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Mierzejewska-Sinner, Elzbieta; Urbaniak, Magdalena; Inui, Hideyuki; THIJS, Sofie & VANGRONSVELD, Jaco (2024) Cucurbit plants for remediation of soils polluted with persistent and emerging organic pollutants: State of the art, future perspectives and challenges. In: Phytomanagement as a nature-based solution for polluted soils, 109, p. 217 -254.

DOI: 10.1016/bs.abr.2023.10.004
Handle: http://hdl.handle.net/1942/44884

Running title: Cucurbits for organic pollutants removal

Cucurbit plants for remediation of soils polluted with persistent and emerging organic pollutants: state of the art, future perspectives and challenges

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Abstract:

Several members of the cucurbit family (*Cucurbitaceae*) have a great potential to take up highly hydrophobic compounds, such as persistent organic pollutants (POPs), from environmental matrices, and translocate them to the aboveground parts of the plants. Moreover, recent research showed that they can effectively enhance the removal of emerging organic pollutants (EOPs) from the environment. Several studies provided evidence that plant-associated microorganisms and root exudates (including plant secondary metabolites, PSMs) can enhance the effective removal of POPs and EOPs from environmental matrices (*i.e.* soil, sediments, water reservoirs) by cucurbits. Hence, the main aims of this chapter are: (i) to gather information about processes underlying an exceptional ability of cucurbits to accumulate hydrophobic compounds; (ii) to combine the most pronounced and recent data on the removal of POPs and EOPs using cucurbits; and (iii) to point out opportunities and challenges for the use of cucurbits as phytoremediators of polluted environments.

Key words: persistent organic pollutants, emerging organic pollutants, cucurbits, phytoremediation, major latex-like protein, plant growth promoting microorganisms, root exudates

1. Introduction

As a consequence of the rapid development of modern society significant quantities of organic chemicals have been released into the environment. Many of them have been used as pesticides, defoliants and industrial chemicals or produced as undesirable industrial by-products, exerting mutagenic, immunotoxic and carcinogenic effects on living organisms (Ehrlich et al., 2023; Nazhmetdinova et al., 2017). Slow decomposition of organic pollutants in the environment causes major hazards for living organisms especially due to their ability to bioaccumulate and biomagnify within food chains (Gui et al., 2014; Nfon et al., 2008).

Therefore, new methods for safe removal of these pollutants are required. One of such method is undoubtedly phytoremediation, which is a cost-effective and environmentally-friendly *in situ* technique that uses plants to translocate, transform or mineralize xenobiotics to less toxic or environmentally-neutral compounds. According to Cunningham et al. (1996), Cunningham & Berti (1993) and Macek et al. (2000) phytoremediation is defined *as the use of green plants to remove, contain, or detoxify environmental contaminants*. Plants used for phytoremediation purposes are characterized by several traits such as: fast growth rate, high biomass production, pollutant accumulation capacity and tolerance to high concentrations of xenobiotics (Schwitzguébel, 2017). Additionally, plants play a crucial role in development of soil structure and stabilization of fundamental soil ecosystem functions. They serve as a primary source of organic matter and energy that stimulates soil microbial activity (Machado et al., 2018). Plants also possess an array of catabolic enzymes, which operate to protect them and detoxify xenobiotic compounds (Singer et al., 2003). Therefore, phytoremediation not only contributes to the removal of pollutants, but also has a positive influence on its functioning. The process of pollutants uptake by plants depends on several edaphic factors such as: regional climate, soil type, and the characteristics of the pollutant (Reshma & Krishna, 2012). Further, accumulation of organic pollutants in plants is determined by their octanol-water partition coefficient (K_{ow}) which describes the hydrophobicity of a given organic pollutant (Collins et al., 2006; Fujisawa, 2002). The $\log K_{ow}$ usually ranges from -4 (extremely hydrophilic compounds) up to 10 (extremely hydrophobic compounds) (Cumming & Rücker, 2017). One of the first studies on the K_{ow} of pollutants and their uptake by plants via roots was published by Burken & Schnoor (1998), who investigated the dependency of different organic pollutants K_{ow} and their uptake by plants in hydroponic cultivation systems. The results showed that the transpiration stream concentration factor (concentration of pollutants in the xylem sap divided by the concentration in the hydroponic solution; TSCF) value had a Gaussian distribution with a maximum when the logK_{ow} of the pollutants was 2.50. In another study by Briggs et al. (1982), the authors found the maximum value of logK_{ow} to be 1.78 for barley, whereas in the study by Hsu et al. (1990) who used soybean, the maximum value was 3.07. Based on these results, it can be assumed that compounds with logK_{ow} between 2-3 are more likely to be transferred to the above-ground parts of the plants via the transpiration stream from roots. However, organic pollutants often are characterized with higher values of logK_{ow} (Table 1) and they do not easily dissolve into the soil solution, from which they could be taken up by plants (Briggs et al., 1982). Based on the above-mentioned reports, it is assumed that TSCF decreases rapidly when logK_{ow} exceeds 5, and that little or no pollutants with higher logK_{ow} are transferred from the roots to the above-ground parts of the plants. A similar trend was also reported using tomato and soybean (Dettenmaier et al., 2009). Hydrophobic compounds that are not transferred to the above-ground parts can be accumulated in the roots. Hence for the efficient removal of pollutants by plants via roots and their systemic transfer into the aerial parts of plant, it is important to target pollutants characterized with logK_{ow} within wide range of values (Table 1). Therefore, the effective removal of a given pollutant from soil requires the selection of appropriate plant species and their cultivars (Machado et al., 2018).

[insert here Table 1; Table 1. Examples of octanol–water partition coefficient values (log K_{ow}) for POPs and EOPs.]

A great deal of studies showed that members of the *Cucurbitaceae* family, developed a considerable potential for: uptake of phosphorus surplus (Sharma et al., 2007); heavy metals (Ciura, Poniedzialek, et al., 2005) and radionuclides (S. Ali et al., 2022). Several review papers on the removal of anthropogenic pollutants using phytoremediation have mentioned cucurbits as effective phytoremediators (Vergani et al., 2017; M. Whitfield Aslund et al., 2010); and the number of studies on cucurbits and their potential to remove POPs and EOPs are consistently growing (Figure 1), expanding our knowledge in the field of removal of hydrophobic pollutants by plants from this particular family. Additionally, more studies attempt to explain the transportation of these pollutants within cucurbits more methodically.

[insert Figure 1 here; Figure 1. The number of documents indexed in the Web of Science database (cucurbit* OR cucurbitaceae OR cucurbita* OR zucchini OR courgettes OR cucurbita pepo OR squash OR pumpkin OR cucumber OR cucumis sativus OR lagenaria OR calarasi OR citrullus OR watermelon OR melon OR momordica) AND (phytoremediation OR remediation OR bioremediation OR rhizoremediation) 03.04.2023 394 searches]

Hence the main aims of this chapter are: (i) to describe the key factors behind the capability of cucurbits to translocate organic pollutants; (ii) to synthesize the information about the role of plant-associated microorganisms and root exudates on the cucurbits phytoremediation potential; (iii) to gather publications demonstrating the effectiveness of selected cucurbits species and cultivars to remove POPs and EOPs from different environments; (iv) to point out opportunities and challenges for the use of cucurbits as phytoremediators of polluted soils.

2. **Characteristics of cucurbits for removal of organic pollutants**

2.1. Transportation of hydrophobic organic pollutants within cucurbits and their accumulation in above-ground parts of plants

Highly hydrophobic organic pollutants from POPs group, such as polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) (hereafter called dioxins) have been reported in crops grown in vicinity of waste incineration facilities (Müller et al., 1994). Hence, to ensure food safety, bioaccumulation of hydrophobic pollutants in crops has been a growing concern since the early 1990s, and accumulation in roots, leaves, stems, and fruits of various plant species has been investigated (Hülster & Marschner, 1993; McCrady et al., 1990; Müller et al., 1993; Prinz et al., 1991). In 1994 Hülster et al. found that hydrophobic organic pollutants, such as dioxins, are taken up and transferred through the roots of selected cucurbits (zucchini, squash, and cucumber) and accumulated in the plants above-ground parts. Subsequently, it was reported that: dichlorodiphenyldichloroethylene (DDE) (White, Wang, et al., 2003), chlordane (Mattina et al., 2004), dieldrin (Otani et al., 2007), and polychlorinated biphenyls (PCBs) (Whitfield Aslund et al., 2010) were also accumulated in the above-ground parts of cucurbits. In addition, drin insecticides, which are rarely detected in the above-ground parts of plants, were found to accumulate at high concentrations in plant from this family (Fujita & Inui, 2021).

2.2.1 Major latex-like protein (MLP) responsible for accumulation of hydrophobic organic pollutants in the aerial parts of cucurbits

Transfer of hydrophobic organic pollutants from roots to stems and leaves is essential for the above-ground accumulation of these compounds in cucurbits (Inui et al., 2011; Lunney et al., 2004). The ability to transfer hydrophobic pollutants within the plants can be different for selected cucurbit cultivars, which are characterized with either high or low accumulation ability (Inui et al., 2011). In order to study the transfer of POPs within cucurbits, Mattina et al. (2004) grew zucchini and cucumber in soil polluted with different isomers of heptachlor epoxide and chlordane. Detection of each isomer in soil, roots, xylem sap and above-ground parts showed similar presence patterns. Obtained findings indicated that hydrophobic pollutants present in the soil, were taken up via roots and xylem sap and subsequently accumulated in the above-ground parts of the studied cucurbits. Dieldrin (Murano, Otani, Seike, et al., 2010) and PCBs (Goto et al., 2019) were also detected in xylem sap of cucurbits, indicating that they were transported to the above-ground parts via the xylem sap. Study of Murano, Otani, & Seike (2010) showed that dieldrin is solubilized in xylem sap of zucchini and cucumber, and that this occurs because it binds to a carrier protein of about 14 kDa. The solubilization of hydrophobic pyrene, a polycyclic aromatic hydrocarbon (PAH), was also found to differ significantly among zucchini cultivars, which show differences in their ability to accumulate hydrophobic pollutants in the above-ground parts. This difference was found to be related with carrier protein composition (Inui et al., 2013): protein analysis showed the presence of a 17 kDa protein (especially in zucchini cultivars, which can accumulate high concentrations of organic pollutants). The amino acid sequence of this protein revealed that the detected carrier was the major-latex protein (MLP), which binds to PCBs and other hydrophobic compounds such as dieldrin and 17β-estradiol (Goto et al., 2019). Whereas MLPs were detected in roots of low and high accumulating cultivars of cucurbits, usage an anti-MLP antibody enabled the detection of MLP in xylem sap of the high accumulating cultivars (Goto et al., 2019). This indicates that the transfer of MLPs to xylem sap is directly related with the above-ground accumulation of hydrophobic pollutants . MLPs in xylem sap, which bind and transport PCBs and dieldrin, have been also identified in cultivars of pumpkin, cucumber, watermelon, loofah, and white-flowered gourd (Iwabuchi et al., 2020). Also, overexpression of the *MLP* genes in non-cucurbit tobacco plants caused accumulation of hydrophobic pollutants in the above-ground parts (Stoykova & Inui, 2021). Hence, these results indicate that the presence of MLPs in the xylem sap of cucurbits is responsible for the transport of hydrophobic pollutants from roots to the above-ground parts of the plants.

2.2. Role of root exudates and symbiotic microorganisms

Due to the existing interactions among plant roots, root exudates, soil and microorganisms, rhizobacteria-assisted phytoremediation is considered one of the most effective method for the removal of organic pollutants (Thijs et al., 2016; Weyens et al., 2009; Zalewski et al., 2021).

Rhizodegradation is a degradation process of organic pollutants in the zone of soil immediately around plant roots (rhizosphere), where the microbial growth and its degradative activity is stimulated by root exudates enriched with plant secondary metabolites (PSMs) (Weyens et al., 2009). The effectiveness of biodegradation in the rhizosphere depends also on the abilities of the microorganisms to settle in the rhizosphere and to adapt to a given pollutant concentration (Lugtenberg et al., 2001).

2.2.1. Significance of plant associated microorganisms

Plant-associated microorganisms (phyllosphere, rhizosphere and endophytic microbiomes) are often described as the most important plant symbionts (Thrall et al., 2007). These microorganisms provide a wide range of benefits for plants, and the plant in return supports the colonization of their rhizo- and endosphere by microorganisms (Figure 2). The relationship between plants and bacteria depends on the degree of plant influence over the bacterial communities (Backer et al., 2018). Rhizobacteria are closely associated with the plant rhizosphere (in proximity of the root surface), whereas endophytic bacteria live inside the host plant for at least part of their life cycle (Afzal et al., 2019). The above-mentioned symbiotic bacteria can enhance plant growth, reduce the impacts of environmental stress and increase the availability of nutrients for plants. For example, research done by A. Ali et al. (2019) showed that the endophytic fungus *Aureobasidium pullulans* can enhance the tolerance of cucumber to higher concentrations of heavy metals in soil.

Literature indicates that cucurbits and their associated bacteria can significantly enhance the removal of POPs from soil (Figure 2). Plant-associated bacteria can improve not only plant tolerance to various environmental stresses, but they can also directly use their own degradative capabilities to metabolize organic pollutants (Glick, 2010). Qin et al. (2014) reported that cultivation of cucurbits on PCB-polluted soil stimulated growth of microorganisms degrading PCBs, probably due to the excretion of root exudates in the rhizosphere. Studies on the plant-associated bacteria showed that exposure to DDE increased the numbers of endophytic bacteria and diversity indices of observed genera in zucchini, indicating the major role of microorganisms for promotion of plant growth in stress conditions (Eevers, Beckers, et al., 2016; Eevers, Hawthorne, et al., 2016). It is worth mentioning that also substances produced by microorganisms can improve the bioavailability of weathered pollutants: amendment of a soil with biosurfactants (rhamnolipids produced by bacteria) increased the uptake of DDE by zucchini and pumpkin cultivars and hence improved the removal of this POPs from polluted soil during the plants growth (White, Parrish, Gent, et al., 2006). A field studies by Eevers et al. (2018) showed that inoculating zucchini cv Raven with a consortium of three endophytic strains: *Sphingomonas taxi*, *Methylobacterium radiotolerans* and *Enterobacter aerogenes* promoted plant growth and simultaneously enhanced the removal of DDE from the studied substratum. On the other hand, White et al. (2006) showed that the bioconcentration factors (BCF) of *p,p*'-DDE in various zucchini cultivars differed significantly (they were enhanced or decreased), when a mycorrhizal inoculum was applied to the root system. These observations indicate cultivar-specific responses to soil amendment with specific microorganisms. On the contrary, cultivation of different zucchini cultivars (*i.e.* Black Beauty and Howden) in PAH-polluted soil showed that the concentration and type of pollutants shapes the plant-associated microbial communities (Pritchina et al., 2011). Ely & Smets (2017) isolated PAH-degrading rhizospheric bacteria from cucumber, which also degrades root exudated aromatic compounds such as flavonoids and simple phenolics. Additionally the study of Al-Awadhi et al. (2009) showed that the soil polluted with hydrocarbons enhances the presence of oil-utilizing bacteria in squash phylo- and rhizosphere. What is more, the number of diazotrophic bacteria was higher in polluted than in pristine sandy non polluted soil. An interesting example of research on the use of cucurbits and POPs-degrading microorganisms is an *ex situ* study on lindane (HCH) degradation by Nanasato et al. (2016). Authors inserted the bacterial gene *linA* (expressed during lindane degradation by *Sphingobium japonicum* UT26) into hairy root cultures of pumpkin cv Heiankogiku. The removal of lindane from the overnight cultures was more than 90%. Li et al. (2021) showed that inoculation of cucumber seedlings with the dibutyl phthalate (DnBP) degrading bacterial strain *Pseudomonas* sp. DNB-S1 did not only accelerate the removal of pollutant in the rhizosphere, but it also alleviated the phytotoxic effects of DnBP on the plant.

In terms of phytoremediation of soils polluted with EOPs, some studies also underlined the changes and functions of plant-associated microorganisms: *e.g.* Mierzejewska et al. (2022) showed that soil pollution with 2-methyl-4-chlorophenoxyacetic acid (MCPA) significantly influenced the structure of the endophytic microbiome in zucchini leaves. What is more, the presence of some potential MCPA-degrading bacteria genera (*e.g. Burkholderia*, *Pseudomonas*, *Sphingomonas*) both in the rhizospheric soil and the zucchini endosphere was confirmed. Another study of Mierzejewska et al., (2023) showed the multidirectional effect of zucchini growth, amendment of soil with syringic acid (PSM) and MCPA pollution on the functional diversity of studied soils. The plant-growth promoting properties of the rhizospheric bacteria *Pseudomonas putida* CSY-P1 isolated from cucumber rhizosphere were also confirmed: this strain was able to degrade p-hydroxybenzoic acid, a strongly autotoxic compound, excreted to the rhizosphere in response to abiotic stress, which limits seed germination and root growth (Chen et al., 2015). Zhao et al. (2012), showed that the rhizospheric bacterial strain *Ochrobactrum haematophilum* (isolated from cucumber) can promote cucumber growth by solubilization of phosphates, production of siderophores and indole-3-acetic acid (IAA). Additionally, the authors confirmed that within 60 h in liquid culture *O. haematophilum* degraded 80%, 85%

and 58% of pesticides: chlorpyrifos (chemical proposed for listing under the Stockholm Convention), β-cypermethrin and imidacloprid, respectively. Derbalah & Belal (2008) suggested that using the endophytic strain *Pseudomonas* sp., isolated from cucumber leaves, can effectively degrade fungicide cymoxanil in aqueous media.

2.2.2. Importance of PSMs for the development of a better cooperation between cucurbits and microorganisms

Often the microbial growth and its degradative activity throughout the rhizosphere are stimulated by root exudates enriched with PSMs (Musilova et al., 2016). Flavonoids, coumarins, phenolic compounds and terpenes, excreted into the rhizospheric soil can: (i) modify soil chemical and physical properties, (ii) serve as allelochemicals, (iii) protect plants against pathogens, and (iv) serve as a substrates or inducers of pollutants catabolic pathways of rhizosphere microorganisms and endophytes (Figure 2) (Pilon-Smits, 2005; Pino et al., 2016; Singer, 2006; Zhou & Wu, 2012). Hence, PSMs significantly contribute to an effective removal of xenobiotics from polluted matrices. PSMs enhance the degree of pollutant removal through either increasing the pollutants' bioavailability in soils or serving as an additional source of carbon and energy for microorganisms (Musilova et al., 2016). It has been also hypothesized that the structural similarity of selected pollutants and PSMs may have a profound impact on the biodegradation of given pollutants (Hu et al., 2014; Uhlik et al., 2013). Usually, PSMs serve as co-metabolites, which provide the energy for microorganisms, whereas the pollutant is being degraded as a secondary substrate (Singer et al., 2003). PSMs can be also used as a primary carbon source by bacterial communities to support their growth and stimulate the expression of desirable genes, involved in the catabolic pathway of a given pollutant.

The exudation of low molecular weight acids such as citric and oxalic acids can significantly contribute to an increase of pollutant bioavailability and thus enhanced phytoextraction of organic pollutants (Gent et al., 2006; White, Parrish, Isleyen, et al., 2006; White, Mattina, et al., 2003). Additionally, Gent et al. (2006) showed that the root exudation of citric acid from zucchini and summer squash is dependent on the phosphorus nutrition. Depletion of phosphorus availability in soil enhanced the excretion of citric acid in the rhizosphere, which was positively correlated with an improved and more efficient uptake of *p,p*'-DDE in the above-ground parts of the plant. It was also implied that this correlation varied considerably between cucurbits species and cultivars. Another example of a research on the effects of cucurbits root exudates on the POPs uptake was described by Ficko et al. (2011). The pretreatment of soil polluted with PCBs with cucurbits roots exudates (by first growing pumpkins in the polluted soil) increased the POPs uptake in the second set of plants (*i.e. Daucus carota* and *Rumex crispus*, *Chenopodium album* and *Plantago major*, and *Biddens cernua*). Also according to Navarro et al. (2009) caffeine amendments of soil polluted with PAHs increased the bioavailability of pyrene in aged soil and sand medium with low organic matter.

Among a variety of PSMs, phenolic compounds (characterized by an aromatic structure and different functional groups) are often excreted under environmental stress conditions. Kruczek et al. (2015) identified several phenolics, *i.e. p*-hydroxybenzoic acid, chlorogenic acid, caffeic acid, syringic acid, ferulic acid and *p*-transcoumaric acid, in different pumpkins cultivars. Among studied cultivars, different amounts of identified phenolics were observed. Another study showed that syringic acid has been added as an amendment to a soil polluted with EOPs such as MCPA in order to enhance the biodegradation of phenoxy herbicides (Mierzejewska, Urbaniak, et al., 2022; Urbaniak, Mierzejewska, et al., 2019). Research by Zhang et al., (2018) showed that root exudates enriched with citric and fumaric acid, stimulated the colonization of cucumber rhizosphere with chlorimuron-ethyl (sulfonylurea herbicide) degradative bacteria *Hansschlegelia zhihuaiae* S113.

3. **Cucurbits for the removal of POPs**

POPs have received the most attention due to their persistence in the environment, bioaccumulation tendency and hazards for biota (Ashraf, 2017; El-Shahawi et al., 2010; Gaur et al., 2018; Jones & de Voogt, 1999; Loganathan & Masunaga, 2015; Schecter et al., 2006; Stockholm Convention on Persistent Organic Pollutants: Text and Annexes, 2019). Originally, the POPs group consisted of 12 compounds (so called: dirty 12) including: PCDDs, PCDFs, PCBs, aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, hexachlorobenzen, mirex, and toxaphene. Currently, the list has been updated and contains 22 chemicals or groups of chemicals such as polybrominated diphenyl ethers (PBDEs), perfluorooctanesulfonate (PFOS) (Stockholm Convention on Persistent Organic Pollutants: Text and Annexes, 2019) and PAHs (UNECE, 1998). Since residues of POPs in the environment became highly persistent and detrimental, the removal of these pollutants is currently a global challenge. The use of plants for environment cleanup is an eco-friendly alternative to conventional remediation technologies. Therefore, below we present examples of research on the use of cucurbits for POPs removal from different matrices (Table 2).

[insert here Table 2; Table 2. Examples of studies on the cucurbits use for the removal of POPs and EOPs]

3.1. Removal of dioxins and PCBs

Worldwide studies have shown that cucurbits readily take up dioxins from soils and translocate them from roots to stems, leaves and fruits (Engwall & Hjelm, 2000; Hülster et al., 1994; Urbaniak et al., 2016). Zhang et al. (2009) showed that in comparison to other plants cucurbits (especially zucchini and pumpkin) were very effective in the uptake of dioxins and its subsequent translocation to the plant aerial parts. TSCF were up to 10 times higher for studied cucurbits than other plants. Inui et al. (2008) showed the differential uptake capabilities of three zucchini cultivars: Patty Green, Black Beauty, and Gold Rush. His research demonstrated also that the dioxin toxic equivalency concentration (TEQ; toxicity parameter determined for individual dioxins and dioxin-related compounds describing the toxic or biological effects in reference to the most toxic dioxin compound - TCDD, Van den Berg et al., 2006) were about 180 times higher in high accumulating zucchini cultivars (*i.e.* Black Beauty and Gold Rush) than in low accumulating cultivar (*i.e*. Patty Green). The authors demonstrated also that dioxins hydrophobicity determines the efficiency of their phytoextraction: the lower the logK_{ow} of particular dioxin congeners the higher their BCFs (ratio of pollutant in plants and soil) (Inui et al. 2008).

Members of the cucurbit family, including zucchini and cucumber, are also able to phytoextract PCBs (Greenwood et al., 2011; Low et al., 2011; Matsuo et al., 2011; Zeeb et al., 2006). Many authors have looked for the factors affecting the effectiveness of this process (Figure 2), *e.g.* White, Parrish, Isleyen, et al. (2006) proved that addition of organic acids such as citric acid enhance the ability of different cucurbits (zucchini cv Black Beauty, summer squash cv Zephyr and cucumber cv Marketmore) to take up PCBs. Whitfield Aslund et al. (2007 and 2008) revealed that the distance from roots to shoots was the main factor influencing the PCB concentrations in aboveground parts of pumpkin cv Howden. Low et al. (2011) also noticed that the cultivation techniques (i.e. nodal adventitious root encouragement) are crucial to improve the uptake and translocation of PCBs within the plant. Inui et al. (2008) revealed that the BCFs of dl-PCBs in the studied zucchini varieties was cultivar specific. Cocultivation of pumpkin and tall fescue also led to a significant reduction of specific PCBs congeners (Terzaghi et al., 2021).

[insert Figure 2 here; Figure 1. Factors determining the removal of POPs and EOPs from environmental matrices using cucurbits; POPs- persistent organic pollutants, EOPs- emerging organic pollutants; PSMs- plant secondary metabolites]

Given the effectiveness of cucurbits for removing dioxins and PCBs, numerous studies have focused on the practical use of these plants to improve the quality of soils polluted with these toxic compounds *e.g.* by application of polluted sewage sludge into the soil. For example, studies by Urbaniak et al., (2016) demonstrated 37% reduction of dioxins concentration from soil fertilized with contaminated sewage by zucchini cv Atena Polka. Application of cucumber cv Cezar resulted in lower removal rate of 24%. At the same time reduction of TEQ concentrations was not only much higher but also more equal among the two cucurbit species being: 68% for zucchini and 66% for cucumber. Other studies by the same authors concerned the possibility of using cucurbits to remove dioxins and dl-PCBs from bottom sediments when applied on land (Urbaniak et al., 2017; Wyrwicka et al., 2014). In this case, cucumber cultivation reduced the concentration of the sum of dioxins and PCBs by 46%, 25% and 15%, and the related TEQ concentrations were reduced by 54%, 31% and 72% respectively for the 3 t ha^{-1}, 9 t ha^{-1} and 18 t ha^{-1} doses of sediment applied on land. Zucchini cultivation resulted in much lower reductions of 25%, 13% and 11% of the sum of dioxins and PCBs, and 22%, 59%, and 71% of TEQ concentrations for the respective sediment doses. Above results showed that in the soil treated with polluted bottom sediment, cultivation of cucumber resulted in higher removal of dioxins and PCBs than for cultivation of zucchini. On the contrary, for sewage-sludge fertilized soil, zucchini was more efficient in removal of dioxins and PCBs (Urbaniak et al., 2017; Wyrwicka et al., 2014). These disparities may be attributed to differences in the composition of the two substrates: sewage sludge contains a number of other pollutants, such as heavy metals, which can adversely affect the health of the plants, and thus influence their remediation efficiency. Sediments in turn have been found to be less toxic to the plant due to high content of iron and calcium which immobilize the metals (Urbaniak et al., 2017).

The high effectiveness of cucurbits was also confirmed in studies on the remediation of sediments from rivers heavily polluted with PCBs. An example of such research are works on the safe disposal of bottom sediments from the Hudson River, which have been historically heavily polluted with PCBs (Urbaniak et al., 2022; Urbaniak, Baran, Lee, et al., 2020a, 2020b; Urbaniak, Baran, Szara, et al., 2020; Urbaniak, Lee, et al., 2020). Studies demonstrated high utility of cucurbits (especially cucumber cv

Wisconsin SMR 58 and zucchini cv ‘Black Beauty’ in practical remediation actions aimed at safe utilization of PCB-contaminated river sediments.

3.2. Removal of organochlorine pesticides from POP group (i.e. DDT/ DDE, dieldrin, endrin, endosulfan, chlordane, heptachlor and chlordecone)

Worldwide studies have mainly shown the effectiveness of cucurbits in removal of DDE (compound formed by the dehydrohalogenation of DDT) (White, 2001). White (2002) studied the availability of DDE in soil for squash, pumpkin, melon and cucumber. The author revealed a significantly higher DDE uptake by squash and pumpkin (BCF=16) than by cucumber and melon (BCF=1.8). Additionally, this study showed that up to 86% of DDE from soil can be transported and accumulated within the aerial part of cucurbits. Authors defined the ability of cucurbits to accumulate high concentrations of POPs as “hyperaccumulating” (which is usually a term reserved for heavy metals accumulating plants) and suggested a possible use of cucurbits for phytoremediation of soil polluted with residuals of highly hydrophobic compounds. Further investigations into the intraspecific variability in DDE uptake by 21 cucurbit cultivars, revealed a 4.6 times higher bioaccumulation potential of zucchini than squash cultivars (White, Wang, et al., 2003).

Only few studies about the use of cucurbits for DDT removal have been published: Whitfield Aslund et al. (2010) studied the accumulation of DDT in pumpkin cv Howden, demonstrating a ca 9 times lower concentration of this compound in leaves as compared to stems. Moreover, the authors revealed that concentration of DDT within above-ground parts of plant (stems and leaves) decreased exponentially with increasing distance from the roots, which is consistent with the finding obtained in the other study for PCBs (Whitfield Aslund et al., 2007). Isleyen et al. (2013) attempted to study genetical basis for

POPs accumulation by cucurbits. For this purpose, low-accumulating cultivars of summer squash (*i.e.* Zephyr and Patty Pan) were hybridized with high-accumulating cultivars of zucchini (*i.e.* Raven and Costata Romanesco). BCF was higher in zucchini-squash hybrids planted in soil polluted with DDT, DDE, DDE, and chlordane, then for parental generation of squash. On the basis of obtained results the authors suggested that the uptake of POPs by cucurbits is controlled either by single gene or single locus.

Several studies investigated the factors influencing the uptake of DDT/DDE by cucurbits (Figure 2). White, Mattina, et al. (2003) demonstrated that the addition of organic acids such as citric or oxalic acid enhanced the DDE concentration in plant shoots up to 66%. Moreover interactions between cucurbits and earthworms (*Eisenia foetida* and *Lumbricus terrestris*) increased the DDE bioconcentration in the plant tissues. The growth of pumpkin cv Prizewinner decreased the concentration of DDE in *E. foetida* and *L. terrestris* by 4 and 7 times respectively (Kelsey & White, 2005). When winter squash cv Baby Bear was grown together with *L. terrestris,* the concentration of DDE in plants was increased by 3 times (Kelsey & White, 2005). Further studies of Kelsey et al. (2011) and Peters et al. (2007) showed that more detailed information on species interactions and soil chemistry (especially soil organic matter content) can predict the bioaccumulation of DDE by plants. Likewise, increased soil moisture and higher planting density led to enhanced accumulation of DDE in cucurbits, while plants age was inversely related to their uptake capabilities (Kelsey et al., 2006; White, 2009; White, Parrish, Gent, et al., 2006). Another study confirmed that cultivation conditions (dense, non-dense and field conditions) can control root morphology and content of root exudates, which subsequently affect the pollutants uptake (Wang et al., 2004). Recent studies also showed that the lichen *Peltigera praetextata* can positively influence the growth of zucchini in DDE-polluted soil (Akpinar et al., 2022). Lunney et al. (2010) showed that soil characteristics *i.e.* soil organic matter content can influence the phytoextraction of DDT by pumpkin cv Howden on industrial sites. In turn, other researches showed that use of zucchini for removal of DDT from soil might possess lower extraction capability than other plants (*e.g.* tomato or grasses) (Mitton et al., 2018; Paul et al., 2015). An interesting observation has been made by Neitsch et al. (2016) who investigated the effect of modern pesticide treatments on the availability and uptake of DDT and DDE by squash. Pesticides formulations which contain surfactants (*e.g.* Tween-based agrochemicals) can enhance the uptake of DDT and DDE by cucurbits by increasing their desorption from soil particles and hence increasing their bioavailability.

Dieldrin and endrin are structurally similar insecticides developed in 1940s as alternatives to DDT. Cucurbit plants were shown to be effective in uptake of those two compounds. Otani et al. (2007) compared the uptake of dieldrin and endrin by 34 cultivars of different cucurbits (including cucumber, melon, loofah, white gourd, white-flowered gourd, balsam pear, pumpkin, winter squash, and fig-leaf squash) and found zucchini being the most efficient phytoremediator. Affholder et al. (2023) studied inter- and intraspecific variability of dieldrin accumulation in 24 varieties from seven *Cucurbitaceae* species, revealing that intraspecific differences were observed especially for zucchini. Hilber et al. (2009) in turn demonstrated that the dieldrin accumulation by cucumbers could be significantly lowered by amending the soil with activated charcoal, which acts as an adsorbent for hydrophobic compounds and reduces bioavailability of POPs.

Other organochlorine pesticides, like heptachlor, chlordane, endosulfan and chlordecone, were also extensively used worldwide polluting agricultural soils. Bottle gourd and cucumber were shown to possess the ability to absorb and bioaccumulate heptachlor in their tissues (Campbell et al., 2009). Chlordane and chlordecone were effectively phytoextracted by cucurbits (Lee et al., 2003; M. J. I. Mattina et al., 2002). The concentration of chlordane-related compounds in zucchini cv Black Beauty was up to 14 times higher than in other studied species (M. J. I. Mattina et al., 2002). In a study by Lee et al. (2003) , zucchini was exposed to air-borne chlordane pollution both in greenhouse and field conditions. Chlordane related compounds were detected in all studied plants tissues: root, stem, leaves and fruits. Also Somtrakoon et al. (2014) described that cucumber monoculture can effectively remove endosulfan from soils up to approximately 70%. However, the concentrations of the insecticide in plant tissues were relatively low, thus authors implied that the bioaccumulation might not be the main mechanism of endosulfan removal from soil. Endosulfan residuals can be degraded in the rhizosphere and within plant tissues by associated microorganisms, however no data on this aspect were presented.

3.3. Removal of PAHs

Cucurbits have also been demonstrated to uptake and accumulate PAHs (Cihangir et al., 2023; Parrish et al., 2006). Zucchini tissues accumulated significantly higher (5.5 times) quantities of PAHs than cucumber and squash (Parrish et al., 2006). Zucchini has also been shown to uptake PAHs from exhaust gas: Cihangir et al. (2023) demonstrated significantly elevated concentrations of PAHs in plants exposed to polluted air. These findings suggest that cucurbits can be used as effective phytoremediation tools not only for soils but also polluted urban air. The studies on the removal of anthracene and fluoranthene from soil using ridge gourd showed that after 45 days of cucurbit cultivation, the concentration of PAHs in soil was reduced up to 99.5% (Somtrakoon, Chouychai, et al., 2014b). In contrast, in the unplanted soil spiked with anthracene and fluoranthene the removal of studied PAHs was approximately 24%. Interestingly, PAHs were not detected in plants tissues, hence the authors suggest that biodegradation and phytostimulation may be the most likely mechanism by which these hydrocarbons were removed from soil. Although there no detailed microbial analysis were made. Another study from Somtrakoon, Chouychai, et al. (2014a) showed that co-cultivation of corn and cucumber can effectively contribute to removal of fluorene (up to 86%), however, after 30 days, the growth of these plants was significantly inhibited.

Kobayashi et al. (2008) tested the influence of soil organic matter content on the availability of pyrene for plants and the efficiency of its phytoextraction by zucchini cv Raven and summer squash cv Sunray. The decrease of the pyrene concentration in the soil ranged between 46–65% for the different treatments. Authors also showed that the BCFs of pyrene tended to decrease (although not statistically significant) after the addition of compost. In turn, fertilization contributed to improved plant growth in polluted soil. Yang et al. (2012) studied the effects of different N sources on tolerance, uptake and accumulation of phenanthrene by cucumber cv Jinchun. They showed that plants growing in PAH-polluted matrices, exhibited better growth and higher phenanthrene accumulation with ammonium nutrition than with nitrate nutrition. This indicates that ammonium fertilizers can enhance the growth of cucurbits in polluted soils, and that this can be applied in nitrogen-assisted phytoremediation.

3.4. Removal of phthalates

Another interesting observation is that cucurbits can also contribute to an enhanced removal of phthalate esters from the environmental matrices, which are currently listed as priority pollutants by the European Commission (2015). Lin et al. (2016) studied the uptake and distribution of DnBP in pumpkin. Over 12h period, pumpkin was able to uptake and distribute DnBP in the root system. More detailed studies showed 80% of the pollutant is being incorporated in cell walls and cell organelles. Other results of Lin et al. (2016) indicated that the transportation of phthalates within plants is a carrier-mediated process. Further investigations showed that the enzyme carboxylesterase, present in root cells (especially in cell water-soluble component), is involved in hydrolysis of DnBP (Lin et al., 2017). Cucumber has also been tested for the uptake of bisphenol A (BPA) (Loffredo et al., 2010) from hydroponic media. Authors showed that removal of BPA depends on the initial concentration of pollutant: hydroponic cultivation of cucumber resulted in approximately 96% and 75% removal of BPA in 4.6 mg L^{-1} and 46 mg L^{-1} BPA aqueous media respectively.

4. **Cucurbits for removal of EOPs**

The term EOPs came into use over 30 years ago. EOPs can be defined as chemicals, which are not commonly monitored in the environment, but have the potential to enter the environment and cause known or suspected adverse ecological and/or human health effects (Rosenfeld & Feng, 2011; Smital, 2008). This group of pollutants is constantly growing and nowadays we can differentiate a wide range of pharmaceuticals and personal care products (PPCPs) such as analgesics, antibiotics, hormones, anti-inflammatory, antidiabetic, antiviral, and psychoactive drugs (Mierzejewska & Urbaniak, 2020). Additionally, pesticides which are currently not monitored and considered as non-harmful for the environment, can potentially have endocrine-disrupting effects on untargeted organisms (Rheinheimer dos Santos et al., 2020). There is a growing number of studies on natural methods of EOPs removal from the environment, however there are still limited data on the use of cucurbits for this purpose (Table 2). Below, we describe some recent findings on this subject.

Mierzejewska, Tołoczko, et al. (2022) studied the effects of growing cucurbits (zucchini cv Atena Polka and cucumber cv Cezar) and application of syringic acid on the phytotoxicity of soil polluted with MCPA. Zucchini was more tolerant to the applied herbicide than cucumber. What is more, studied treatments exerted multidirectional effects on the phytotoxicity of polluted soil: the growth of zucchini and simultaneous application mitigated the phytotoxic effect of MCPA. Growing zucchini in combination with amending the soil with PSM (syringic acid) improved the removal of the phenoxy herbicide MCPA from the soil by approximately 50% in comparison to unamended samples (Mierzejewska, Urbaniak, et al., 2022). Aryal & Reinhold (2013) demonstrated that pumpkin cv Howden and zucchini cv Gold Rush grown hydroponically can accumulate antimicrobial compounds such as triclosan and triclocarban. Several studies also describes the bacteria-assisted phytoremediation of matrices polluted with chlorpyrifos, imidacloprid, β-cypermethrin (Zhao et al., 2012); cymoxanil (Derbalah & Belal, 2008); and chlorimuron-ethyl (Zhang et al., 2018) (see section 2.2.1).

5. Opportunities and limitations of cucurbits

Cucurbits can be considered as versatile plants for the phytoremediation of matrices polluted with organic compounds especially POPs, nevertheless there is still a limited number of publications on the use of these plants for removal of EOPs. Hence, there is a need to study the uptake and microorganism-enhanced phytoremediation of environmental matrices polluted with EOPs. Another approaching issue is suitability of cucurbits for clean-up of co-polluted sites with different compounds such as: organic pollutants (e.g. POPs and EOPs) and inorganic pollutants (*e.g.* heavy metals, radionuclides) (S. Ali et al., 2022; Ciura, Poniedziałek, et al., 2005; M. I. Mattina et al., 2003).

Application of cucurbits can be also challenging because they are annual plants, thus they should be planted regularly. Additionally, cucurbits used for soil purification, cannot be reused for nutritional purposes because it would create a substantial health hazard. Recently the production of safe vegetables has become a great concern, thus several research showed that amendments of soil with *e.g*. biochar can minimize the uptake of organic pollutants by cucurbits (Denyes et al., 2012, 2013, 2016). Another approach is that the application of a fungicide to zucchini plants suppresses the transcription activity of *MLP* genes (Fujita et al., 2020). Since MLPs are responsible for the transfer of organic pollutants from roots to above-ground parts, accumulation of pyrene and dieldrin was decreased.

Since, the circular economy paradigm became a great opportunity for further utilization of plant biomass, a number of studies showed that cucurbits biomass can be processed and used for a production of biosorbents for further removal of organic pollutants (Piutti et al., 2022). An interesting perspective for a possible use of cucurbits biomass is phytosynthesis of nanoparticles for removal of organic dyes: Kalpana & Rajeswari (2018) described usage of bottle gourd peel for phytosynthesis of palladium nanoparticles used for photocatalytic degradation of dyes and insecticidal, fungicidal and antidandruff purposes. Also Alghamdi & El Mannoubi (2021) described watermelon seeds and peels as an effective, natural biosorbent for methylene blue dye in aqueous medium. Bitter melon leaves can be used as naturally derived sorbents for removal of methyl orange dye and heavy metals (Shahab et al., 2023). Kaur et al. (2021) showed that activated carbon, synthesized from pumpkin seed shell can effectively adsorb antibiotic doxycycline hydrochloride from water.

Another opportunity of cucurbits biomass reusage is purification of plant enzymes responsible for phytodegradation of organic compounds such as: petroleum hydrocarbons (Bulai et al., 2021), chlorinated and native phenols (Akhtar & Husain, 2006). Bulai et al., 2021 showed that reusage and fermentation of watermelon garbage resulted in activation of hydrolytic enzymes, which activity led to an overall removal efficiency of oil related compounds up to 45%. Also Akhtar & Husain, 2006 immobilized bitter gourd peroxidase on bio affinity support, which was subsequently used for an efficient removal (up to 92%) of phenols from wastewater.

6. **Conclusions**

Cucurbits possess a considerable potential for removal of organic pollutants from environmental matrices. This chapter illustrates a wide range of studies on chemical, molecular, biochemical and ecotoxicological aspects of the use of cucurbits in phytoremediation of matrices polluted with organic compounds. The described findings provide a scientific insight into the complex processes, possibilities, and limitations of synergism between plants, roots exudates and plant-associated bacteria in remediation of soils polluted with organic pollutants i.e. POPs and EOPs.

7. Acknowledgments

This work was supported by: JSPS Bilateral Program Number JPJSBP120224602; by the UL IDUB project B2211002000146.07 (decision 55/2021) "Control of bioaccumulation of Persistent Organic Pollutants in cucurbits - production of safe food vs. bioremediation of contaminated lands"; and UHasselt Methusalem project 08M03VGRJ.

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9. Tables

Table 1. Examples of octanol–water partition coefficient values (log *Kow*) for POPs and EOPs

Organic pollutant	**logK_{ow}**	**Reference**
POPs		
2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD)	7.20	Marple et al. (1986)
1,2,3,4,6,7,8,9-Octachlorodibenzo-p-dioxin	8.20	
PCB 52	5.84	Yates et al. (2007)
PCB 118	6.74	
PCB 170	8.62	Jonker et al. (2015)
DDT	6.91	Howard et al. (1997)
DDE	6.51	
dieldrin	5.40	Qiao et al. (2000)
pyrene (PAH)	5.00	Yates et al. (2007)
di-n-buthyl phtalate	4.50	Ellington (1999)

EOPs		
MCPA	2.41-2.49	Paszko et al. (2016)
triclosan	4.76	Pintado-Herrera et al. (2016)
chlorpyrifos	5.10	Gomez Arguello et al. (2020)

Table 2. Examples of studies on the cucurbits use for the removal of POPs and EOPs

Pollutant	**Cucurbit species**	**Main observations**	**Literature**
POPs			
PCDD/PCDF	zucchini	reduction of total PCDD/PCDF concentration in soil amended with sludge by 37% and 32% in soil treated with sediment from an urban reservoir	Urbaniak et al. (2016)
		TEQ concentration of PCDDs/PCDFs in zucchini cv 'Black Beauty' and 'Gold Rush' were about 180 times higher than	Inui et al. (2008)

		in 'Patty Green'	
		concentration of dioxin-like compounds was approximately two magnitudes higher in zucchini plants than in other studied vegetables	Hülster et al. (1994)
	zucchini and cucumber	cucumber cultivation led to significant drop in polluted soil phytotoxicity (83%), zucchini in turn was more effective in dioxins removal, however TEQ reductions were similar for both studied species (68% and 66% for zucchini and cucumber cultivation, respectively).	Urbaniak et al. (2017)
		cucumbers had a higher ability to take up dioxin-like compounds than the zucchinis in sludge amended soil	Engwall & Hjelm (2000)
	zucchini, pumpkin, cucumber and towel gourd	zucchini and pumpkin, have the higher ability to translocate dioxins from roots to shoots	Zhang et al. (2009)

PCBs	pumpkin	PCBs were detected in xylem sap confirming that translocation of POPs occurs via this medium (lower chlorinated PCBs congeners were detected in higher amounts than higher chlorinated congeners)	Greenwood et al. (2011)
		enhanced growth of nodal adventitious roots at stem nodes significantly increased the PCB concentration in the primary stem of cucurbit	Low et al. (2011)
	zucchini	growth of zucchini on PCB-polluted sediment mitigated the ecotoxicity of substrate	Urbaniak, Baran, Lee, et al. (2020a)
		studied varieties of *C. pepo* were more effective at extracting PCBs from soil than other plants	Zeeb et al. (2006)
	zucchini and cucumber	zucchini was found to be more resistant than cucumber to sediment pollution and PCBs removal in substratum planted with zucchini was higher than in the case of cucumber	Urbaniak, Lee, et al. (2020)

PCDD/PCDF and PCBs	squash and zucchini	zucchini accumulated higher concentrations of dioxins and PCBs in their aerial parts at higher concentrations than squash	Matsuo et al. (2011)
	cucumber	growth of cucumber plants reduced PCB concentration in soil amended with sewage sludge or urban sediment	Wyrwicka et al. (2019)
DDT/DDE	zucchini	inoculation of endophytic consortium of three bacteria strain enhanced plant growth and DDE removal from soil	Eevers et al. (2018)
		the addition of DDE to the growing medium caused shift in plant-associated bacteria communities	Eevers, Beckers, et al. (2016); Eevers, Hawthorne, et al. (2016)
	pumpkin	DDT concentration was significantly lower in plant leaves than in stems; DDT concentration in leaves and stems decreased exponentially as distance from the root increased	Whitfield Aslund et al. (2010)

	zucchini and pumpkin	significant decreases of DDE were found in either the near-root zone or the rhizosphere; the concentration of DDE in the roots of both zucchini and pumpkin was more than an order of magnitude larger than in the bulk soil, followed by significant translocation through the plant tissues to the fruit	White (2001)
DDT/DDE/DDD and chlordane	zucchini and squash	zucchini had 2.2 and 3.7 times greater stem-to-soil BCF, (pollutant concentration ratio of stem to soil) than the squash for chlordane and DDT/DDE/DDD respectively; also translocation factors of chlordane and DDT/DDE/DDD, (the ratio of pollutant content in the stems to that in the root), were 2.1 and 3.2 times greater for zucchini than for squash	Isleyen et al. (2013)
Dieldrin	24 cultivars of 7 cucurbits plants species	this study confirmed the interspecific variability of dieldrin concentration in cucurbits fruits, as well as intraspecific variability in zucchini fruits	Affholder et al. (2023)
	34 cultivars of	zucchini extracted dieldrin and endrin than	Otani et al. (2007)

	cucurbit plants	the other families and cultivars of cucurbits	
Chlordane and chlordecone	zucchini	air-borne and soil-borne chlordane uptake route showed significantly different distribution patterns	Lee et al. (2003)
PAHs and hydrocarbons	zucchini	the average PAH concentration in zucchini exposed to exhaust gas was ~1.5 times higher than in the control group (not exposed).	Cihangir et al., (2023)
	ridge gourd	authors suggest phytostimulation as a dominant process for removal of selected PAHs from soil	Somtrakoon, Chouychai, et al., (2014a, 2014b)
	cucumber	ammonium amendment improved the uptake of phenanthrene by cucumber seedlings	Yang et al. (2012)
	zucchini, cucumber and squash	zucchini accumulated up to ~5.5 times more total PAH than other cucurbits, including up to three orders of magnitude greater levels of the six ring PAHs	Parrish et al. (2006)

phthalates	cucumber	cucumber seedlings inoculated with *Pseudomonas* sp. DNB-S1 showed better tolerance to di-*n*-butyl phthalate	Li et al. (2021)
	pumpkin	phthalate esters were transported to sequestered in cell water-soluble components; the uptake of phthalates within the plant is energy-consuming and carrier-dependent process	Lin et al. (2016, 2017)
		EOPs	
MCPA	zucchini and cucumber	growth of zucchini and application of syringic acid mitigated the MCPA phytotoxic effect on soil	Mierzejewska, Tołoczko, et al. (2022)
	zucchini	cultivation of zucchini and application of syringic acid enhanced the removal of MCPA from soil and affected the changes in phytomicrobiome of plants and functional diversity of soil	Mierzejewska et al., (2023); Mierzejewska, Urbaniak, et al. (2022)

triclosan and triclocarban	zucchini and pumpkin	pumpkin and zucchini growth significantly reduced soil concentrations of triclosan, while zucchini significantly reduced soil concentrations of triclocarban	Aryal & Reinhold (2011)
chlorpyrifos, imidacloprid, β-cypermethrin	cucumber	rhizobacteria *Ochrobactrum haematophilum* significantly promoted cucumber growth in polluted soil and contributed to a substantial removal of chlorpyrifos, imidacloprid, β-cypermethrin from liquid culture and soil	Zhao et al. (2012)
cymoxanil		endophyte *Pseudomonas* sp. (EB11), isolated from cucumber leaves effectively utilizes cymoxanil in aqueous media	Derbalah & Belal, (2008)
chlorimuron-ethyl		bacteria *Hansschlegelia zhihuaiae* S113, inoculated into cucumber rhizosphere, enhanced utilization of herbicide in cucumber rhizosphere	Zhang et al. (2018)

10. Figure legends

Figure 1. The number of documents indexed in the Web of Science database (cucurbit* OR cucurbitaceae OR cucurbita* OR zucchini OR courgettes OR cucurbita pepo OR squash OR pumpkin OR cucumber OR cucumis sativus OR lagenaria OR calarasi OR citrullus OR watermelon OR melon OR momordica) AND (phytoremediation OR remediation OR bioremediation OR rhizoremediation) 03.04.2023 394 searches

Figure 2. Factors determining the removal of POPs and EOPs from environmental matrices using cucurbits; POPs- persistent organic pollutants, EOPs- emerging organic pollutants; PSMs- plant secondary metabolites