
	40–70	0.013	0.043	0.007	< 0.003	< 0.003	< 0.003	< 0.003	7.05	5.48	0.16
	70–90	0.034	0.205	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003	7.24	6.12	0.15
10	0–20	3.046	2.046	3.175	0.567	0.635	4.779	< 0.017	9.03	8.84	4.23
	0–40	0.793	1.059	0.625	0.153	0.185	1.798	< 0.017	9.24	8.64	1.42
	50–100	0.209	0.349	0.106	< 0.003	0.087	0.159	0.138	9.55	8.78	0.10

is probably due to the fact that area 8 once housed a repair shop where oils contaminated by PCBs could be used and area 10 had the largest amount of deposited waste. In the research area 7, adopted as a low anthropopressure area, the accumulation of PCBs was not the lowest. This is due to the fact that it was hard to find the area with no access to additional PCBs sources like road transport. Taking into account the groundwater flow direction (Figure 1) and the PCBs content in the soil (Table 2),

no impact of water flow direction on the soil PCBs contents was found. The poor water solubility of PCBs and a high number of partition coefficient contributes to a weak migration of PCBs with water in the soil.

PCBs in plants
Contents of PCBs congeners determined in plants are presented in Figure 3.
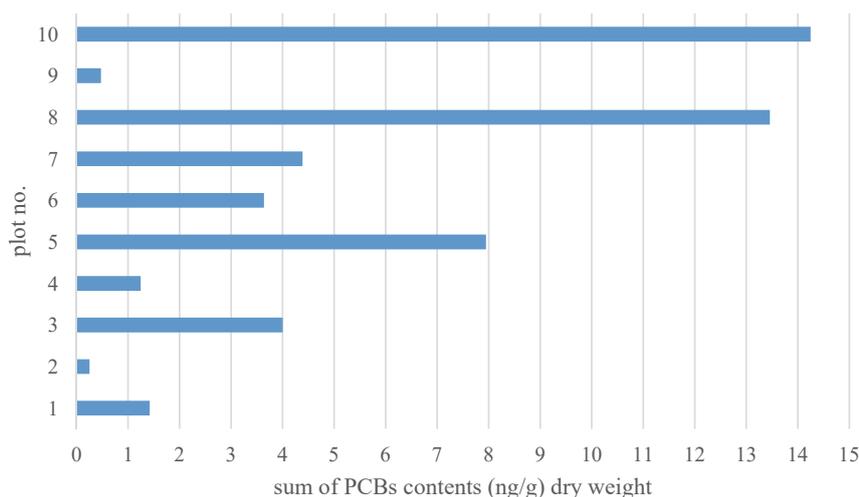
**Fig. 2.** The sum of tested PCBs contents in the top soil layers
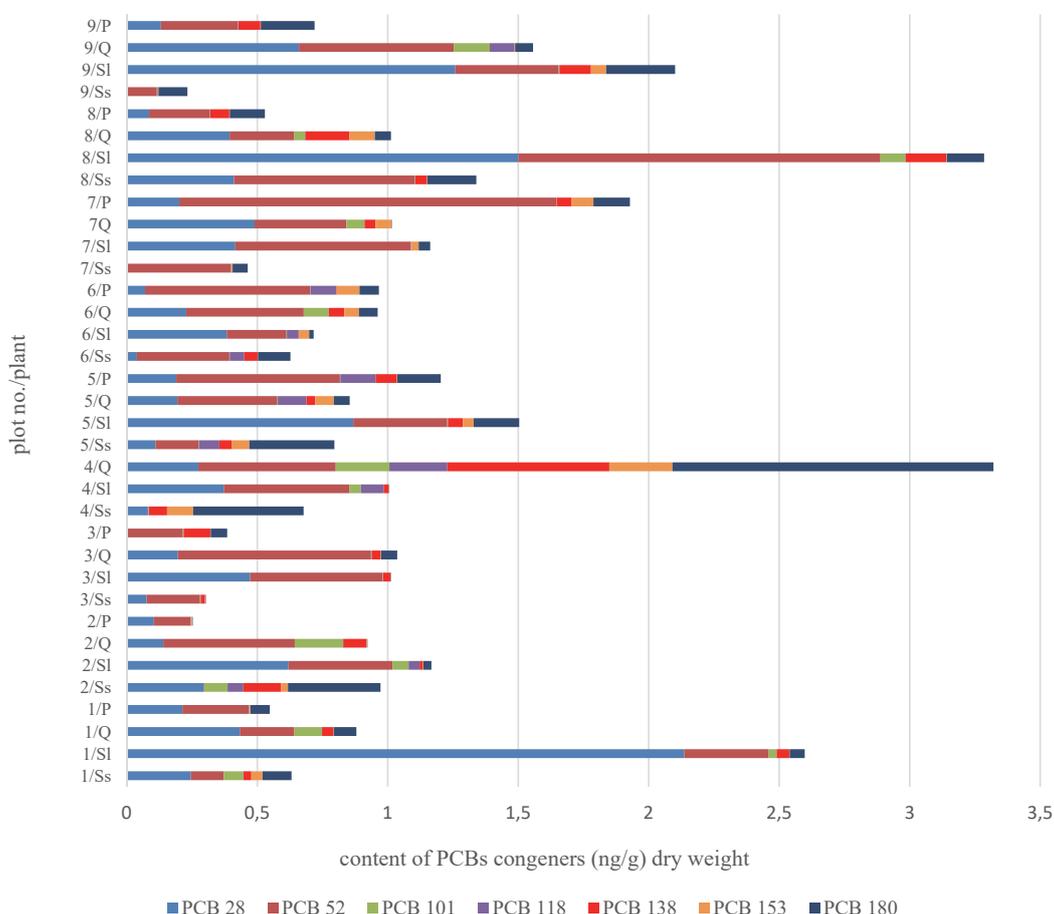
Fig. 3. PCB homologues contents in plants, where: Ss – *Solidago canadensis* stem, Sl – *Solidago canadensis* leaves, Q – *Quercus L.* leaves, P – *Poaceae*

Among the examined plants, the largest amounts of PCB congeners were determined in *Solidago canadensis* leaves and *Quercus L.* leaves (Fig. 3). The stems of *Solidago canadensis* contained on average three times less PCB than its leaves what indicates that air deposition could be the main source of pollution. The plants were not washed for PCBs determination and the leaf surface was covered with wax. Therefore, PCBs, having high octanol-water partitioning coefficients, were absorbed by the wax layer on the plants. Moreover, leaves have a larger area than stems which in total could cause that PCBs contents in the leaves were higher than in the plant stems. In most cases, *Quercus L.* leaf samples had higher PCB content than *Poaceae* samples. This is due to the fact that the shape of the *Quercus L.* leaves favors greater aerial PCB deposition. Both leaves and stems of *Solidago canadensis* had the highest contents of PCBs congeners 28 and 52 which may indicate translocation of these compounds from soil to plants. The highest contents were found in leaves of *Solidago canadensis* taken from areas 1 and 8. Area 1 was close to the road. which was affected by road transport as an additional source of pollution (Gabryszewska et al., 2018). The high PCBs content in plants taken from research area 8 is probably due to the same fact, as for soil, that there was a repair shop where oils contaminated with PCBs could be used. The dominant PCBs congeners in plants were: PCB 28 (tri-CB) and PCB 52 (tetra-CB). In the study on the cultivation of poplars, it was shown that the PCBs compounds were taken up by plants and translocated. A translocation was observed for mono-, di- and tri-CB compounds (Liu and Schnoor 2008)di-, tri-, and tetra-chlorinated polychlorinated biphenyls (PCBs.

PCBs in water

The source of PCBs releases to groundwater was the flow of pollutants with precipitation water through micro- and macropores of soil. Due to low water solubility and high octanol-water partitioning coefficients, most PCBs were absorbed into the soil and only a small amount of PCBs was released into groundwater. In most cases, all the PCB congeners determined were detected in trace amounts, below the limit of quantification (Table 3.). Only small amounts of PCBs congeners 28 and 52 were determined above the limit of quantification, which may be due to the fact that the solubility of these congeners is the highest and the partition coefficient of octanol-water the lowest among the tested compounds. PCBs concentrations in the water sample from the research area 7 (low anthropopressure area) did not have the lowest values. No influence of groundwater flow direction on PCBs concentrations in water was observed.

Indicators

For the calculation of BAC and MR coefficients, the results below the determination limit were not taken into account. It is assumed that compounds for which the bioaccumulation factor is greater than 1 are accumulated (Whitfield Åslund et al. 2008) respectively. Values of BAC for PCB 101, PCB 138, PCB 153 have shown limited possibilities of their uptake by plants. In the case of PCB 28, PCB 52, PCB 180 the BAC values significantly exceeded the value of 1 indicating high uptake by plants (Fig. 4). In the topsoil layer PCB 138 (homologue hexa-CB) was found to occur with the highest contents but in plants it was small. This indicates that plants do not take PCBs compounds with large amounts of chlorine atoms in the molecule from the soil. The BAC values were about three times higher in the leaves than in the stems, indicating the deposition of PCBs from the air. Additionally, plants were not washed before PCBs determination. Such high BAC values for these congeners are due to the substantial PCBs content in plants, which can be the result of PCBs deposition on plants.

The high values of MR coefficients of the PCBs migration from the soil to groundwater (Table 4) showed an insignificant impact of the PCBs contents in soils on water pollution. The values of PCB 28 migration coefficients are many times lower than the values of PCB 52 coefficients. It is because the water solubility of PCB 28 is greater than for PCB 52, also values of octanol-water partition coefficients for PCB 28 are lower than for PCB 52. Hence PCB 52 is subject to stronger sorption in the soil and less eluted than PCB 28. High values of PCBs migration coefficients (MR), above 3000, are due to the high content of PCB 28 and PCB 138 congeners in the soil and their low concentrations in water. This showed the insignificant influence of PCBs content in soil on water pollution.

Conclusions

The highest accumulation of PCBs congeners was observed in the topsoil layers as it was proved in research for waste landfill, waste incinerators and former factory (Gabryszewska and Gworek, 2020 a; Gabryszewska and Gworek, 2020 b; Gabryszewska and Gworek, 2021). Among the analyzed PCB congeners, PCB 28 and PCB 138 reached the highest content in the soil. The pattern of dominating PCBs in soil was different for waste incinerators and former factory. The most significant accumulation of PCBs in the topsoil layer occurred in research area 10 and was 14.2 ng/g. It was probably due to the fact that area 10 had the largest amount of deposited waste.

No impact of water flow direction on the soil PCBs contents was found.

Table 3. PCBs concentarations in groundwater (ng/ml)

| Plot no.	PCB 28	PCB 52	PCB 101	PCB 118	PCB 138	PCB 153	PCB 180
1	0.0003	0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0001	< 0.0003
2	0.0003	0.0003	< 0.0002	< 0.0002	< 0.0002	< 0.0001	< 0.0003
5	0.0002	< 0.0002	0.0002	< 0.0002	< 0.0002	< 0.0001	< 0.0003
7	0.0005	0.0005	< 0.0001	0.0005	0.0004	< 0.0001	0.0005
9	< 0.0001	< 0.0002	< 0.0002	< 0.0002	< 0.0002	0.0001	< 0.0003
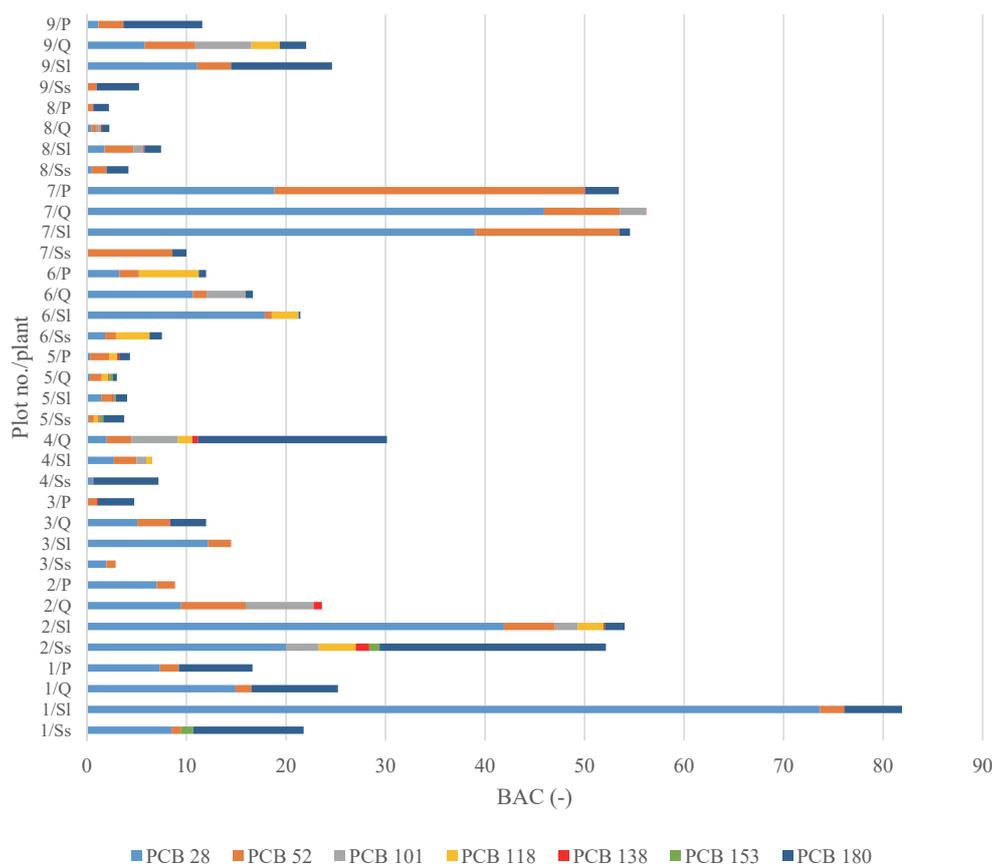
Fig. 4. The values of PCBs bioaccumulation coefficients (BAC) in plants, where: Ss – *Solidago canadensis* stem,
Sl – *Solidago canadensis* leaves, Q – *Quercus L.* leaves, P – *Poaceae*

Table 4. The values of PCB migration coefficients from soil to groundwater

Plot/point No.	MR (–)						
	PCB 28	PCB 52	PCB 101	PCB 118	PCB 138	PCB 153	PCB 180
1	97	675	–	–	–	–	–
2	49	259	–	–	–	–	–
5	3033	–	465	–	–	–	–
7	23	93	–	69	3493	–	83
9	–	–	–	–	–	–	–

Among the examined plants, the largest sum of determined PCBs congeners was in *Solidago canadensis* leaves – 3.26 ng/g and *Quercus L.* leaves – 3.32 ng/g. Determined PCBs contents in *Solidago canadensis* leaves were three times higher than in stalks indicating that air deposition could be the main source of pollution. The dominant PCBs congeners in plants were PCB 28 and PCB 52. The accumulation of PCB 138 was usually connected with the highest contents in the topsoil layer but the content of this congener in plants was small. This indicates that plants do not take PCBs compounds with large amounts of chlorine atoms in the molecule from the soil. The highest PCBs accumulation in the plant was found in leaves of *Solidago canadensis* taken from area 8. This is due to the same fact, as for soil, that there was a repair shop where oils with PCBs could be used. The BAC values of PCB 28, PCB 52, PCB 180 significantly exceeded the value of 1 indicating high accumulation of these PCBs by plants. Due to low PCBs solubility in water only small amounts of PCBs congeners 28 and 52 were determined above the limit of quantification, the rest of tested congeners were below the limit of quantification.

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