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The use of oxytrees in the purification of the soil and water environment in the area of municipal waste landfills

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Abstract: Municipal waste landfills are an important source of soil and water pollution due to the generation of leachates rich in heavy metals, salts, and organic pollutants such as polycyclic aromatic hydrocarbons (PAHs). Conventional remediation methods are expensive, sparking interest in phytoremediation as a sustainable alternative. This study evaluates the potential of *Paulownia tomentosa* (oxytree) in remediating soils contaminated by landfills. Seedlings were grown under controlled conditions and irrigated with distilled water, 50% landfill leachate, and 100% landfill leachate. Chemical analysis of the soil, roots, stems and leaves revealed the selective accumulation of macronutrients (particularly nitrogen and phosphorus) and selected potentially toxic elements (such as lead, zinc and copper), with the contaminants primarily retained in the roots. Stress biomarkers indicated significant physiological responses, including increased proline levels and decreased phenol and flavonoid content, reflecting plant stress under elevated leachate exposure. Notably, *P. tomentosa* demonstrated the ability to reduce 4- and 5-ring PAH concentrations, particularly at moderate leachate levels. However, its overall remediation effectiveness was limited in comparison to phytoremediation grasses, which exhibit stronger contaminant removal potential. These results indicate the limited suitability of *Paulownia* for landfill remediation, emphasizing the need to optimize leachate concentrations.

Keywords: remediation, metals, plants, leachates

INTRODUCTION

Landfilling remains the most widely used method of waste management. Although it primarily concerns developing nations (Hussein et al. 2021), it is still a common practice across the globe (Renou et al. 2008). However, the core issue – one that also impacts smart and sustainable cities – is the very process of waste generation (Esmaeilian et al. 2018). Even though economic growth has a strong influence on the amount of waste produced (Minelgaitė & Liobikienė 2019), a significant portion of this waste still ends up in landfills. Many landfills, especially old ones, do not have

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any substrate seals, so pollutants leaching from waste are transferred to the soil and water environment (Koda et al. 2017, Dąbrowska et al. 2018, Wdowczyk & Szymańska-Pulikowska 2020). Pollution indicators characteristic of municipal waste landfills include, among others, increased EC and higher concentrations of Cl^-, SO_4^{2-}, nitrogen, B^+, Cr^{6+}, Cu^{2+}, Zn^{2+}, Pb^{2+}, Hg^{2+}, Co^{3+} and Ni^{2+} (Clark & Piskin 1977, Slack et al. 2005). In addition to heavy metals monitored in waters in the area of pollution sources, they also include pesticides and petroleum hydrocarbons (Mandal et al. 2014). Polycyclic aromatic hydrocarbons (PAHs) are among the most common organic groundwater contaminants in the area of municipal landfills. They are used in the manufacture of personal care products, fertilizers and plastic packaging, among other products. Numerous studies show that these compounds can be carcinogenic and mutagenic (Li et al. 2017, Fang et al. 2018).

The magnitude of this issue is illustrated by the inspection of 684 active municipal landfill sites in 2010, which revealed that as many as 49 of them (over 7%) lacked any form of substrate sealing. Therefore, it is crucial to carry out thorough and reliable monitoring of groundwater quality in areas surrounding both existing and potential pollution sources (Witkowski & Żurek 2007, Rykała & Dąbrowska 2020). However, of even greater importance is the need to find methods to purify water and soil in the area of landfills. Nearly 90 substances have been identified that are considered persistent, toxic and capable of accumulating in the soil (Ulanicka 2019). Traditional soil reclamation methods are very expensive (Mir et al. 2017); hence phytoremediation seems to be much more practical. The answer to this problem may be the use of *Paulownia* (Berg et al. 2020). *Paulownia* is a perennial woody plant native to China and Southeast Asia (Nagata et al. 2013), which was discovered in 1835 (Christenhusz et al. 2017), but it was only in the last dozen or so years that it began to be used in various fields of science.

Paulownia (oxytree) is considered a tree of great economic importance, ornamental and high-quality wood (Dubova et al. 2019). It should be noted that *Paulownia* is also used in herbal medicine (Cheng et al. 2019) and as an additive to animal feed (Wang et al. 2019). Oxytree is a tree formed by the crossing of two species: Paulownia Fortunea (*P. fortunei*) and Elongata (*P. elongata*). This tree produces numerous very large leaves that can reach a diameter of approx. 60 cm. In the process of photosynthesis, leaves absorb large amounts of carbon dioxide, hence its name – the oxygen tree. It is worth highlighting the fact that the tree tolerates both high and low temperatures (its frost resistance is estimated at about –25°C or slightly more) and there is no specific indication of the soil pH value (Zajączkowska et al. 2018). The tree can be planted in fall or spring.

Paulownia is currently used as a source of biomass (Tyśkiewicz et al. 2019, Hamdan & Houri 2022), a tree for the production of furniture (Kaygin et al. 2015) or a tree with properties that absorb carbon dioxide from the atmosphere (Smarul et al. 2017, Haldar & Sethi 2021). In 2015, research was launched in Poland to determine the ability of oxygen forests to cleanse soils previously exploited for mining (Zajączkowska et al. 2018).

Heavy metal contamination of soil is one of the biggest environmental problems (Doumett et al. 2008, Wuana et al. 2011). Therefore, research involving an attempt to clean the soil is all the more necessary. It is worth mentioning that *Paulownia* has thus far only been investigated to a limited extent on mining waste materials. No research has been conducted on the accumulation of noble or rare earth elements (Zhang et al. 2019). To date, the influence of *Paulownia* on the possibility of accumulation of pollutant loads Cd, Cu, Pb and Zn in soils in mining areas has been tested (Zajączkowska et al. 2018). Similar studies were conducted by Wang in 2019, where the purification potential of Pb and Zn was investigated. Macci et al. in 2015 and Tzvetkova et al. in 2015 also tested the properties of *Paulownia* in the field of soil remediation. In 2018, an experiment was performed at the Adam Mickiewicz University in Poznań to characterize the potential of the *Paulownia elongata* and *Paulownia fortunei* hybrid to uptake 67 elements together with an estimation of the physiological response of plants cultivated in highly contaminated post-industrial waste materials. The experiment was carried out in laboratory conditions with the constant measurement of soil moisture.

Phytoremediation has many advantages, but the biggest problem with implementing this method in soil reclamation is finding appropriate plants. In the case of municipal waste landfills, high contamination not only with heavy metals, but also with chlorides and ammonium ions should be taken into account (Oseni et al. 2020). In the paper of Buzan et al. (2018), special attention was paid to the use of *Paulownia* in the purification of soil from zinc (di Baccio et al. 2003) and heavy metals, without taking into account other parameters.

The aim of this article is to investigate the possibility of using *Paulownia* to clean soil of both organic and inorganic pollutants generated during the migration of leachate from municipal waste landfills. The tests were carried out with two concentrations of leachate and compared with the conditions of watering with distilled water. Research shows that *Paulownia* can be used as a plant for the remediation of areas around waste disposal sites, but only if the appropriate concentration of leachate and selected metals are maintained. In addition to evaluating the remediation potential of *Paulownia tomentosa*, the study aimed to assess the physiological responses of the plant to exposure to landfill leachate, in order to identify the stress thresholds that limit its effectiveness in remediation.

MATERIALS AND METHODS

The tree seedlings (Fig. 1) were cultivated (1 plant per pot; 1.5 L of soil; 6 replicates) in commercial peat-based substrate (organic matter content 30%, pH 5.5–6.5 – $CaCl_2$). The cultivation was carried out for 60 days at a temperature of 24/22°C (day/night), at a light intensity of 10,000 lx, a photoperiod of 16/8 hours, and a humidity level of 82%.

Fig. 1. *Analyzed seedling of plants (phot. A. Nadgórska-Socha)*

Once a week, the plants were watered with a 100% and 50% solution of leachate, respectively. Substrate without the leachate was established as a control. After 60 days of cultivation, part of the plant material (aerial parts) was stored at –80°C prior to analysis. The part of the plant material – aerial parts and roots – intended for element analysis were washed with tap and deionized water and dried to a dry weight at 105°C.

Chemical analysis of leachates

Leachate from the municipal waste landfill in Tychy was used to water the plants (Dąbrowska & Witkowski 2022). The chemical composition of the leachate was analyzed for pH, electrical conductivity (EC), sulfates, sulfur, phosphates, ammonium nitrogen, total nitrogen, nitrates, bicarbonates, chlorides, total organic carbon, aluminum, copper, iron, manganese, nickel, strontium, calcium, magnesium, potassium and sodium.

After testing in the laboratory, the soil samples were subjected to batch leaching tests. The static method involves inducing a reaction between the tested soil and a liquid in a closed vessel. In these tests, the type of leaching liquid, its amount in relation to the solid phase, and the contact time of the liquid with the tested sample play an important role. Static tests were carried out in accordance with the standard PN-EN 12457-4:2006 (PKN 2006), with a liquid to solid ratio of 10:1 L/kg. The samples were prepared in accordance with the PN-EN ISO 15587-2:2005 standard (PKN 2005).

Determination of trace element and macronutrient in plants and soils

To assess the concentrations of trace elements (Al, Cu, Pb, Zn, Fe, Mn, Ni) and macronutrients (K, Mg, Na, Ca, P, S) in plant samples, the material was first washed with tap water to remove dust and substrate residues, rinsed twice with deionized water, and dried at 105°C. Subsequently, 0.25 g of the dried sample was digested with 4 mL of concentrated nitric acid for 24 hours at room temperature. The mixture was then heated in digital drying baths (The Labnet Digital Drying Baths, dual block; temperature range: +5°C above ambient temperature to 150°C; temperature uniformity: ±0.2°C) at 120°C until complete digestion occurred. After cooling, the digests were filtered into 50 mL plastic bottles and diluted to a final volume of 25 mL with deionized water (Lin et al. 2008). The concentrations of trace elements and macronutrients were then determined using inductively coupled argon plasma optical emission spectrometry (SPECTROBLUE ICP-OES, Spectro Analytical Instruments, Germany).

For soil analysis, air-dried samples were sieved through a 2 mm mesh following the procedure described by Zheljazkov et al. (2008). Trace elements and macronutrients were extracted using concentrated HNO_3 (65%). Specifically, 0.5 g of soil was placed in digestion tubes, soaked overnight in 5 mL of concentrated nitric acid at room temperature, and subsequently digested on an aluminum block at 150°C for 8 hours. The resulting solutions were filtered and diluted to 25 mL with deionized water. Concentrations of trace elements and macronutrients in the filtrates were then measured using inductively coupled plasma atomic emission spectroscopy (SPECTROBLUE ICP-OES, Spectro Analytical Instruments, Germany).

Determination of total flavonoids

The standard procedure of Christ and Müller (1960), described for medicinal plants by Bojić et al. (2013), was used for the spectrophotometric method to quantify total flavonoids expressed as milligrams of quercetin equivalents per gram ($mg \cdot g^{-1}$). This method contains the acid hydrolysis of flavonol glycosides, followed by the formation of colored complexes of these flavonoid compounds with $AlCl_3$. A VIS spectrometer was used to measure the absorbance at a wavelength of 425.0 nm.

Determination of phenolic compounds

The Folin–Ciocâlteu method was used to determine the total phenolic content. The estimation of the reduction capacity of plants in terms of total phenolic content can be an indication of the antioxidant potential and the resistance of plants to environmental stress. 250 mg of leaf samples were boiled in 80-percent ethanol to precipitate proteins. The samples were then homogenized in 80-percent ethanol and centrifuged at 4,000 × *g* for 20 min. 0.2 mL of the supernatant, 0.8 mL of distilled water, 0.5 mL of 20-percent Na_2CO_3 and 0.125 mL of diluted Folin–Ciocâlteu reagent were transferred to test tubes. The reaction mixture was incubated for 20 min, after which it was either centrifuged at 4,000 × *g* for 20 min or filtered through a hard filter. The absorbance of the resulting solutions was measured at a wavelength of 760 nm, and the results were expressed as milligrams of gallic acid equivalents per gram ($mg \cdot g^{-1}$ GAE).

Determination of proline

The proline content was determined using the acid ninhydrin method following the procedure described by Bates et al. (1973). Plant material was homogenized in a 3-percent sulphosalicylic acid solution (3 g per 100 mL). The proline concentration, expressed as millimoles of proline per gram of fresh weight ($mM \cdot g^{-1}$ f.w.), was then calculated according to the method of Bates et al. (1973).

Determination of ascorbic acid

A spectrophotometer was used to determine the ascorbic acid content of the leaf samples. The ascorbic acid content was calculated using the formula of Keller and Schwanger (1977):

$$\textit{ascorbic acid}\left[\mathrm{mg}\cdot\mathrm{g}^{-1}\ \mathrm{f.w.}\right]=\frac{\left(E_o-E_s-E_t\right)\cdot V}{W\cdot 100}\cdot 100 \quad (1)$$

where V is the volume of the extract [mL], W is the weight of the leaf sample [g], and E_o, E_s and E_t are the optical densities of the blank, plant and ascorbic acid samples, respectively.

Determination of malondialdehyde (MDA) content

The malondialdehyde (MDA) content in plant tissues – an indicator of cytoplasmic membrane lipid peroxidation under stress – was determined using the thiobarbituric acid (TBA) method and measured spectrophotometrically at 532 nm (Malar et al. 2016). Fresh leaf tissue (0.2 g) was homogenized in 2 mL of 5-percent trichloroacetic acid (TCA) in an ice bath and centrifuged at 10,000 rpm for 10 min at 4°C. Subsequently, 2 mL of the obtained supernatant was mixed with 2 mL of 0.67-percent TBA solution and boiled for 30 min. After cooling, the mixture was centrifuged again, and the absorbance of the supernatant was measured at 450 nm, 532 nm, and 600 nm. The MDA concentration was then calculated and expressed in micromoles per gram of tissue ($\mu mol \cdot g^{-1}$) according to Malar et al. (2016).

Preparation of extracts for soil samples on GC-MS

The obtained soil samples were properly described and dried in a sterile place in the laboratory. They were then weighed and extracted by organic solvent – dichloromethane (DCM) in an ultrasonic bath (time: 15 min; temperature: 30°C). The extracts were filtered through paper filters; class 3 m/N; diameter 110 mm. Finally, the extract yield was calculated after evaporated the solvent.

The leachate was subjected to solid phase extraction (SPE) on a column (6 mL, 500 mg mass per column – Bakerbond Octadecyl (C18) Polar Plus) to isolate organic compounds. The extract was passed through a column preconditioned with methanol (45 min). The fraction was eluted by ethyl acetate (10 mL) and finally dried using helium, redissolved in 1 mL DCM, and transferred to a vial.

The soil used for the study was the same soil used during the growth of Paulownia plants. The soil was collected separately from each individual plant grown in the laboratory. Each soil sample underwent the same sample preparation procedure for laboratory testing, in accordance with analytical practices.

Gas chromatography-mass spectrometry (GC-MS)

The equipment used was an Agilent Technologies 7890A gas chromatograph and Agilent 5975C network mass spectrometer with a triple axis detector system at the Department of Natural Sciences, Sosnowiec, Poland. The carrier gas was helium (flow rate of 2.6 mL/min).

Parameters: mass spectra, electron impact mode (45–550 Da 0–40 min and 50–700 Da >40 min), and ionization energy of 70 eV. The GC-MS oven temperature – from 45°C (1 min) to 100°C at 20°C/min, then to 300°C (hold 60 min) at 3°C/min, with a solvent delay of 10 min; separation with a J&W HP5-MS (60 m × 0.32 mm inner diameter, 0.25 μm film thickness) fused silica capillary column coated with a chemically bonded phase (5% phenyl, 95% methylsiloxane). To identify the compounds, a comparison of peak retention times with those of standard compound mass spectra, and their mass spectra was used. In addition, the analysis employed literature data and the interpretation of MS fragmentation patterns (Philp 1985).

Quality control and assurance (QC/QA) was associated with a blinded assay that accompanied the test samples, covering the entire analysis procedure to determine potential contamination during testing. Limits of detection (LOD) were applied three times with the standard deviation of background peaks in the procedural blanks repeated three times (average values 2.0 ng/mL ±0.05 ng/mL). Quantitative analysis for PAHs: 5-point calibration curves for the analytical standards; peaks integrated manually; correlation coefficient values within the range of 0.997–0.998. The NIST SRM 1649b reference material and the certified concentrations of the tested PAHs confirmed the effectiveness of the method.

The data on biochemical parameters and metal concentrations were tested for normality and equality of variance. A one-way ANOVA was used to assess differences in mean values between sampling sites, and statistically significant differences were determined using Tukey's test at $p < 0.05$.

RESULTS AND DISCUSSION

Inorganic parameters in leachates

The leachate used to water the plants had an electrical conductivity of 14 mS/cm and a pH of 7.8. The pH values in leachates from old landfills (operated for more than 10 years) are usually greater than 7.5 (Nájera-Aguilar et al. 2019), which is characteristic of the methanogenic phase of landfills.

The chemical composition of the leachate was determined primarily by high concentrations of chlorides (1,800 mg/L), ammonium nitrogen (1,200 mg/L), and sodium (1,400 mg/L). Ammonium nitrogen is indicated in the literature as one of the main pollutants present in leachates, usually reaching values up to 2,000 mg/L, and decreasing slowly with age; therefore, even in leachates from old landfills, it occurs in high concentrations (Costa et al. 2019), which is confirmed by the obtained results. The pollutants most commonly found in leachates, apart from ammonium nitrogen, include chlorides (Moody & Townsend 2017, Wowkonowicz & Kijeńska 2017), which were also found at high concentrations in the tested leachates. The major cations include sodium at 1,400 mg/L and potassium at 920 mg/L, both extremely elevated and contributing to the overall salinity. Calcium (80 mg/L) and magnesium (160 mg/L) are moderately high, contributing to water hardness. Sulfate is 188 mg/L, which is elevated but not as at extreme levels as other ions.

The high sodium content in the analyzed leachates may indicate the presence of plant residues and other bio-wastes in the landfill and confirms that even with the passage of time of landfill operation, it is not subject to changes due to the processes occurring inside it (Christensen et al. 2001). Among the heavy metals, the largest share is manganese and iron (Fig. 2). The increased concentrations of manganese (220 mg/L) and iron (4.4 mg/L) can be explained by oxidizing conditions, during which insoluble metal sulfides are converted to soluble sulfates, or by the influx of groundwater containing higher concentrations of iron and manganese into the landfill due to a failure of the insulation system (Röling et al. 2001).

The results of leachability tests from natural soil indicate a conductivity of 510 µS/cm, while the conductivity from soil samples flooded with 50% leachate concentration is 670 µS/cm, and 100% leachate concentration is 960 µS/cm. The latter value is less than 7% of the initial value of specific electrolytic conductivity from landfill leachate. Others, while studying the effect of leachate application on soil properties, also observed an increase in electrical conductivity in leachate-irrigated plots compared to control plots (MacDonald et al. 2008), indicating the need for continuous monitoring. The raw leachate had significantly higher electrical conductivity than the leachate leached from the soil, which is consistent with the observations of other researchers who reported higher electrical conductivity in raw leachate than in leachate leached from leaching columns after soil irrigation (Smith et al. 1999).

The calcium content (Fig. 3) remains at a similar level in both landfill leachate and leachability test samples. The leachability of magnesium in the tested samples is only 4% of the initial concentration of this ingredient in leachates. For potassium it is about 10%, and for sodium it is about 6%. The metal content in leachates was up to over 2,000 times higher than in natural soil.

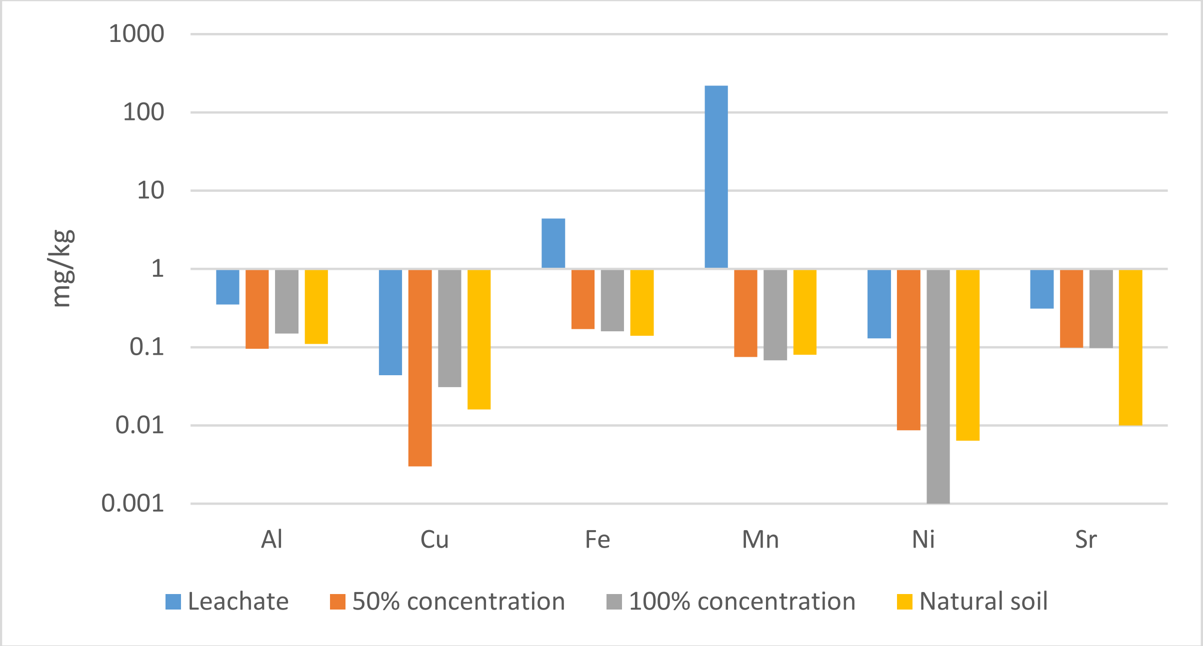

Fig. 2. *Concentrations of inorganic compounds in samples*

This situation was observed in the case of manganese. For iron and strontium, the concentration in leachates was over 30 times higher than in natural soil. Other researchers conducting laboratory analyses of landfill leachate transport in soil have also observed a simultaneous significant reduction in manganese and iron (Islam & Singhal 2004).

Comparing the leaching values of metals from natural soil and from soil flooded with 100% leachate concentrate, it can be concluded that only in the case of strontium the concentration was 10 times higher in leachate from landfills and copper was approximately twice as high. In the remaining cases, these values were similar, and for nickel and manganese, greater leaching from natural soil was observed. This confirms the observations of other authors that the use of leachates does not significantly affect the concentration of metals in the soil, which was explained by the low rate of metal addition (MacDonald et al. 2008) we studied an onsite disposal system in Ottawa County, Michigan, where leachate was spray irrigated on the vegetated landfill cover. We established six 20-m-diameter circular experimental plots on the landfill; three were spray irrigated as part of the operational system, and three remained as untreated control plots. We quantified the effects of leachate application on soil properties, soil solution chemistry, vegetative growth, and estimated solute leaching. The leachate had high mean levels of electrical conductivity (0.6–0.7 S/m).

In order to determine the level of organic pollutants, both the control sample, PK, and the leachate which was used to water the remaining soil samples were tested. The results obtained were compared quantitatively and qualitatively to present the impact of the growth of the *Paulownia tomentosa* plant species on reducing the content of potential organic pollutants in landfills.

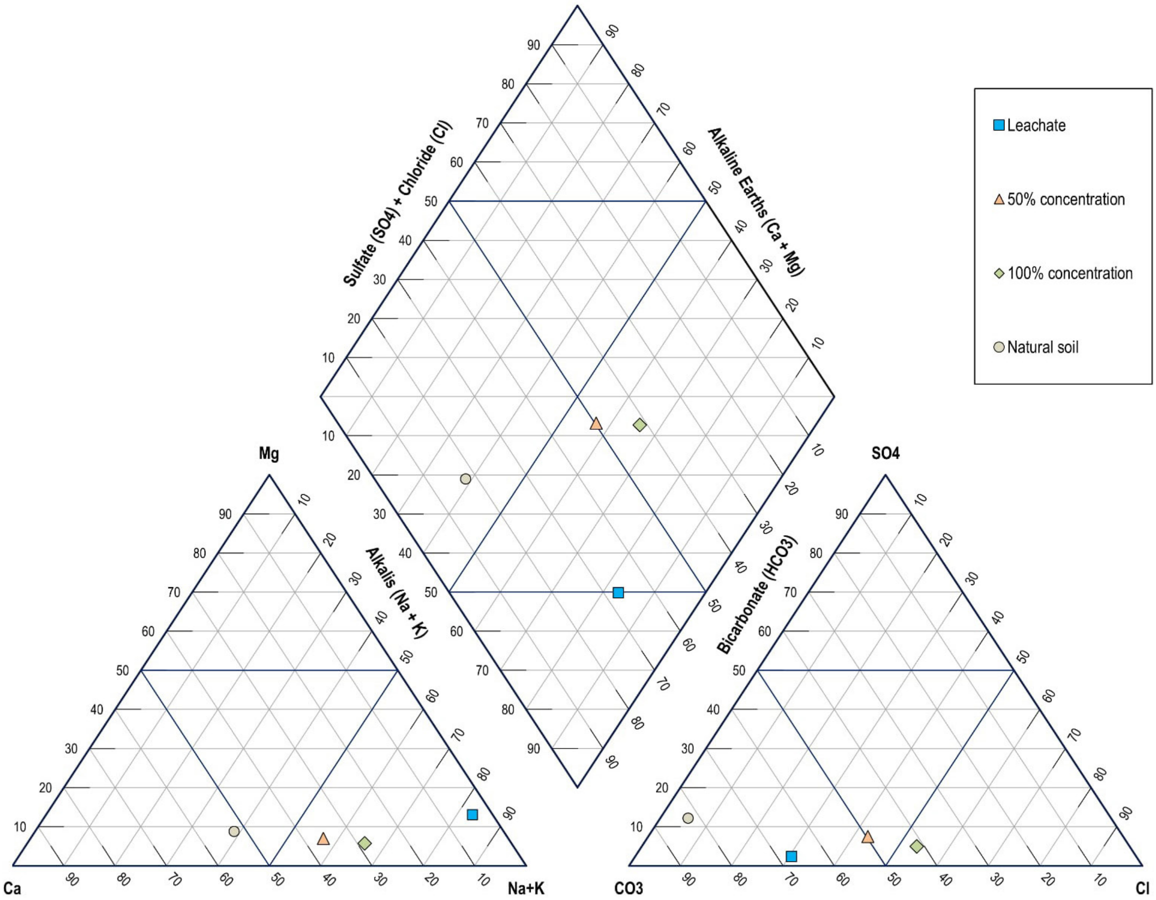

Fig. 3. *Piper's diagram of the water samples*

Polycyclic aromatic hydrocarbons (PAHs)

A number of PAHs were observed in the tested samples and constitute the typical anthropogenic pollutants occurring in the world (Robin & Marchand 2022). Rainwater, by washing solid waste lying in a landfill, creates leachate, which may leak into the nearby ground and water environment on inadequately protected surfaces. Consequently, due to the strong accumulation of PAHs in the soil, contamination may persist for many years. Both in soil samples and the sample of leachate from the landfill that was watered to the plants detected: 2-ring, 3-ring, 4-ring and 5-ring PAHs. However, the heaviest 6-ring PAHs were not detected.

Comparing individual group contents of the sum of PAHs, in the control sample (PK), the highest amount was observed among 3-ring PAHs (27.67 ppm), while the lowest was observed among 5-ring PAHs (1.21 ppm) (Table 1). This is a sample that has not yet been exposed to leachate from a solid waste landfill. It therefore serves as a reference point for interpreting other sample results. In a soil sample of P50 in which plants were planted and watered with diluted leachate in a ratio of 1:1 (distilled water/leachate), their quantitative increase was observed in one ring group of PAHs out of four – the 2-ring. However, in the remaining cases a significant decrease was recorded. A similar situation can be observed in soil sample P100, which was watered with undiluted leachate from a landfill. There was a decrease in the quantity of 3-, 4- and 5-ring PAHs, while naphthalene remained at a similar level. Under conditions of limited oxygen availability around the roots, the activity of aerobic PAH-degrading bacteria may sometimes decrease (Wdowczyk et al. 2026), which may indicate a poor ability of plants to metabolize 2-rings PAHs. Changes in the level of soil properties in the environment may result from the partial replacement of the liquid in the soil pores with PAHs and their blocking with other pollutants. This may lead to a decrease in soil aeration and water infiltration (Sakshi et al. 2019). It can be assumed that *Paulownia tomentosa* plants are best at removing heavier PAHs during their growth. Research shows that plant roots are a common route between the soil and the plant, as the tissues that first connect with pollutants during the gathering of PAHs found in the substrate (Sushkova et al. 2020). The uptake and effect of PAHs on plants depend mainly on the species of the plant itself, the physicochemical properties of the soil and the original concentrations and chemical properties of PAHs (Zhang C. et al. 2017, Zhang S. et al. 2017). When interpreting this type of results of the PAH content in soils, try to use the same or identical soil sample, as the difference in PAHs in other types may probably be associated with the different content of organic matter (Gworek et al. 2016).

The greatest percentage of change compared to the PK sample was in the group of 4- and 5-ring PAHs (Fig. 4).

Table 1
The sum of the values of individual PAH ring groups [ppm] (mean values ± SD, n = 3)

Sample	2-ring[1]	3-ring[2]	4-ring[3]	5-ring[4]	Sum[5]
PK	14.68 ± 1.630	27.67 ± 2.265	1.39 ± 0.1929	1.21 ± 0.051	44.95
P50	19.56 ± 0.903	23.25 ± 1.575	0.89 ± 0.2810	0.37 ± 0.729	44.07
P100	15.75 ± 0.910	23.08 ± 1.430	1.27 ± 0.9930	0.80 ± 1.002	40.90

[1] Naphthalene.

[2] Fluorene, anthracene, acenaphthylene, acenaphthene, phenanthrene.

[3] Pyrene, fluoranthene, benzo(a)anthracene, chrysene.

[4] Benzo(a)fluoranthene, benzo(b+k)fluoranthene, perylene, benzo(a)pyrene, benzo(e)pyrene.

[5] The sum of all PAHs included in the study.

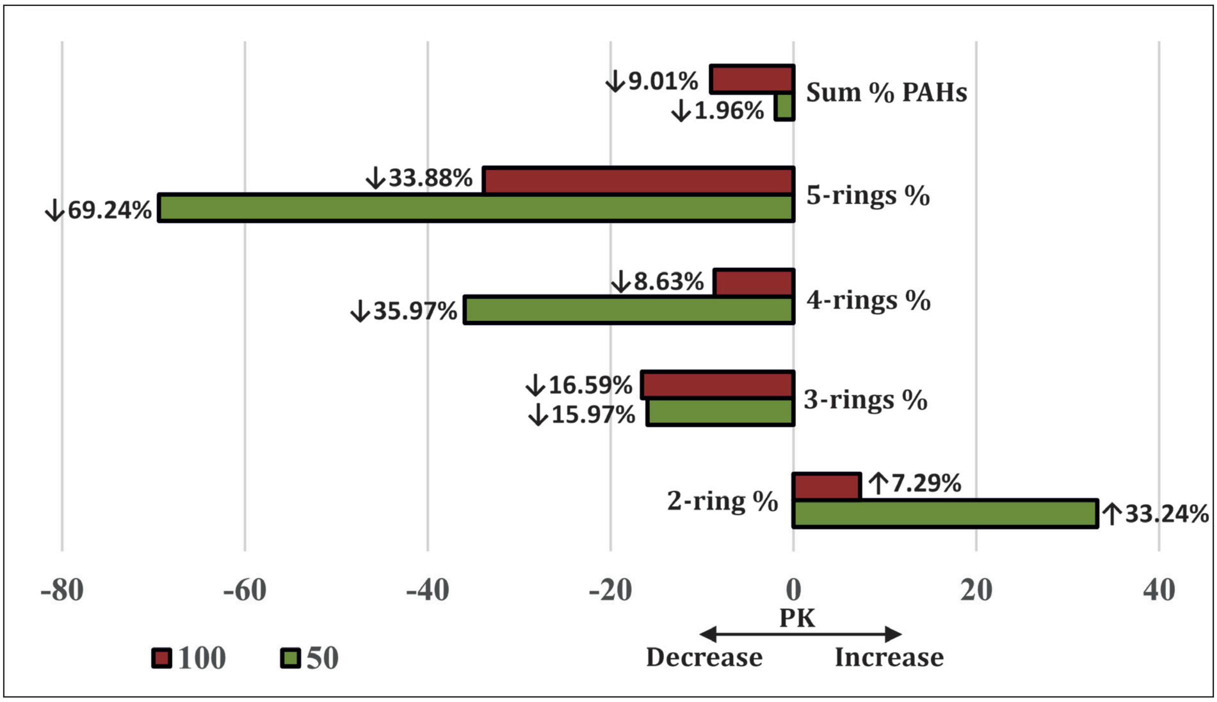

Fig. 4. *Percentage of change in individual PAH group content relative to the PK control*

In sample P50, there was a decrease in PAH concentrations by 35.97% and 69.42%, respectively. In the sample of P100, these were smaller value declines of 8.63% and 33.88%. In the group of 3-ring PAHs, similar decreases in these concentrations were observed in both soil samples P50 and P100 (15.97% and 16.59%, respectively). However, a different situation occurs with 2-ring naphthalene, where in both samples it increases by 33.24% (P50) and 7.29% (P100). This may be due to the chemical properties of high molecular weight PAHs and their relatively low solubility in water (Hutchinson et al. 2003). The greatest declines that were associated with the growth of *Paulownia tomentosa* were recorded in the soil sample diluted with 50/50 leachate. It was then that the plant coped best with removing 4- and 5-ring PAHs from the soil. These observations partially coincide with other studies on PAHs, where the highest removal was found when irrigating plants with leachate at a concentration of 30% (Salehi et al. 2020). *Paulownia tomentosa* plants showed the best effectiveness against 5-ring PAHs for removing them from the soil substrate. Many studies indicate that plants are important accumulators of PAHs (Kacalkova & Tlustos 2011, Yakovleva et al. 2016).

The leachate taken into account in the research was collected from a landfill that is over 20 years old, which may indicate its high intensity towards PAHs and emphasize the weaker mobility of *Paulownia tomentosa* plants. At the same time, it should be remembered that the plants' reaction to leachate depends on the species (Zalesny et al. 2007).

Phytoremediation technology is a method that uses plants in the process of purifying the soil and water environment. This technique is ecological and cheaper than the other chemical and physical treatments. Thanks to it, it is not necessary to remove contaminated soil from its place of origin. It is popular for removing PAHs because plant species secrete various enzymes into the soil (including dehalogenase, hydrolase, monooxygenase, dioxygenase), which have the ability to degrade or transform aromatic pollutants (Campos et al. 2008). The intensity and diversity of pollutants in leachates from landfill wastes depend, among other things: the landfill age, the level of decomposition of the waste contained therein (Richard 1992).

Chemical properties of soils, stems, leaves and roots

The values of individual components in the soil are presented in Table 2. The soil taken into account was not contaminated with leachates, soil after watering with leachates mixed with leachates in a 1:1 ratio, and 100% leachate concentration.

Chemical analyses of soils revealed that the concentration of macronutrients such as calcium, nitrogen, potassium and magnesium increased with the proportion of leachate. Nitrogen exhibited the most pronounced increase, reflecting its high concentration in landfill leachate. Conversely, phosphorus concentrations were higher in the 50% leachate treatment than in the 100% treatment, indicating nonlinear behavior of this element under increasing leachate load.

Trace element concentrations in soil showed no uniform trend. Iron and manganese exhibited only minor fluctuations between treatments, whereas lead and zinc increased markedly in soils irrigated with leachate. In stems and leaves (Table 3), macronutrients such as potassium, sulfur and phosphorus increased with leachate concentration, indicating effective translocation to aboveground tissues.

Table 2
The concentrations of macroelements [mg·kg^{-1} d.w.] in the soil (mean values ± SD, n = 3). The different letters denote significant differences between the macroelement concentrations ($p < 0.05$)

Sample	Ca	K	Mg	Na	S	P	Al
PK	18,199.767 ± 1,280.648	1,250.933 ± 113.053	927.633 ± 77.107	330.833 ± 20.716	1,774.367 ± 238.531	455.550 ± 43.644	1,489.317 ± 109.203
P50	21,938.567 ± 1,991.084	1,822.183 ± 290.869	1,131.283 ± 32.968	1,029.017 ± 118.662	2,203.267 ± 140.546	544.250 ± 65.557	1,442.633 ± 269.582
P100	22,524.2 ± 1,155.935	2,361.417 ± 147.723	1,156.683 ± 66.114	1,701.617 ± 124.766	2,307.133 ± 289.961	479.100 ± 9.152	1,214.467 ± 127.388
Sample	**Cu**	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**	
PK	6.567 ± 1.561	1,957.150 ± 155.798	55.817 ± 10.669	8.483 ± 1.125	14.033 ± 2.040	17.183 ± 2.950	
P50	6.067 ± 0.597	2,015.100 ± 212.350	57.117 ± 0.769	10.133 ± 0.850	10.183 ± 0.577	19.767 ± 0.701	
P100	6.233 ± 0.711	1,859.283 ± 145.704	57.300 ± 4.245	9.850 ± 0.529	9.217 ± 0.558	26.400 ± 5.624	

d.w. – dry weight.

Table 3
The concentrations of macroelements [mg·kg^{-1} d.w.] in the plant leaves and stems (mean values ± SD, n = 3). The different letters denote significant differences between the element concentrations in the same organ ($p < 0.05$)

Sample	Ca	K	Mg	Na	S	P	Al
PK	9,268.102 ± 695.595	23,052.387 ± 1,193.182	1,174.706 ± 11.556	518.385 ± 54.509	1,415.105 ± 100.757	1,552.680 ± 79.546	65.296 ± 13.696
P50	11,314.211 ± 714.554	19,654.602 ± 682.876	1,856.802 ± 60.395	165.302 ± 13.144	1,653.831 ± 40.727	3,002.107 ± 56.766	38.651 ± 8.413
P100	12,581.167 ± 799.236	20,914.241 ± 60.955	1,463.981 ± 48.658	258.977 ± 28.430	1,986.266 ± 84.619	3,585.829 ± 141.114	46.003 ± 6.201
Sample	**Cd**	**Cu**	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**
PK	0.122 ± 0.002	2.245 ± 0.475	178.498 ± 7.461	23.991 ± 1.865	14.518 ± 1.158	1.348 ± 0.224	49.160 ± 4.41
P50	0.122 ± 0.001	2.191 ± 0.532	162.217 ± 9.650	43.999 ± 3.716	15.818 ± 1.492	1.218 ± 0.197	57.264 ± 13.49
P100	0.115 ± 0.002	2.329 ± 0.311	173.632 ± 8.397	37.434 ± 1.056	15.271 ± 0.755	7.503 ± 5.779	41.251 ± 1.812

d.w. – dry weight.

Magnesium concentrations were high in all treatments, with the highest values observed in the 50% leachate variant.

Among trace elements, lead showed the most pronounced increase in aboveground tissues at 100% leachate concentration, whereas copper, iron and manganese varied only slightly between treatments. All trace element concentrations remained below levels considered phytotoxic.

As shown in Table 4, roots exhibited pronounced accumulation of nitrogen and phosphorus with increasing leachate concentration. Phosphorus increased consistently across the treatments, whereas nitrogen exhibited a clear increase from the control to the 100% leachate treatment. Magnesium and sulfur concentrations were highest at the 50% leachate treatment, followed by a slight decrease at 100%, indicating a non-linear response to increasing leachate load.

Iron concentrations decreased progressively with an increasing proportion of leachate, while copper increased gradually. Lead showed a sharp increase in root concentration at a leachate concentration of 100%. Higher concentrations of manganese and nickel were observed in the 50% treatment than in the 100% treatment, suggesting that moderate leachate dilution may favor the uptake of these elements.

The results obtained for trace metal concentrations in the tested plants were below the concentrations considered toxic to plants (Cd 5–30, Zn 100–400, Pb 30–300, Cu 20–100, Mn 400–1,000 $\mathrm{mg \cdot kg^{-1}}$) (Kabata-Pendias 2001, Massa et al. 2010, Nadgórska-Socha et al. 2013). Similar heavy metal contents as shown in this study in *Paulownia* were found in the tested plant species (*Mimosa pudica* L., *Brachiaria mutica Forssk.*, *Ricinus communis* L., *Celosia argentea* L., *Urena lobata* L.) collected directly from the landfill site. (The MSW sanitary landfill site is located at the Comprehensive Waste Management Center (CWMC) in Rayong, Eastern Thailand). The researchers emphasize that when a landfill is situated near residential or agricultural areas, heavy metals contained in leachate and landfill soil may spread to the surroundings, potentially threatening human health (Montreemuk et al. 2025). Phytoremediation is an effective method for removing heavy metals from soil, valued for its low cost, simplicity, and ease of maintenance. It is particularly suitable for soils with low levels of heavy metal contamination, although the process usually requires extended periods due to the slow growth of plants. However, in soils with high levels of contamination, plants often experience stress and growth inhibition caused by the toxic effects of heavy metals (Vongdala 2019, Montreemuk, et al. 2025).

Table 4
The concentrations of macroelements [$\mathrm{mg \cdot kg^{-1}}$ d.w.] in the plant roots (mean values ± SD, n = 3). The different letters denote significant differences between the element concentrations in the same organ ($p < 0.05$)

Sample	**Ca**	**K**	**Mg**	**Na**	**S**	**P**	**Al**
PK	1,826.781 ± 150.825	11,555.660 ± 752.763	1,706.861 ± 82.660	455.787 ± 19.970	605.347 ± 19.058	1,191.818 ± 35.086	13.555 ± 1.731
P50	2,006.241 ± 106.521	13,734.688 ± 70.339	2,143.833 ± 5.053	630.830 ± 55.242	870.154 ± 31.603	1,888.955 ± 106.346	14.210 ± 4.628
P100	1,717.752 ± 195.874	13,441.428 ± 1464.631	2,086.037 ± 180.281	841.051 ± 93.003	852.409 ± 20.150	1,918.915 ± 23.808	6.421 ± 2.433
Sample	**Cd**	**Cu**	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**
PK	0.120 ± 0.004	2.715 ± 0.399	171.623 ± 11.016	8.357 ± 0.964	15.127 ± 1.479	1.275 ± 0.301	37.867 ± 23.729
P50	0.121 ± 0.003	3.310 ± 0.070	110.111 ± 10.296	15.328 ± 0.960	16.026 ± 0.232	1.090 ± 0.023	40.310 ± 2.655
P100	0.120 ± 0.003	3.553 ± 0.807	105.766 ± 3.073	14.424 ± 1.564	12.650 ± 0.367	9.085 ± 4.936	37.099 ± 2.110

d.w. – dry weight.

Warming, changing rainfall patterns and extreme weather events such as floods, heatwaves, droughts and storms, as well as increasing water and soil pollution, introduce environmental stress and limit plant growth and survival, which negatively impacts both plant quality and may cause negative environmental and health impacts (Kumar 2016). Metabolic and chemical stress means that some pollutants are not accumulated in leaves or stems, but remain in the soil and roots, which in turn causes further leaching of pollutants into the aquatic environment.

In the case of calcium, the increase in soil content with increasing leachate content is due to the high calcium content in municipal leachates. Calcium is poorly mobile, therefore, greater accumulation occurs in the soil and roots than in stems or leaves. Additionally, this variability may be influenced by high potassium, sodium, or magnesium content in the soil, which limits calcium migration. A similar relationship occurs for magnesium. Despite high potassium content in leachate-contaminated soil, the content in roots does not increase significantly. This may be related to ion competition or inhibition of active transport due to chemical stress. Nitrogen also shows the greatest accumulation in roots. A different behavior is observed for phosphorus. High content in leaves indicates efficient transport of this element.

Table 5 presents the results of biomarkers of oxidative and metabolic stress in plants. Proline, an amino acid accumulated in plants under the influence of osmotic or toxic stress, natural antioxidants such as phenols, flavonoids, and ascorbic acid, as well as a marker of cellular damage, malondialdehyde, were taken into account.

Physiological stress indicators showed that *Paulownia tomentosa* responded to leachate exposure by increasing proline accumulation by around 50% in both the P50 and P100 treatments. This response is typically linked to osmotic and ionic stress rather than direct metal toxicity.

Total phenolic and flavonoid content decreased progressively with increasing leachate concentration, likely reflecting their consumption in antioxidant defense mechanisms or inhibition of biosynthesis under stressful conditions. Changes in ascorbic acid content were minor and did not suggest a significant compensatory antioxidant response.

Malondialdehyde (MDA) concentrations increased slightly in the P50 treatment compared to the control, indicating enhanced lipid peroxidation. However, the non-detectable MDA level in the 100% treatment should be interpreted with caution, as it may reflect analytical limitations rather than complete suppression of oxidative damage. Reanalysis would be required to confirm this observation. Notably, the observed physiological stress responses are more plausibly linked to the high salinity, ammonium content, and electrical conductivity of the leachate than to trace metal toxicity alone, given that all measured metal concentrations remained below phytotoxic thresholds.

Comparing the values of individual parameters from the leachates and the concentrations observed in plants, the greatest accumulation occurred in nitrogen, phosphorus, and magnesium. These elements were measured at high concentrations in leaves and roots. Despite the fact that the leachates do not contain high levels of nickel and copper, aerobic trees are highly sensitive to the presence of these metals.

Considering that the leachate had a pH of 7.8 and a conductivity of 14 mS/cm, these values are typical for leachates from municipal waste landfills (Wdowczyk & Szymańska-Pulikowska 2020).

Table 5
The results of biomarkers of oxidative and metabolic stress in plants [mg·kg^{-1} d.w.]

Sample	**Proline [mM·g^{-1}]**	**Phenols [mg·g^{-1}]**	**Flavonoids [mg·g^{-1}]**	**Ascorbic acid [mg·g^{-1}]**	**Malondialdehyde [µM·g^{-1}]**
PK	4.96	60.39	559.74	0.24	0.06
P50	7.64	46.91	456.92	0.21	0.05
P100	7.61	41.56	384.87	0.23	n.d

n.d. – not detected, d.w. – dry weight.

The pH is increased by the process of methanogenesis and the dominance of anaerobic microorganisms, which produce methane and hydrogen instead of organic acids, as well as by the very high concentrations of sodium, potassium, and ammonium ions. The analyzed aerobic trees showed similar nitrogen and phosphorus uptake behavior to the macrophytes studied by Wdowczyk and Szymańska-Pulikowska (2022). The study included *Phragmites australis* and *Ceratophyllum demersum*, which accumulated more macronutrients in their roots than in their leaves. The analysis of nickel, copper, and lead accumulation is similar for aerobic trees, with *Phragmites australis* exhibiting higher concentrations in the roots. Selective accumulation of heavy metals such as nickel and lead in roots has been observed in mangroves (Zhou et al. 2021, Alharbi et al. 2023). Studies on mangroves, however, showed that MDA values remained high in leaves and roots, indicating high oxidative stress, but these values did not drop to 0. Additionally, proline and flavonoid levels remained high throughout the experiment in mangroves, while they decreased in *Paulownia*. It can be seen that a similar response to pollutants occurs in these two species only when watered with a 50% concentrate.

Research conducted worldwide is consistent with the results obtained in this study. In the study by Doumett et al. (2008), selective accumulation of metals, especially lead, was observed. Another study examined *Paulownia fortunei* L. in lead remediation (Du et al. 2023). In this case, the results showed that at lead concentrations exceeding 400 mg/L, chloroplast enzyme activity is inhibited and chlorophyll content is reduced, thus accelerating leaf senescence and inhibiting plant growth.

The study of *Paulownia tomentosa* did not take into account low leachate concentrations, which could trigger the phenomenon of hormesis. Such studies at leachate concentrations of 2.5% and 5% were conducted, among others, for maize (Sang & Li 2004), for which root and bud growth was observed.

Studies on *Paulownias* show that they perform less well in environmental purification than phytoremediation grasses. Numerous studies conducted worldwide on grasses (*Vetiver grass*, *Typha domingensis, Rhodes grass*, and *Elephant grass*) indicate their potential for environmental purification, not just the accumulation of pollutants. Gravand's and Rahnavard's (2021) study demonstrated that vetiver grass can actively remove nickel, manganese, lead, and cadmium. In the study by Palm et al. (2021), it was shown that the species *S. alba* and *T. aestivum* grow even at 70% landfill leachate concentration.

CONCLUSIONS

This study demonstrated that *Paulownia tomentosa* exhibits differentiated responses to municipal landfill leachate, reflected in both soil–plant element distribution and plant physiological parameters. Increasing leachate concentrations resulted in elevated levels of calcium, lead and zinc in soils, while macronutrients such as potassium, sulfur and phosphorus increased in aboveground tissues.

In plant roots, nitrogen and phosphorus consistently increased with rising leachate concentrations, indicating the preferential retention of these nutrients in the soil. Conversely, magnesium and sulfur concentrations peaked at 50% leachate and decreased slightly at 100%, suggesting a non-linear response to increasing leachate load. Iron concentrations decreased progressively with an increasing proportion of leachate, whereas aluminum exhibited a slight increase at moderate exposure to leachate, followed by a marked decrease at the highest concentrations. Lead accumulation was particularly pronounced in the roots at a leachate concentration of 100%, confirming the preferential retention of certain potentially toxic elements in the soil.

Analysis of physiological stress markers revealed that *P. tomentosa* activated defense mechanisms in response to leachate exposure. The increased proline levels in the 50% and 100% treatments primarily point to osmotic and ionic stress associated with high salinity, ammonium content, and electrical conductivity, rather than to direct trace metal toxicity. This is because all of the measured metal concentrations remained below the commonly accepted phytotoxic thresholds. The concurrent decrease in phenolic and flavonoid contents suggests their involvement in antioxidant defense or the inhibition of biosynthesis under stressful conditions. Changes in ascorbic acid were minor and did not indicate a strong antioxidant response.

Malondialdehyde (MDA) concentrations increased slightly under moderate leachate exposure, indicating enhanced lipid peroxidation. However, the non-detectable MDA level observed at a leachate concentration of 100% should be interpreted with caution, as it may reflect methodological limitations rather than the complete suppression of oxidative damage.

Research indicates that *Paulownia* (oxytree) can be used for environmental remediation in landfills, but its effectiveness is limited by leachate concentration. These plants selectively accumulate inorganic pollutants, primarily in their roots, meaning they are not effectively removed from the environment. However, *Paulownia tomentosa* plants show promise in removing PAHs from areas near solid waste landfills. Further research is recommended to precisely determine the occurrence of PAHs in soil and identify plants that can effectively neutralize these pollutants from the ground. The study highlights the need for careful consideration of leachate concentration and specific contaminants when using *Paulownia* for phytoremediation.

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