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Plants for saving the environment - Phytoremediation

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Abstract

A large part of the civilizational progress has been achieved at the expense of the natural environment, which recently reached the stages that threaten its creator. Plants play an important role in various areas of our lives, and it turned out that we can rely on them to reduce this threat. The ability of living organisms and the systems they create to protect and restore the environment is at the core of a technology called environmental biotechnology. Advances in science and technology have created a plant-based discipline known as phytoremediation. This technology allows us to remove or reduce the level of pollutants in our surroundings. We can phytoextract heavy metals from contaminated soil and water with the help of resistant plant species and recover noble metals and rare elements. When the soil or water is contaminated with organic compounds, we try to eliminate them completely with the help of plants and their microbiome. Phytoextraction from water is related to the accumulation of pollutants in water and sediments, in which macrophytes from all water groups participate, including free-floating submerged and emerged plants. The task of these plants, apart from the accumulation of metals or organic toxins, is also the uptake of phosphorus and nitrogen to prevent the eutrophication of water. In recent years, the quality of air has deteriorated. Nowadays, 90% of the population breathes air that does not meet WHO standards. It should be emphasized that in the case of outdoor air, there is no industrial system for removing pollutants. In fact, we can only count on nature: rainfall and plants. Indoor air is sometimes even more polluted than outside and, therefore, we should be safe in it with the help of plants that are able to create a refuge. Additionally, it fulfills biofilling desires and improves our mood.

Keywords

heavy metals; plant tolerance; macrophytes remediation; air pollution; indoor pollution

1. Introduction

Air, soil, and water, as critical components of the environment, determine the health status and life quality of the human population. This is largely due to the world of plants that surrounds us, which has been playing an important role in our existence on Earth: it feeds us, provides us with energy, medicine, and ensures our well-being. Humanity's disrespectful and plundering treatment of nature has led to changes that threaten our own existence, and it has turned out that in order to repair the damage, we turn to plants again for help. Plants as sedentary organisms, and in order to survive under sometimes extreme conditions during evolution, they have developed efficient defense mechanisms. The second aspect that makes them an attractive partner is the huge surface of leaves and needles, which is especially valuable in the phytoremediation of the air. Another advantage of plants is the root system ubiquitously penetrates the soil. The advancement of knowledge about plants in such disciplines as plant physiology, molecular biology, toxicology, microbiology, and soil sciences enabled the emergence and development of a new discipline of environmental biotechnology in which plants play a fundamental role-phytoremediation. It is defined as the use of plants to remove pollutants from the environment or to reduce them to less harmful (Salt et al., 1998). Phytoremediation derives from the Greek word 'phyto,' meaning plants, and the Latin word 'remedium,' which means a tool against negative impact. Plants within this technology are used to remove or reduce the level of pollutants in soil, water, and air. Both the world of plants and possible pollution are very diverse and, in each case, different. This requires distinct strategies in each case. As a consequence, phytoremediation applied to different areas of environmental protection differs with regard to goals and performance.

Phytoextraction is the use of pollutant-accumulating plants to remove metals or organic compounds from soil, water, and air by concentrating them in easily harvestable parts of plants.

Phytodegradation, in turn, means the use of plants with their microbiome to degrade organic pollutants. This is the dominant technology in the removal of pollution by crude oil, pesticides, and dyes.

Rhizofiltration is the use of plant roots or root tissue culture on the frame to absorb and adsorb, mainly, metals from the wastewater.

Phytostabilization means that plants with a microbiome can reduce the bioavailability of pollutants in the soil as well as retention for decades in tree trunks.

Phytovolatilization is practically a dilution of pollutants in the air, not always accepted by the public. A phenomenon known in nature as the defense of plants and microorganisms against certain metals.

Phytomining is the acquisition of valuable metals with the help of plants (Au, Pt, Pd. Ni).

A relatively well-known and one of the most common group of pollutants dangerous for all living organisms are heavy metals (HM). The first signals indicating the relationship of plants with some elements in the soil come from the 16th century (Brooks, 1998). The 'father' of botanical taxonomy, Antoine Laurent de Jussieu, distinguished the leadwort family (Plumbaginaceae), represented by species very tolerant to lead – e.g., the Sea Thrift (*Armeria maritima* Willd), the Cape Leadwort (*Plumbago auriculata* Lam.) and some species from genus *Limonium* growing in lead polluted sites. The high metal content of the soil environment, which creates very toxic conditions, can only be tolerated by a small number of species called hyperaccumulators (Brooks, 1998). The list of hyperaccumulators in the entire plant kingdom amounts to 721 species so far, and new ones are still being found. The greatest number of hyperaccumulators was recorded in the taxonomic family of Brassicaceae, numbering 83 species, and the next in the order - Phallanthraceae, with 32 species (Reeves et al., 2017). Due to the accumulation of high concentrations of metals in their tissues, hyperaccumulators are a very interesting group of plants, but unfortunately, they form a small biomass because most of the energy obtained is directed to defense against toxic elements. Only a few species of them make up more biomass, and these are being tried to be used for phytoremediation. The hyperaccumulators are an indicator of the presence of certain metals while these are being mined, and it is important that these species return to the same sites during environmental restoration and phytosuccession, as most of them are endemic (Medianista & Labay, 2017). At the same time, attention is paid to plant species that are not hyper-accumulative but are present in positions contaminated with metals. Both of these groups can be named metallophytes. On the territory of Poland, metallophytes also have been found, such as the Buckler mustard *Biscutella laevigata* L. (Godzik, 1991), the Carpathian carnation *Dianthus carthusianorum* L. (Załęcka & Wierzbicka, 2002), and *Callitriche cophocarpa* water plants tolerant to chromium (Augustynowicz et al., 2010). Knowing the abilities of metallophytes and the fact that they are native species permit us to introduce them to devastated post-industrial areas (Hanus-Fajerska et al., 2019; Muszyńska et al., 2017; Pogrzeba et al., 2019). In the case of heavy HM, we are also interested in phytoextraction. It is true that we are engaging plants in very dirty and dangerous work of removing sometimes very toxic elements introduced into the environment by nature or by humans. Plants take elements from the soil, and more precisely, with soil solution. During this process, undesirable elements can also penetrate through the cell channels. Like in the case of arsenic, which penetrates through the phosphorus channels, thus competing with this element. This phenomenon is utilized in phytoremediation by limiting phosphorus fertilization to the necessary minimum. On the contrary, in countries where cultivated soils contain some arsenic, high-phosphorus fertilization is recommended to reduce the presence of arsenic in the crops (Strawan, 2018). Generally, plants use two major strategies to protect and reduce these non-degradable toxins: avoidance and tolerance. An example of an avoidance strategy is the presence of metal-binding polygalactouronic acid in the mucigel secreted upstream of the root cap to allow it to pass between soil particles and protect the root tip from drought (Wright & Northcote, 1974). Some species create a barrier by the release of sugar callose on the surface of the root (Samardakiewicz et al., 1996). The tolerance strategy involves the inactivation or removal of the toxic metal that has entered the plant. The plant tries to keep the metal taken from the soil in the roots (usually, there is most of it). Smaller amounts are translocated to the stem and much smaller amounts to the leaves. The seeds are the most protected by the plant as they are decisive for the next generation. In the course of evolution, plants have created a number of genes that control the process of taking up elements and their transport to different organs and organelles. This area of knowledge currently has extensive literature (Lane et al., 2016). Transporter genes have been systematized into families, among which one of the best-known and studied is the ZIP family (Krishna et al., 2020). Unfortunately, along with the uptake of the elements necessary for plant life, unnecessary and often toxic metals such as Cd, Pb, or Hg also penetrate. This allows their affinity for the elements that the plants need. One of the ways is protein channels through which the plant takes highly needed elements, and despite their specificity, unwanted elements, too. The entry into the plant by toxic elements has also been confirmed by the use of transporters of elements necessary for the plant. The penetration of metals into plants depends on a number of factors, but the plant thus has a number of tools to control this process. Poles also contribute to the research on this vital process (Antosiewicz & Hennig, 2004; Maślińska-Gromadka et al., 2021; Palusińska et al., 2020). Already in the cell, the plant activates several additional defense mechanisms referred to by most scientists as tolerance. Having no possibility of degrading them, they try to bind them by using the two major processes. The first is the formation of low-molecular-weight, cysteine-rich proteins - metallothioneins that bind and render the metal inactive. Plants, with the help of metallothioneins, not only bind toxic heavy metals but also control the homeostasis of metals necessary for life, e.g., Cu, which in a free form at a higher level becomes toxic to the plant (Fürst et al., 1988; Kumar et al., 2021). Metallothionein genes are found in all living organisms, from bacteria and plants to animals, and, of course, including us. Such omnipresence indicates their key role in protecting against metals throughout the entire evolutionary process. The second dominant process in plant tolerance to heavy metals is the synthesis of phytochelatins by phytochelatin synthase enzyme, using the glutathione tripeptide as a substrate. The generated peptide chains contain from two to eleven glutathione oligomers. The defense mechanism based on phytochelatins is very efficient because each oligomer contains cysteine with a metal-binding sulfhydryl group and, in the presence of glutathione, their efficient, fast synthesis is possible (Hendrix et al., 2020; Li et al., 2020; Wójcik & Tukiendorf, 2011). The defense mechanism of plants is also the change in the valence of the elements on which their toxicity depends. This defense process is known for Cr, where the Cr VI of the plant is reduced to the less toxic Cr III, although the reduction process requires energy (Srivastava et al., 2021).

1.1. Toxic elements uptake from the soil

The plant world varies in tolerance to environmental pollution, and this is where the taxonomy comes in handy, as there are botanical families in which a significant number of species are tolerant (Brooks, 1998). Regarding the phytoextraction of heavy metals, the Brassicaceae family stands out as the source of the greatest number of hyperaccumulators. The weakness of this family is the crumbling of the dry leaves and some of the excavated metal remains on the surface of the soil. In practice, oilseed rape is sometimes grown, which has a large mass of stems and shoots. The oil obtained from such post-industrial areas is used as an additive to fuels.

Noteworthy is the Poaceae family, which has a number of species that meet the requirements for phytoremediation, such as tolerance to contamination with metals and organic compounds and the production of large biomass. A valuable advantage of this family is that the leaves remain dry on the stem, which enables long-term harvesting. The species used are long-straw varieties of wheat and barley. However, the latter species requires more acidic soils. Recently, the recommendations of this group of plants are dominated by *Miscanthus giganteus*, which is not a food plant that creates a large biomass, and as in the case of perennial plants, we cultivate contaminated soil only once at the beginning of plantation establishment.

Another family is Asteraceae, used in the phytoremediation of both heavy metals and organic compounds. A valuable feature of plants from this family is the ability to uptake radioactive elements Cs-137 and Sr-90 (Fuhrmann et al., 2002). The most common phytoremediant of this family is the common sunflower, while in warmer areas than Poland, an attractive candidate is the perennial Jerusalem artichoke.

A smaller number of useful species come from the Betaceae and Amarantaceae families, both of which are related to tolerance to a more acidic soil environment and salinity, which is often the case in degraded areas. Considerable amounts of metals and other elements are taken by plants from the Careophyllaceae family, also from salted sites. In the temperate zone, there are no species that accumulate large biomass. Therefore, they do not play a major role in this technology. There are also single species from other botanical families, such as willow or hemp.

1.2. Heavy metals and metalloids

Forty elements with a molecular weight above 5 g/cm^3 belong to this group. The leading ones are (Pb), zinc (Zn), cadmium (Cd), arsenic (As), mercury (Hg), chromium (Cr), and copper (Cu), and usually one of them dominates. All, except for the mercury, are in solid form, but due to high temperatures during the combustion process, they are emitted into the atmosphere in a gaseous form, and only after cooling down they fall in a solid form at different distances from the emission source. All plants perform phytoremediation by taking up metals dissolved in the soil water from the soil. During the transport of water to the aboveground organs, some are retained in the roots, and some are transported to the stems and leaves. The intensity of uptake of metals from the soil also depends on the properties of a given element and the role it plays in the plant's life. Plants absorb metals from the soil solution, so their solubility in water and soil pH plays a key role. Heavy metals are more soluble in various ranges of soil acidity. Usually, their uptake increases at a lower pH. It should be remembered that most plants tolerate soil pH close to neutral well. Many metals play an important role in plant metabolism, but when their levels are high in the soil, they become toxic to them. On the other hand, due to poor solubility in soil water, the uptake of lead (Pb) and chromium (Cr) by plants is limited to the roots. Although Cr VI is very efficiently taken from the soil solution, after penetrating the root cells as highly toxic, it is reduced to Cr III and retained in them. These two elements in the soil phytoremediation technology are hardly practiced, and their presence in a greater amount in parts of the plants above the soil indicates accumulation from polluted air (Grigoratos & Martini, 2015).

1.3. Noble metals and rare earth elements

Phytoremediation of these elements is carried out for economic reasons on the top layer of areas where industrial exploitation is unprofitable. In one of the first attempts to extract gold with the use of phytoextraction technology, among the assessed species, the Indian mustard *(Brassica juncea)* was the best (Anderson et al., 1998). Platinum and palladium are released from car catalysts and accumulate in the vicinity of highways. The content, in some places, approaches the level of profitability of extraction. Due to their high specific gravity, most are located within three meters from the edge of the road, and most are not further than eight meters (Gawroński et al., 2022; Schäfer & Puchlet, 1998). There are multiple possibilities to recover platinum, palladium, and rhodium from around roads. Plants growing in these areas accumulate noble metals on their aboveground surface and simultaneously absorb them from the soil. Several plant species efficiently uptake noble metals from the ground in the vicinity of roads. The most effectively absorbed from the ground was palladium, followed by platinum and rhodium (Schäfer et al., 1998). Generally, anthropogenic activity introduces smaller amounts of rhodium into the soil environment, but its bioavailability allows it to be uptaken and transported in the plant (Kowalska et al., 2022). Noble metals are less toxic than heavy metals, but their catalytic activity stimulates a number of processes in living organisms, such as photosynthesis and respiration in plants and possibly in animals and humans. This creates concerns regarding possible cancerogenesis. The authors of these results noted the phenomenon of hormesis in all experiments with platinum in low concentrations (Gawrońska et al., 2018). The demand of the modern industry, pushing up the price of precious metals, induces recycling and searching for places in an urbanized environment where they can accumulate in greater amounts. The latter is referred to as urban mining (Gawroński et al., 2022).

Like any technology, phytoextraction has its limits. One of them is the length of the process, usually lasting up to several years. To speed up, chelating compounds are introduced into the soil, and then metals are absorbed in the chelated form in much larger amounts. Initially, with the use of chelating agents, high hopes were raised to enhance the metal extraction process and make the technology more economical. It turned out, however, that the metal contained in the chelate becomes easy to take up, but in this form, it is also easily washed into groundwater. As a result, in most countries, chelates have not been approved for application.

The natural environment functions in a complex system of co-dependencies, ensuring its buffer capacity and support in the difficulties of stabilization. Plants conducting phytoremediation of metals under stressful conditions are supported by mycorrhizal fungi in the process of mycoremediation. Both processes take place simultaneously and are an example of synergy, which ensures the colonization of the contaminated area by both partners. In the case of heavy metals, fungi from order Glomerales are involved in this process. Arbuscular mycorrhizal fungi (AMF), in particular, can greatly improve the phytoremediation capacity of many plants by providing them with phosphorus and nitrogen supply, and water during periods of stress (Zai et al., 2021). There is even direct protection of plants against heavy metals, which are retained in the mycelium of the fungus and do not reach the plant tissues (Dhalaria et al., 2020). Based on this phenomenon, seedlings with mycorrhiza allow the introduction of perennial vegetation and afforestation of areas contaminated with metals (Adriaensen et al., 2006; Turnau et al., 2008).

2. Water phytoremediation

Water is an important component of the environment, but today, its quality and availability have become a great concern. The aquatic environment is polluted by many components: metals, water-soluble chemical compounds, and solid substances such as microplastics. Their reduction is a big challenge. In order to reduce and eliminate these threats, various treatment systems are installed, among them those based on plants and their microbiome. The best known is the use of plants in hydro-botanical sewage treatment plants – constructed wetlands built next to individual houses, livestock farms, or wastewater from food processing factories. In this technology, pollution-resistant macrophytes are used. They are very often obtained from polluted sites in which nature has conducted resistance selections for us. Aquatic macrophytes accumulate pollutants from water efficiently because, apart from the root system, pollutants are collected by other organs immersed in the water. We have three types of aquatic plants used for this kind of phytoremediation. Free-floating plants, submerged plants, and emergent plants. The constructed wetland of the reservoir with floating plants allows it to flow freely and collect the biomass for utilization at the end and let the water flow on. The most commonly used floating plant species are the water hyacinth (*Eichhornia crassipes*.), the common duckweed (*Lemna minor*.), the greater duckweed (*Spirodela polyrhiza*), the water lettuce (*Pistia stratiotes*) and the duckweed fern (*Azolla filiculoides*). Heavy metals' active transport in free-floating plants starts from the roots and reaches other parts of the plant body. Passive transport is associated with the direct contact of the plant body with the pollution medium. In passive transport, heavy metals mainly accumulate in the upper parts of the plant (Ali et al., 2020).

Another group of macrophytes are plants completely immersed in water, defined as submerged, absorbing contaminants by their entire surface (Nyquist & Greger, 2007). They belong to various botanical families. Best known for their phytoremediation abilities in the temperate zone are *Elodea canadensis, Callitriche stagnalis, Potamogeton natans*, and *P. pectinatus*. Free-floating and submerged macrophytes are used primarily for phytoremediation of common heavy metals and metalloids: Cu, Zn, Cd, Pb, As, but also Cr, Ni (Augustynowicz et al., 2020; Delgado-Gonzales et al., 2021.) and U (Favas et al., 2014), and to a lesser extent, also for phytoremediation of organic compounds and textile dyes (Ansari et al., 2020). In emerging macrophytes, the root system develops in soil or sediment, while the upper part of the plant is above the water level. These plants have the ability to bioconcentrate pollutants from water and sediments as well as transport them to above-ground parts. Most of them develop best when the water layer is about 50 cm, but some of them can root up to 2 m. The most widely cultivated species are *Phragmites australis, Typha latifolia, Scirpus* sp., and the tropic *Cyperus papyrus*. In the temperate climatic zone, the first two species are placed at the mouth of rivers, drainage channels for the phytoremediation of nitrogen and phosphorus, which flow from farmlands and lead to the eutrophication of sweet water reservoirs and the Baltic Sea. In the group of emerging water plants, apart from those already mentioned, are often used: *Juncus effusus, Iris versicolor, Phalaris arundinacea, Acorus calamus*, and others present in this area. All three groups of aquatic macrophytes are used in different variants in constructed wetlands for treatment of stormwater, mine-tailing drainage, and landfill leachate treatment systems, but are most commonly used for sewage treatment and wastewater polishing before waters are released to natural waterways (Hassan et al., 2021). Wastewater polishing turned out to be very difficult because of microplastics, fine and ultrafine particles that are not retained, except in very modern sewage treatment plants. Microplastics in water from the sanitary system at home are polyester from washed clothes, polyethylene, and polypropylene from packaging, while in stormwater, it is rubbed from tires and, car brakes, and asphalt. The possibility of improving this state is provided by the constructed wetland, in which the microplastics can be decomposed and removed by bacteria with rates of 81.63% in the surface flow system and 100% in the horizontal subsurface flow system (Chen et al., 2021). Many research centers are currently working on solving the problem of microplastics in the aquatic environment, including the possibility of bacteria capable of decomposing the substance (Wang et al., 2020).

3. Air pollution

Air pollution is defined as the alteration of the natural properties of the atmosphere by any chemical, physical, or biological factor. About 90% of people breathe air that does not comply with the WHO Air Quality Guidelines (WHO, 2021). Every year, 4.3 million deaths occur from exposure to indoor air pollution, and 3.7 million deaths are attributable to outdoor air pollution. Air pollution is natural: volcanic eruptions or sand storms, but the vast majority of it is due to the transport combustion of fossil and wood. Some of these energy sources are non-flammable, or the combustion is incomplete and forms new compounds, for example, benzo(a)pyrene and dioxins, NO_2 and SO_2. These pollutants are largely released into the air. Some of them will drop, while some will remain for a long time. Therefore, our opportunities to remove them are limited. Despite intensive efforts, no industrial system for their removal from the outside air has been developed so far. In fact, we can only count on nature: rainfall and plants. There is no other method or technology to remove pollutants from the outside air around us. From the two mentioned factors, we only have an impact on plants, ensuring their presence in the environment (Gawroński et al., 2017). The deposition of particular matter (PM) on the leaves is greater than the usual fall because thousands of metabolic compounds contained in the leaf create an electromagnetic charge conducive to the accumulation (Gawrońska & Bakera, 2015). Rain removes pollutants from both the air and from the surfaces of leaves, contributing to air purification; however, between rainfalls, only plants accumulate pollutants from the air. Contaminants washed away by rain reach the soil, where the metals are maintained in a sorption complex, and the organic pollutants are degraded at different speeds by the soil metagenome. On a global scale, the most important physical parameter of terrestrial plants in the context of air pollution is their huge biologically active surface, which plays the role of the so-called Earth's lungs. The global leaf area is estimated as 508 million km^2, with only one side of the leaf (Vorholt, 2012). Therefore, exceeds several times the surface of land on the Earth, estimated as 149 million km^2. Assuming that the area of one square centimeter of a leaf is covered with 10^6–10^7 bacterial cells, it is estimated that epiphytic bacteria count up to 10^{26} cells on Earth (Lindow & Brandl, 2003), but plants are associated with many other organisms, such as fungi and archaea, colonize different plant organs and compartments. This close relationship of these organisms functioning in nature is also considered as meta-organisms named a holobiont (Hassani et al., 2018). The aboveground part of the plant called the phyllosphere, creates a large habitat for various microorganisms that show a high degree of adaptation to their environment (Perreault & Laforest-Lapointe, 2021). The microbiome is dominated by bacteria; however, we should remember about the much smaller presence of archaea and fungi. The latter secrete enzymes outside of bodies, so they are the first to disturb the structure of organic pollutants, allowing the bacteria to continue the degradation process (Imperato et al., 2019). The microorganisms present therein are referred to as phyllobiome, which consists of epiphytic bacteria living on the leaf and shoot surface, named epibiome. They are on the front line and are the first to come into contact with polluted air and to start the process of degradation. The second group of phyllosphere is endobacteria, constituting an endobiome. The latter inhabits inside plants, where they have a very stable environment. They live at the plant's expense, but very often, they lead to the degradation of toxins, which the plant is unable to neutralize by itself. Interestingly, some of them are kept only when the plant grows in a polluted area. The underground plant organs, mainly roots, contain large amounts of bacteria deposited on their surface, referred to as the rhizosphere, which, together with a much smaller group of free-living bacteria in the soil, constitute a metagenome. Soil metagenome is one of the most efficient machinery in degrading pollutants in nature, and its efficiency is determined by the presence of plants. Plants increase the amount of bacteria in the soil metagenome up to 100 times or even more (Thijs et al., 2014). Our knowledge of the processes of degradation and detoxification of pollutants in nature has considerable achievements. However, there are still large gaps. Gaseous and solid organic compounds are degraded jointly by plants and microorganisms, but plants run a very rational economy, and often, the obtained metabolites become incorporated into their own organisms. If this is not possible, the common end product is CO_2, which they are able to reabsorb. In this action, we can observe considerable differences between plant species for various pollutants.

4. Outdoor air phytoremediation

4.1. Particulate matter (PM)

Currently, the number one air pollutant is a complex mixture of chemicals in solid or liquid particles suspended in the air to form an aerosol. PM can remain suspended in the air for minutes, hours, days, or even months before settling, mainly depending on their size. PM is assumed to be particles smaller than 100 μm, often being toxins or serving as a substrate for the deposition of other pollutants. Inhaled PM passes into the respiratory tract depending on its size. Large PM particles (10–100 μm) are easily excreted by sneezing and coughing, coarse particles (2.5–10 μm) tend to accumulate in the upper airways, while fine particles (0.1–2.5 μm) and ultrafine particles ($\leq$0.1 μm) particles can reach the lungs. The least is known about the finest ultrafine PM fraction ($\leq$0.1 μm). Unfortunately, as recently confirmed, they can penetrate directly into the brain within 4 to 24 h after exposure (Schraufnagel, 2020). As already mentioned, plants are our only helpers in reducing outdoor air pollution. At the front, there are woody species that form a large surface from the leaves or needles. The group of plants that accumulate PM very efficiently are conifers, and they do it so well that they fall victim to their own abilities. In addition to abundant wax, it is favored by evergreen and often the presence of needles exceeding the period of one year. Consequently, they are rarely used with the exception of yews (*Taxus* sp.). which have a PM removal mechanism and can survive in even very polluted sites. *Juniperus chinensis* is characterized by slightly lower tolerance, while *Pinus nigra* and *Picea pungens* can be planted at some distance from the emission source. We can count on the following deciduous tree known as the potentially good phytoremediation species: *Pinus sylvestris, Betula pendula, Fraxinus pennsylvanicus, Fraxinus excelsior, Pyrus calleryana, Sorbus intermedia, Populus* sp., *Alnus spaethi, Robinia pseudoacacia, Sophora japonicum, Elaeagnus angustifolia, Ligustrum lucidum, Quercus ilex, Tilia europaea* 'Pallida.' Equally excellent functions for phytoremediation perform shrubs that are growing closer to the ground like *Pinus mugo; Syringa meyeri; Spireae* sp., *Stephanandra incisa, Taxus media, Taxus baccata, Hydrangea arborescens; Acer campestre, Physocarpus opulifolius; Sorbaria sorbifolia; Forsythia x intermedia* (Dzierżanowski et al., 2011; Popek et al., 2013; Sæbø et al., 2012; Sgrigna et al., 2015). In the dense buildup city centers where the surface for growing plants is limited, the following climbers can fulfill a role in phytoremediation: *Hedera helix; Parthenocissus tricuspidatea, Parthenocissus quinquefolia, Vitis riparia*, and *Polygonum aubertii* (Borowski et al., 2009; Ottelé et al., 2010) in the cities, vegetation in areas name as urban wastelands plays an important role in PM accumulation, so maybe we named them wrongly (Przybysz et al., 2020).

The list of pollutants in the form of PM is quite long. However, it is dominated by three of them: black carbon particles (BC), microplastics (MP), and organic compounds, most often polycyclic aromatic hydrocarbons (PAH). Black carbon particles are products of incomplete combustion: open fire cookers, fireplaces, and smoking. The direct toxicity of BC is now being investigated more closely, as it was previously considered a less toxic product. However, it is an excellent carrier of impurities on its surface, e.g., metals or organic compounds. BC particles comprise a significant fraction of PM originating from combustion and are commonly referred to as soot. Pure BC, commonly referred to as elemental carbon (EC), as a component of PM, is not considered toxic to human health, but it plays the role of a carrier or vehicle for other toxic compounds on its surface. Their adverse role is strong light absorption and heat generation, and therefore, they directly impact climate change by decreasing the Earth's albedo (EEA, 2013). The BC affects plants similarly, i.e., it increases the leaves' temperature, reduces the light transmittance to the photosynthetic apparatus, and clogs the stomata (Naidoo & Chirkoot, 2004).

Microplastics (MP) are contaminating the air we breathe, the food we eat, and the water we drink. As a consequence, according to researchers from the University of Newcastle in Australia, we consume 5 g of plastics during the week, as they write, the equivalent weight of a credit card (WWF, 2019). Their amount and ubiquity in the air were not expected and have a significant share in the composition of PM because they may constitute one-third of the composition of PM (Gasperi et al., 2018) and are also a carrier of other pollutants. If it is present on the surface when exposed to UV radiation, it decomposes slowly but almost to a chemical molecule (Kleinteich et al., 2018), whereas when covered with soil, it lasts for hundreds of years because the number of microbial species decomposing them is limited. The world is intensively searching for such microorganisms (Dris et al., 2017; Imperato et al., 2019; Lear et al., 2021; Prata, 2018). They are found, but the degradation process, however, is very slow, so the possibilities of its intensification are being investigated.

The five- and six-ring (PAHs) are products of combustion, and they are one of the most undesirable toxins in our environment. They appear in solid form, also referred to as the heavy molecular weight HMW-PAH, and are mostly retained in the cuticle tissue, and their transfer to inner plant components is limited by the diameters of their cuticle pores and ostioles (Molina & Segura, 2021). As a component of PM, it very often acts as a carrier for other pollutants. Benzo(a)pyrene (BaP), known to be carcinogenic and usually present in significant amounts, creates the most concern. The BaP that falls into the soil is retained by the sorption complex, but some of it is taken up by plants and translocated to their organs. However, when taken in larger amounts, it inhibits plant growth (Sun & Zhou, 2016). A number of plant species efficiently degrade BaP in ornamental plants, *Chlorophytum comosum* the metabolic pathway of the decomposition of this compound, has been recognized (Setsungnern et al., 2017). Simultaneously, degradation is carried out by microorganisms. The structure of the compound first disturbs the fungi, which enzymes secrete outside the cells, and usually, bacteria take part in further stages. However, there are species of bacteria that are able to carry out the degradation process from the first stage, including BaP (Nzila et al., 2021). The PM pollution of the plant surface has taken place since their landfall, but some species have created a system of their removal (Barthlott & Neinhuis, 1997). The leaves of these plants are covered with a wax of uneven texture, and the mini-peaks formed are dense and have a smooth surface. On these water-repellent leaves, the particles were removed completely by water droplets that rolled off the surfaces. The leaves of *Nelumbo nucifera* afford a most impressive demonstration of this effect, which is, therefore, called the "Lotus-Effect". Technology is an attempt to utilize this phenomenon on the basis of biomimicry (Yang & Guo, 2015), for example, for self-cleaning walls in skyscrapers.

4.2. Gaseous pollutants

The list is opened by one of the very dangerous gases, which is carbon monoxide (CO). It is toxic to both humans and plants, but during evolution, plants created a system of detoxification, mainly by further oxidation to CO_2 or reduction to carboxylic group COOH. Many years ago, the enormous threat of this gas highlighted the role of 35 plant species in its liquidation. Seventeen of them made this process very efficiently, including woody species, such as *Acer saccharum, A. saccharinum, Gleditsia triacanthos, Pinus resinosa, Populus nigra*, *Fraxinus pennsylvanica*, and two shrubs species *Syringa vulgaris* and *Hydrangea* sp. (Bidwell & Bebee, 1974). Recent studies have shown that microorganisms capable of oxidizing CO are abundant in both marine and soil samples (Bay et al., 2021; Cordero et al., 2019). As recently demonstrated by Palmer and his colleagues (2021), in the phyllosphere microbiome, 25% of species have genes responsible for CO oxidation. Taking into account the size of the surface of the phyllosphere and its direct exposure, it can be assumed that plants, together with their microbiome, play one of the most important roles in the global transformation of this gas and its mitigation.

The atmosphere is often contaminated with nitrogen-containing gasses such as NO_X and NH_3 in both outdoor and indoor air. Usually, higher concentration indoors is due to additional emission sources. In urban areas, NO_x (primarily NO_2) are dominant, which are the result of vehicular emission. Plants are capable of utilizing nitrogen in the form of NO_2, as proved by the Japanese scientist Morikawa and his team (1998). They investigated the ability of 217 herbaceous and woody species to take up NO_2 and discovered significant differences in uptake and assimilation between them. They reported the following woody species to be the most efficient: *Magnolia kobus, Eucalyptus viminalis, E. grandis, E. globulus, Populus nigra, Populus* sp., *Robina pseudoacacia, Sorbaria japonicum, Prunus cerasoides* and as herbaceous species: *Nicotiana tabacum* and *Erechtites hieracifolia* calling them NO_2-filice. Further investigation on 70 species of woody plants recommended for cultivation in the vicinity of heavy traffic roads revealed greater differences in the response to NO_2. Among the tested species, *R. pseudoacacia, S. japonica, P. nigra*, and *Prunus lannesiana* proved to be the most tolerant to high levels of NO_2 and efficiently assimilate this form of nitrogen. Therefore, they are recommended for air phytoremediation (Takahashi et al., 2005). Ammonia (NH_3) is also considered to be one of the primary N-containing air pollutants. All plants are able to take up ammonium directly from the air to a certain extent. Adverse effects on vegetation occur when the rate of foliar uptake of NH_3 is greater than their level of tolerance (Ghaly & Ramakrishnan, 2015).

Ozone (O_3) contained in the troposphere, with its enormous oxidation capacity, is a threat to every living organism, including plants. Significant inter-specific and intra-specific differences in ozone tolerance are noted, depending on the genetically determined potential of the antioxidant system. As a result of climate change, temperatures above 30 °C and direct sunlight lead to the conversion of NO_2 to O_3 and their enhancement. Ozone penetrates the apparatus through all leaf stomata, giving characteristic symptoms of simultaneous damage to the entire surface. The above-mentioned conditions are to a large extent present in Southern Europe, but recently more and more often in our country. In recent years, studies have been undertaken on the active protection against ozone damage in plants by the application of synthetic antioxidants, i.e., ethylene diurea (EDU) to *Fraxinus. excelsior* (Paoletti et al., 2007) and *F. ornus* (Salvatori et al., 2017), previously damaged by ozone. The application of EDU turned out successful against ozone-induced injury.

In many countries around the world, the problem is air pollution with sulfur dioxide SO_2. In Poland, we encounter this problem very rarely, and even in some areas, as it was necessary to fertilize agricultural lands with this compound.

4.3. Gaseous organic compounds

Their list in rooms is opened by formaldehyde (Zhou et al., 2011). It is ubiquitous in the environment and generated by numerous natural sources, but high levels are achieved through anthropogenic activities such as industrial emissions and transport. It is used in the production of resins as a disinfectant and fixative (plywood furniture) and as a preservative. All these products are the main sources of formaldehyde, especially in rooms where we incinerate kitchens and fireplaces (WHO, 2010). The natural origin of formaldehyde favored the evolution of its degradation mechanisms. This can be performed by some plant species that make this process very efficient and are the basis of phytoremediation (Shao et al., 2020). The degradation of formaldehyde in plants is caused by formaldehyde dehydrogenase, leading it through acid metabolites to CO_2, which, in the process of photosynthesis, is incorporated into its glucose product (Schmitz et al., 2000).

Benzene, ethylbenzene, toluene, and xylene (BETX) are usually present in low concentrations but can occur in both indoor and outdoor air, with the usual dominance of the first one. However, indoor concentrations are generally higher than outdoor (transport) concentrations due to the existence of additional sources (cooking system, solvents, etc.) also taking place. The toxicity of benzene, including its carcinogenicity, is widely known, but it causes many other injuries (WHO, 2010). After penetration in plants, the cyclic hydrocarbons are transformed by oxidative reactions and conjugated with cell endogenous compounds. The initial stage of oxidative degradation consists of hydroxylation reactions. The aromatic ring can then be cleaved and degraded into organic acids of Kreb's cycle (Mithaishvili et al., 2005).

Three and four-ring aromatic hydrocarbons (PAHs) are mainly combustion products from the transport, industry, and fireplaces. The absorption of low molecular weight (LMW-PAHs) to the inner tissues of the leaf is mainly conducted by passive diffusion through the hydrophobic cuticle and the stomata (Molina & Segura, 2021). As the number of rings increases, the toxicity of aromatic hydrocarbons increases and the carcinogenicity of some of them is already noted in tetracyclic hydrocarbons. Plants, along with the microbiome, degrade gaseous forms of LMW-PAH (Yutthammo et al., 2010).

Biogenic volatile organic compounds (BVOCs) are natural organic compounds and should also be taken into account as substances polluting the air as they are released into the environment in considerable quantities. Plants, as sessile organisms, use such compounds to defend themselves against pathogens, herbivores, and other stress factors. Typically, these are compounds of low molecular weight, including isoterpenes, monoterpenes, sesquiterpenes, and other C10–C15 chemical structures (Curtis et al., 2014). BVOCs are easily released to the atmosphere in gaseous form, and in the presence of NOx and light, they contribute to photochemical reactions involved in the formation of secondary pollutants. The introduction of biogenic and anthropogenic VOC shifts the equilibrium of the atmospheric processes in which NO and NO_2 are involved toward higher ozone contents (Calfapietra et al., 2013). Studies allowed distinguishing between two groups: low BOVC and high BOVC emitting plants. The low BVOC emitting group of plants includes genera such as *Malus, Camphora, Citrus, and Pyrus* and species such as *Ginkgo biloba* and *Juglans nigra*. High-emitting BVOC plants belong to the following genera: *Salix, Quercus, Populus, Pinus*, and *Liquidambar* (Calfapietra et al., 2013; Curtis et al., 2014).

Plants, together with their microbiome, take up and accumulate all forms of pollution in the above-ground part, and by shedding leaves, they give us a chance to remove them from the environment.

5. Indoor air phytoremediation

5.1. Pollutants and sources

Clean air in rooms where we stay is crucial for our health because we spend up to 80% of our time there (Russell et al., 2014). It must be taken into account that air in rooms is often more polluted (usually 2–3 times or more) than outside because there are additional sources of pollution, such as building materials, furniture, cleaning agents, cosmetics, and microplastics from equipment and materials. Indoor plants try to clean the air they use and, therefore, carry out the phytoremediation process. Some of them do it more efficiently than others, though. Indoor plants additionally optimize the environment and ionization level, emit oxygen, regulate air humidity, limit the bacterial population with biocide compounds, and improve our well-being in general (Kuo, 2015; Montacchini et al., 2017). The latter is particularly important now - during lockdowns related to the COVID-19 pandemic (Dzhambov et al., 2021). There is also a hypothesis that contact with nature is beneficial for our microbiome by increasing its richness and potential (Robinson et al., 2021; Rook, 2013). Plants trap air pollutants in the ground part and in the soil, which get there with the air while the soil in the pot drains. During watering, the expelled air is significantly cleansed. The soil-free-living bacteria and rhizobacteria that lead this process are very efficient. They degrade 50% or more of pollutants (Kim et al., 2008). The inside air is in some balance with the outside air, so after a while, we have all the contaminants present outside as well additional sources of contamination, such as building materials, furniture, cleaning agents, cosmetics, and microplastics abraded from equipment and materials. As we can see, the list of PM pollutants in the rooms where we are staying may be relatively long. But in recent years, we have been additionally concerned about a significant proportion of microplastics (MP), which has been identified in the composition of PM, reaching one-third of its amount (Gasperi et al., 2018). The harmfulness of MP to humans and the environment is being intensively studied (Dris et al., 2017; Kannan & Vimalkumar, 2021; Prata, 2018; Zhang et al., 2020).

The list of indoor gaseous pollutants is opened by benzene (WHO, 2010), which can originate from outdoor air and indoor sources. Therefore, new buildings or recently renovated indoor environments have been associated with high concentrations of benzene from materials and furniture and the existence of many additional sources (cooking systems, solvents, etc.). The toxicity of benzene, including its carcinogenicity, is widely known, but it causes many other injuries (WHO, 2010). Several plant species efficiently degrade benzene, most often in the first stage by oxidation to phenol. It can be done by *Chlorophytum comosum* grown in our homes and green walls (Setsungnern et al., 2017). As demonstrated by the example of six species of ornamental plants, both endophytic and epiphytic bacteria also actively participate in the process of benzene degradation (Sriprapat & Thiravetyan, 2016).

Highly ranked on the list of gaseous pollutants in the rooms is formaldehyde (Zhou et al., 2011). This compound is ubiquitous in the environment formed by numerous natural sources, but these are at very low levels or not at all. However, high levels are achieved through anthropogenic activities. It is used in the production of resins, utilized as a disinfectant, fixative for plywood furniture, and as a preservative. All of these products are the main sources of formaldehyde, especially in kitchens and fireplaces (WHO, 2010). The natural origin of formaldehyde contributed to the evolutionary creation of mechanisms of its degradation, including some species that make this process very efficient, and these can be used in phytoremediation (Shao et al., 2020). Formaldehyde dehydrogenase causes degradation in plants by leading it through acid metabolites to CO_2, and this is incorporated into glucose in the assimilation process. Schmitz and colleagues (2000) have followed this process on two species, *Epipremnum aureum* and *Ficus benjamina*, known for their high phytoremediation abilities.

Naphthalene is the only bicyclic aromatic hydrocarbon found in small amounts in some organisms. It is produced in large amounts because it is a precursor for other chemicals, and many of them are in our environment, being the source of naphthalene. Fortunately, it is not too toxic, and as long as it does not exceed the level of 1 $\mu g/m^3$, it is not a threat (WHO, 2010). Plants break down naphthalene (Mohapatra & Phale, 2021) with their rhizobacteria (Schwab et al., 1998).

The indoor pollutants discussed above are present in varying amounts but are almost always present, while the three others considered by WHO (2010) to be equally dangerous occur accidentally. Most often, we can meet with CO plants grown at home. If the gas is in low concentrations, it is efficiently removed and used by them. Unfortunately, if it occurs in high concentration, it is similarly toxic to both humans and plants.

Radon is a derivative of uranium (^{238}U), which is contained in many rocks, usually in small concentrations of 1–3 ppm. The next stage of its decomposition is radium (^{226}Ra), a parent of the most stable isotope of radon (^{222}Rn). It is a naturally radioactive gas and the main radioactive factor in human exposure. Radon formed by the decay of radium in soil and rocks and entering the indoor air spaces of buildings (mainly in the basement parts) or other enclosed locations may reach concentrations of concern for health. Lung cancer is a major risk related to long-term exposure (WHO, 2010). The plant *Tillandsia brachycaulos* epiphyte from the family Bromeliaceae was effective in reducing airborne Rn via the leaves. The specialized trichomes on the leaves, densely covering the leaves of *Tillandsia*, play a major role in Rn uptake as they increase the surface area, and their wax-coated trichomes on the leaves accumulate liposoluble Rn (Li et al., 2017).

Trichloroethylene (TCE) and tetrachloroethylene (PCE), these two chlorinated ethylene compounds, are used in several sectors of the economy on a large scale, thus getting into the environment, including our homes. It is disturbing because their level in urban areas exceeds WHO (2010) standards. In the first years after synthesis, it served as a disinfectant and then a cleaning agent. It has now been discontinued due to its strong narcotic and carcinogenic properties. TCE is mainly used for the vapors degreasing and cold cleaning of manufactured metal parts (80–95% of consumption). Unfortunately, during these activities, it is released into the environment. It is still used as an ingredient in adhesives, paint removers, typewriter correction fluids, and spot removers. TCE in laundries was replaced with PCE, but both compounds, despite their poor solubility in water, managed to contaminate ground waters, from where they steam into our homes and locally to drinking water. Currently, it is not allowed to pour liquids from laundry, degreasing machines, or stored weapons into the sewage, but many places are already heavily polluted. To prevent contaminated water from reaching drinking water intake points, it is pumped out, and these compounds are evaporated. In practice, whenever possible, it is usually done with poplar plants that act as solar pumps (Ferro et al., 2001). The fate of TCE in poplar plants was studied. Plants are able to take up TCE and metabolize it to trichloroethanol, trichloroacetic acid, and dichloroacetic acid. It has also been shown that poplars transpire TCE in measurable amounts, and some quantities are retained in the tissues. So, it has been proven that they are suitable candidates for being phytoremediants (Newman et al., 1997).

5.2. Plants and recommendations

All plants perform phytoremediation but vary in efficiency. There is a range from tolerance to high contamination to stunted growth and dieback. This differentiation applies to each of the air pollutants. In such conditions, the list of species is not very long because there is no taxon tolerant to all factors. Therefore, in indoor phytoremediation, it is recommended that species biodiversity be preserved. One relationship that has been noted is that tolerant species usually have a very efficient redox system for scavenging free radicals (Pandey et al., 2015). Nonetheless, the species recommended for phytoremediation, in addition to tolerance, must lead to the inactivation or degradation of these undesirable substances. Most plants are descended from the lower layers of a tropical or subtropical environment, which allows them to grow and bloom in limited sunlight and, therefore, to perform photosynthesis in domestic lights. The list of indoor ornamental plants recommended for phytoremediation includes several dozen species, starting from the list of Dr. Wolverton (2008), the "father" of indoor phytoremediation, review articles prepared in subsequent years (Cruz et al., 2014; Kim et al., 2008; Yang et al., 2009) and recently published by Bandehali et al. (2021). The list compiled by Dr. Wolverton included 50 species exposed to formaldehyde and some species to other air pollutants. Additionally, the influence on indoor humidity and plant resistance to pests was assessed. The taxonomic Palm family (Arecaceae) ranks high on this list: *Rhapis excels, Chrysalidocarpus lutescens, Chamaedorea seifrizii*, and *Phoenix roebelenii*. The last three species are too large for apartments, so they are mainly used in representative spaces. In the first study, the Moraceae family was also highly rated. In-home conditions, we mainly grow *Ficus elastica, F. maclellandii, F. benjamina*. Other authors mention two more species: *F. benghalensis* and *F. religiosa* (Ter et al., 2020). The last species protects man medically and, as the name suggests, also spiritually. *Ficus benjamina* is the most popular. It tolerates pruning well, and it allows for its spatial location in the room. In this first list is a significant number of genera and species from the Araceae family: *Anthurium andraeanum* and *Philodendron erubescens. P. selloum, P. oxycardium, P. tuxla*, *Spathiphyllum* sp., *Epipremnum aureum*, *Homalomena wallisii*, *Syngonium podophyllum, Diffenbachia* sp., and *Zamioculcas zamiifoli*. An interesting fact is that *E. aureum* has the ability to absorb and break down nicotine (Weidner et al., 2005). The family of Asparagaceae with *Chlorophytum comosum*, which deserved in the amount of absorbed and degraded pollutants and the study of these toxins in the plant. In practice, it is valued for the ease of reproduction and high tolerance to not-always-good treatment. In this family, the genus *Dracaena* is highly ranked with the species *Dracena deremensis*, with indication cultivars: '*Janet Craig*' and '*Warneckei*' as well as *D. fragrans and D. marginata*. In the study by Wolverton (2008), ferns also have a place. He lists two species, *Nefrolepis exaltata* cv. 'Bostonensis' and *N. obliterate*. The *Osmunda japonica* fern deserves our attention in assessing the ability to absorb formaldehyde by 86 species turned out to be the most effective (Kim et al., 2010). The Araliceae family is represented by *Schefflera actinophylla*, frequent in our apartments, and *Hedera helix* climber - in our conditions growing indoors and outdoors.

The situation of indoor phytoremediation is different in the bedroom, where we sleep and breathe, increasing the level of CO_2. Plants will also contribute to this. Increased CO_2 levels during sleep have a negative effect on our condition on the following day and, to a lesser extent, on the following days (Strøm-Tejsen et al., 2016). Fortunately, not all plant species contribute to the accumulation of CO_2 in our bedroom, and even on the contrary, absorb it and improve our sleep conditions. This is done by plants with a photosynthetic CAM pathway (crassulacean acid metabolism) able to absorb CO_2 at night. The plant world also has facultative CAMs, which activate this system under stress conditions, usually drought or intensive light (Sriprapat & Thiravetyan, 2013). The epiphytic species from two botanical families, the Orchidaceae kept in our rooms - *Phalaenopsis* sp. and *Dendrobium nobile* and from Bromeliaceae, the most frequently *Guzmania* sp. and *Aechmea fasciata*, are perfect for this task. It is believed that these tropical tree-dwelling species are exposed to many gaseous organic substances and are able to detoxify a number of gaseous toxins, and the preliminary results confirm this. Often placed in the bedroom as CAM plants are *Sansevieria trifasciata* (Asparagaceae), especially its erected form, as convenient for placement. Advantageous is also a CAM plant, *Aloe barbadensis* (Asphodelaceae), with dense foliage that takes up not a lot of space. In addition to this short list of ornamental plants with the photosynthetic CAM system, there are species that become facultative CAMs under stressful conditions: drought, intense light, and sometimes an air pollutant. The best-known representatives are *Zamioculcas zamiifolia* from the Araceace family and *Kalanchoe blossfeldiana* from the family Crassulaceae. Botanical air filtration's efficiency is linked to their main life processes: photosynthesis and respiration. Plants absorb the surrounding air while they emit oxygen and CO_2 at night (most plants), significantly changing its composition.

The ability of plants to remove contaminants is relatively accurately determined by weight per unit area of the plant leaf and by time (mg m^{-2} h^{-1}) and also can be helpful in assessing the required leaf area and, thus, the number of plants. The positive changes in the air throughout the room can be obtained by increasing the number of well-developed plants or the dynamics of airflow. Most of the information on the abilities of plants to reduce the level of contamination has been obtained under controlled experimental conditions. A number of teams also assessed the feasibility of indoor phytoremediation under real-world conditions. According to Wolverton et al. (1989), the minimum number of plants is at least two good-sized plants for every 9.3 m^2 of internal space. In another experiment, in the real situation of an office with an area of 100 m^2, a positive effect was obtained by placing 22 plants from six species in this area (Kim et al., 2011). Wood with the team (2006) assessed the possibility of reducing total volatile organic compounds (TVOC) below the permissible level of 100 ppb in the buildings In 60 offices with an area of 10–12 m^2 with the use of dracaena (*D. deremensis* 'Janet Craig'), the reduction to the acceptable level was already achieved with three plants. In a summary of these and other authors' results (Kim et al., 2011; Pegas et al., 2012; Song et al., 2007) in a room with an area of 25 m^2, it is recommended to keep 5 to 8 well-developed, meaning growing in pots with a diameter of 25 to 30 cm, with preferences for different plants species. The recommended number of plants in pots is probably minimal to obtain the removal of pollutants. We will intensify the process by increasing the number of plants (as in the case of green walls) and for many species - by intensifying the lighting (Song et al., 2007). There are several technical solutions, including a recently developed efficient system when air first penetrates the substrate in the pot and then flows on the above-ground part of the plant. The last variant, known as active green walls, is in competition with technical purifiers. The key elements, which are filters, raise more and more problems with their disposal. They are saturated with toxins and end up in landfills where their detoxification by nature can take up to hundreds of years (Chamas et al., 2020). Biological filtration deactivates pollutants and, if possible, allows for the use of them as substrates in the metabolic processes of the plant. In other words, zero waste for this group of pollutants is emitted, and indestructible metals are accumulated in the sorption complex of the substrate from which they can subsequently be recovered.

By inviting nature to our homes, we can make our surroundings safer, fulfill our biofilling desires, and improve our mood - so their presence in our homes seems to be something obvious.

6. New challenge

Per- and polyfluoroalkyl substances (PFAS) are man-made chemicals that do not occur naturally. The first compounds from this group were synthesized in the 1930s, with the most famous Teflon, created in 1938 (Trier et al., 2017). Their specialized use limited their production and application while appreciating their properties. New compounds are being created all the time. Because of their extreme persistence and bioaccumulation, they become ubiquitous in our environment and, in some places, appear in amounts that are hazardous to human health. PFAS can repel water, fat, and dirt and are resistant to aggressive chemicals and physical strain. Due to these unique and desirable properties, they have numerous uses in industrial and commercial products, such as fire-retardant foam, household appliances, water, and grease repellants. These compounds have a special chemical structure, multiple fluorine atoms attached to an alkyl chain. The bond between carbon (C) and fluorine (F) is one of the strongest bonds known. Additionally, the size of the fluorine atoms is just right to pack closely around a carbon chain and shield it from interaction with other atoms (Krafft & Riess, 2009). Environmentally, once PFAS are released into the environment, they will stay there and potentially contaminate the environment for decades. Their properties allow them to be located in water, soil, air and taken by plants, so they reach animals and us. PFAS with hydrophobic carbon–fluorine (C–F) bonds forming a "tail" and hydrophilic functional groups forming a "head" compounds with this structure are referred to as amphiphilic, which allows them to be present in the entire environment and, after degrading the functional group, also in the air. Introduced into the environment, they circulate in a bio-cycle, increasing their presence every year and giving them the colloquial name of 'unforgettable chemicals.' After decades of accumulation, they are now almost everywhere in the environment, putting us at risk of chronic exposure. PFAS may act as endocrine and metabolic disruptors, increase cholesterol levels, adversely impact the immune system, and cause cancer of the liver, kidney, and thyroid (Cousins et al., 2020).

Their presence in water predominates, and this is the main way to enter our body; ingress with food is the second, and the third takes place if they are present in the air.

Effective uptake of PFAS offers the benefit of using this mechanism as a tool to remediate PFAS from contaminated soils and air. Short-chain PFAS taken by plants can readily be translocated to the leaves, whereas the roots adsorb more of the long-chain compounds (Jiao et al., 2020). In general, plants take up organic compounds from the soil, although PFAS as amphiphilic compounds are taken up very easily. The translocation is dominated by their distribution in vegetative organs, mainly in intensively transpiring leaves (Jiao et al., 2020; Xu et al., 2022). The accumulation of PFAS in the eatable plant organs in an increased amount allows for the grouping of vegetables from the highest to the lowest as follows: leafy vegetables > root vegetables > floral vegetables > shoot vegetables, which may be important as dietary intake is identified as one of the dominant routes of exposure on these chemicals (Xu et al., 2022). PFAS in the air occur in the vicinity of the production site of these compounds (Brandsma et al., 2019) and is used in technological processes (refining industry) in landfills. They also can be raised by stormy sea (as they are often present on the water surface). PFAS in the air occur in two forms, gaseous and solid deposited on the surface of particulate matter (PM). The gaseous form penetrates the plants through the stomata, while the solid has a chance to diffuse into the plant when it is caught on the surface of the organs with wax. Plants take up PFAS from the surrounding environment simultaneously, but unfortunately, they are unable to degrade them. It is also difficult to manage plant material by combustion because most compounds require combustion temperatures above 2000 °C. Therefore, we need more effective and cheaper ways of disposal.

Pollution with PFAS is currently a challenge, but many biologists believe that there is a chance to find or develop a consortium of microorganisms that, together with the plant, would form a holobiont that degrades these compounds (Mei et al., 2021). The human-induced ubiquity of PFAS in nature, due to its scale, cannot be eliminated or even limited by technical methods. The hope is to use the forces of nature that must be supported by us so plants with their microbiome have a chance to play a crucial role in this process.

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