Ornamental plants for the phytoremediation of heavy metals: Present knowledge and future perspectives.

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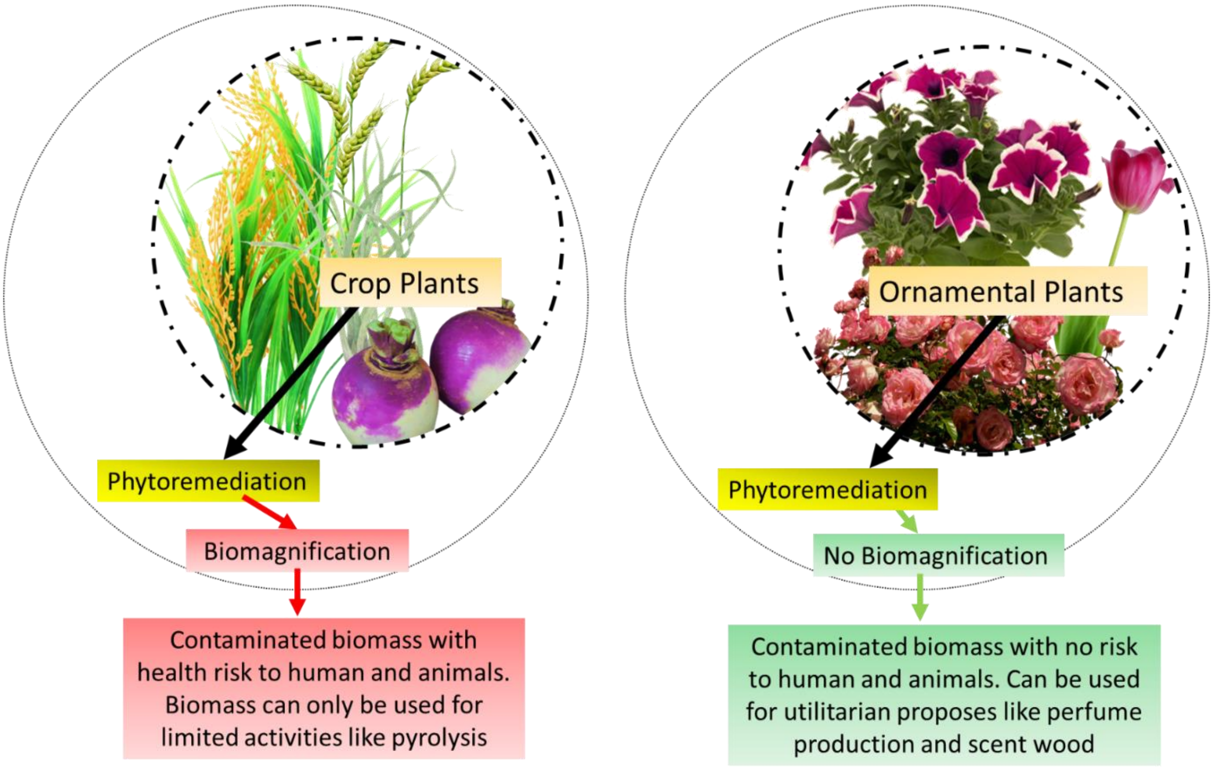
Graphical abstract



Abstract

Environmental matrices are polluted with the plethora of contaminants, and among these, the concerns related to heavy metals (HMs) are also included. Due to the low cost in a long-term application and environmental friendliness, the use of biological remediation has gained significant attention in recent decades. The use of ornamental plants (OPs) in the field of phytoremediation is scarcely reported, and the impacts of HMs on OPs has also not been investigated in great depth. The OPs mediated HMs remediation can simultaneously remove contaminants and bring improvement in aesthetics of the site. The biomass of OPs produced after such activities can be used and sold as pot plants, cut flowers, essential oils, perfumes, air fresheners production, metal phytomining, and feedstock in silk production. The OPs also present a lower risk of HMs bioaccumulation compared to crop plants. This review focuses on the current knowledge of HMs toxicity to OPs, their applicability advantages, methods to improve the tolerance of OPs with incremented HMs uptake, challenges in the field, and future application perspectives. The practical application of OPs case studies from China, Iran, India, Oman, Pakistan, and Turkey was also discussed. This work fetches the inter-disciplinary features and understanding for the sustainable treatment of HMs in a new novel way, to which no previous review has focused.

Keywords: Ornamental plants, heavy metals, horticulture, phytoremediation, plant toxicity

1. Introduction

The expanding human population needs a substantial amount of product and services to maintain the livelihood on earth (Shang et al., 2019). The human population is going through an exponential phase, hence adopting a j-shape graphical growth, that is not converted into s-shaped and sustainable development, catastrophic environmental events are expected (Cazalis et al., 2018). The menace related to environmental pollution is already evident, due to the unsustainable human development, greedy economic growth, and compromise on ecological sustainability (Vita et al., 2019). In the recent decade, some well-known hazards that came into debate were linked to heavy metals problems.

Technically, the term “heavy metals” does not have a compressive definition, defining it in terms of toxicological, physical, biological and chemical aspects (Pourret, 2018). But due to its broad use and unavailability of another word to replace it, the name heavy metals “HMs” should not be considered an offence to science. Heavy metals are of concern due to their capacity to induce harmful and toxic effects on plants and animals. Some HMs are known to have importance in growth at minute quantities (Cu, Fe, Mn, Zn, and Mo), but surplus levels negatively affect growth and development (Alirzayeva et al., 2017). Another major problem associated with them is the capacity to bio-magnify in the food chain (Arshad et al., 2017; Majed et al., 2016). They are the part of earth composition, present in different ores.

Further, they are indestructible. The xenobiotic concentration of HMs leads to an environmental problem because of their toxic, non-biodegradable and persistent nature (El-Naggar et al., 2018). In such a condition, choosing plants that can take up HMs with reduced risk of biomagnification is significant merit. For these ornamental plants (OPs) are the potential candidates. These include aquatic and terrestrial herbs, shrubs, or trees cultivated for soft landscaping and decorative purposes. Standard ornate features include leaves, scent, fruit, stem, and bark.

In this literature review, impacts of heavy metals on plant growth, notably ornamental plants, possible use of OPs in phytoremediation of HMs, and application in green and blue-green infrastructures are discussed. The HMs response of OPs was reviewed against, but not limited to, Cd, Cr, Cu, Ni, and Pb. Due to the frequent uses and release of these HMs in most domestic and industrial activities and notorious environmental impacts this review's discussion is centred more towards these HMs (Iqbal et al., 2019; Khan et al. 2019a). Methods through which the tolerance of ornamental plants can be enhanced, with the pros and cons are also discussed. This review also iterates the knowledge related to the use of ornamental plants in research as the model plant in the field of phytoremediation. Critical due attention was shaded on the dendroremediation of HMs using ornamental trees. The current challenges associated with ornamental plants' usage in green and blue-green infrastructures and phytoremediation of HMs are discussed. The importance of continual screening of novel plants, particularly the previously neglected ornamental plants, has also been highlighted.

Further, the review also presents understanding for step required for establishing an operational constructed wetland using OPs and OTs. This review can contribute towards the identification of new and more effective phytoremediation approaches. Hence, this review's main objectives included established the understanding that OPs can play a role in HMs phytoremediation. Through this review, it was emphasized that though there is room for opportunity, care should be taken to select and screen OPs. It helps identify potential OPs, and can also reduce an economic loss if a wrong non-tolerant OPs is selective for urban green spaces.

2. Ornamental plants and trees under the influence of heavy metals

2.1. Response regarding HM uptake and compartmentalization

The exposure to these selected metals (including Cu, Cr, Cu, Ni, and Pb) and OPs and other plants' physiological response are listed in Table 1. Notably, the reaction in some OPs is very drastic, while for other shows tolerance. The details related to the response of OPs upon metal uptake is as identical to that of other terrestrial and aquatic plants. A summary is presented in the supplementary information discussing the translocation and impacts selected metals within the plants. To counter these negative impacts, ornamental plants, like any other terrestrial or aquatic plants, utilize complex enzymatic and non-enzymatic machinery. Under normal conditions, OPs also produce a limited amount of reactive oxygen species (ROS) reported in chloroplasts, mitochondria, and peroxisomes (Murik et al., 2019).

Generally, plants, including ornamental plants, are classified based on the metal uptake mechanisms. Excluders restrict HMs uptake and translocation to the shoot. Indicators/accumulators dynamically accumulate HMs in their above soil-plant parts comparatively the same as the soil levels. While hyperaccumulators uptake and translocate HMs to shoots and leaves without any toxic symptoms. Few examples of hyperaccumulator, accumulator and excluder, ornamental plants are presented in Table 2. In OPs, HMs detoxification is primarily achieved through compartmentalization, deposition, distribution, and stabilization within the cell walls, vacuoles, and metabolically inactive tissues (Lajayer et al., 2019; Levizou et al., 2016). *Abelmoschus manihot* L. plants were reported to tolerate Cd toxicity through accumulation in vacuoles and cell wall (Wu et al., 2018).

Similarly, Caldelas et al., (2012) reported Cr's compartmentalization by *Iris pseudacorus* L. (Common name: Yellow iris) in the root cortex cell wall and the intercellular spaces of rhizome cytoplasm. Chelation of the HMs by a ligand, followed by the sequestration of the metal-ligand complex into the vacuole is another potential mechanism of HMs tolerance in OPs. Biochelators are needed for the HMs detoxification by the plant cell (Liu et al., 2017). These include metallothioneins (MTs), organic acids, and phytochelatins (PCs). As bio-chelator synthesis is an energy-consuming process that can limit the plant growth, it is not used very frequently by metallophytes. Metallophytes perform HMs compartmentalization through translocation. While in non-metallophytes, these bio-chelators contribute to stress due to shift metabolic towards defence (Lajayer et al., 2019).

2.2. Notable OPs families studied for HMs remediation from environmental matrices

Ornamental plant many plant families has been subjected to phytoremediation studies. Members of Lamiaceae family, mostly include annual herb and shrubs, were tested for HMs tolerance. Among them included *Anethum Graveolens* (Common name: Indian Dill), *Lavandula vera* and *Lavandula anqustifolia* (Common name: English lavender) that were used for soil HMs remediation, and the biomass produced is reported to be used for essential oil production (Angelova et al., 2015; Barouchas et al., 2018; Zheljazkov et al., 2006).

From Solanaceae family, the *Petunia* (Perennial and annuals herbaceous plants) and *Nicotiana* (Tall, bushy tender perennial plants) genera have been used extensively used in research as model plants (Khan et al., 2019ab; Taheri-Dehkordi et al., 2018). Both plants Very commonly used plants, and many have economic value in the horticulture market. Notable *Petunia* species included *P. axillaris, P. exserta, P. grandiflora, P. hybrida, P. inflata,* and *P. integrifolia* (Khan et al., 2019b; Silva et al., 2018). For *Nicotiana, N. alata, N. benthamiana, N. clevelandii, N. glauca, N. plumbaginifolia, N. rustica, N. sylvestris,* and *N. tabacum,* have been used in multiple studies (Chen et al., 2015; Vallejo et al., 2015; Wu et al., 2011). The plants from both genera have also been used in many phytoremediation experiments, including treating dyes, heavy metals, and organic contaminants. However, research related to intrinsic plant potential, the effect of soil amendments, and plant-microbe interactions concerning heavy metals exposure are minimal for *Petunia hybrida* L. and *Nicotiana alata* L., despite their well-developed market.

Plants belonging to Asteraceae family, like *Tagetes erecta, Calendula officinalis,* and *Chrysanthemum indicum*, were also reported to perform well in HMs contaminated soils (Coelho et al., 2017; Goswami and Das, 2016; Mani et al., 2015). All these plants are known to have economic values in floriculture and horticulture. Hence, it can be forecasted that HMs phytoremediation through OPs brings dual benefits. These include the HMs removal and along with the simultaneous beautification of the site. Some of the OPs used in HMs phytoremediation were presented in Table 1, 2, and 3.

2.3. Dendroremediation of HMs using ornamental trees

Phytoremediation, using small herbaceous OPs, can only be applied for shallow depth, where plants' roots can penetrate and interact with metals. The use of trees for the clean-up of contaminants is known as dendroremediation. This word is originated from the Ancient Greek *dendron* meaning “tree” and Latin *remediare* representing “reuse”. The HMs remediation at higher soil depths with ornamental trees and shrubs offer a selective advantage over OPs. These include the deep rooting system (Saxena et al., 2019). Many contaminants can be targeted using ornamental trees and shrubs (OTs) mediated dendroremediation (Komives and Gullner, 2006). These systems perform hydraulic retention of HMs, preventing HMs from entering the saturated aquifers (Hashim et al., 2011). They also act as a riparian buffer to avoid the nutrient and HMs from city and agricultural runoff getting into freshwater streams (Komives and Gullner, 2006). Further, these systems also can potentially remediate brownfields (pieces of land that was previously developed land used for industrial activities but not currently in use due to potential contamination) (Saxena et al., 2019).

Populus deltoides Bartr. ex Marsh. clone ‘Bora’ (Common name: Eastern cottonwood) and *Salix viminalis* L. clone ‘SV068’, (Common name: Basket willow) were reported to phytoextract Zn and Cd in aerial parts, while Cr, Ni, Pb, and Cu were phytostabilized in the roots (Pilipović et al., 2019). Jiang et al., (2019) reported that 1.92–7.89 g Cd and 9.70–83.58 g Pb every year can be phytoextracted by a hectare *Morus alba* (Common name: Mulberry tree) shoot. They also concluded that these trees could be an alternative plant to use heavy metal polluted paddy soils. The similarity in another study conducted by Wan et al., (2017), reported that *M. alba* planting is safe on soils with Pb and As concentrations lower than 369 and 180 mg kg^{-1}, respectively. Further, Silkworms fed with mulberry leaves collected from slightly contaminated soil exhibited productive growth and normal silk production. As bioindicators, trees can be used to study the historical concentrations of atmospheric HMs. Turkyilmaz et al., (2019) studied the deposition of Al, As, B, Ba, Ca, Cd, Cr, Cu, Fe, Mg, Mn, Na, P, and Zn in the rings of *Quercus laevis* (Common name: Oak trees). They concluded a significant positive relationship between the HM concentrations in tree rings and the concentrations of atmospheric HMs, at a confidence interval of 95% for As, 99% for Cd, and 99.9% for other elements.

The OTs can utilize the leftover contaminated urban land gets contaminated, and but the use of natural vegetation they can accumulate HMs. Abbas et al., (2019) conducted one such study. They reported using *Prosopis glandulosa* (Common name: Honey mesquite tree) to perform phytoremediation of sewage sludges and sewage-amended soils. The contaminated soil was polluted with metals such as Cd, Zn, Ni, Co, and As. They concluded that *P. glandulosa* concentrated more Cd, Cu, Fe, Pb, and Zn in its aerial part, As, Co, and Ni was evenly distributed in the tree. Like any other trees, the OTs are sustainable solar energy-driven pumps, and they can control significant phytohydraulics that has the potential for hydraulic retention through evapotranspiration. It is an excellent approach to control subsurface percolation of the HMs with water. One such study was conducted by Nguyen et al., (2020), who, by the help of the simulation model, presented mangroves' potential in the retention of chromium. This case study was conducted in the Thi Vai River Catchment, Vietnam. Like the OPs, OTs are also used in the field.

The distant advantage of their usage is that the biomass produced can be used for timber, scent wood, or pulp and paper production. A few examples of such OTs included *Azadirachta indica* (Common name: Neem tree) belonging to Meliaceae family, *Holoptelia integrifolia* (Common name: English beechwood) belonging to Ulmaceae family, *Gmelina arborea* (Common name: belonging to Verbenaceae family, *Dendrocalamus Strictus* (Common name: Bamboo) belonging to Poaceae, and *Leucaena leucocephala* (Common name: River tamarind) belonging to Fabaceae family (Pandey and Souza-Alonso, 2019). These findings will support the practicability of these plants for the phytoremediation of heavy metals. Understanding the tolerance potential of these plants can also reduce capital loss and atheism when exposed to HMs. All these trees are known to produce vegetative canopies and can be grown in urban areas. Hence, they can be used for the recreational purposes of the contaminated brownfields. The list of such OPs and OTs having the capacity to perform HMs phytoremediation is improving over time. However, more research in term of practical application is needed. Further, the season-dependent effectiveness, slow growth, lack of suitable monitoring methods, and unique constraints require action for successful application in the future (Redfern and Gunsch, 2016).

3. Advantages for OPs mediated HMs remediation and current knowledge related to their applications in green and blue-green infrastructure

Due to the capital-related, technical, and environmental problems, conventional physical and chemical remediation (including chemical precipitation, adsorption, ion exchange, membrane filtration, coagulation-flocculation, floatation, physical encapsulation, soil excavation) are less feasible for the field application (Mahmood 2010; Lajayer et al., 2017). The use of plants for the remediation has gained considerable attention for absorption, accumulation, and transfer of contaminants from the environment within plants, which can occur within edible and non-edible parts. Further, some studies reported using grasses, OPs, and trees (Lajayer et al., 2019; Maleki et al., 2017). The use of crop plants should not be promoted for the phytoremediation. It is due to the possibility of HMs biomagnification in the food chain (Cazalis et al., 2018; Gill and Tuteja, 2011). As it is a threatening issue for human and animal health, the use of ornamental plant species is a more workable option. With tremendous diversity and abundance of many available OPs, it will be beneficial to screen the potential local OPs for the phytoremediation of HMs contaminated environments (Lajayer et al., 2019). One distinct advantage of the use of OPs is the simultaneous improvement of the aesthetics and the cleaning of the contaminated site, which can be even more acceptable for the urban areas and green infrastructures (Haase, 2015; Prapagdee and Wankumpha, 2017). Depending on the contaminated environmental matrices (soil, water, or air), the OPs are categorized into aquatic and terrestrial plants (Nakbanpote et al., 2016). Few examples OPs used for the exposure analysis and phytoremediation of HMs-contaminated matrices were presented in Table 2 and Table 3.

A very massive portion of the world's population (more than 50%) is living in cities due to the rapid migration towards the urban cities, and future population growth is further expected to happen in urban centres (Haase, 2015). The most common reasons expected to induce problems associated with the HMs exposure are contributed by industrial, domestic, economic, and transportation sectors (Arbolino et al., 2018), whereas, the contribution of enhancement in the living standards cannot be neglected. The leading cause of this will be the compromise on sustainability leading to contamination of environmental matrices (Vita et al., 2019). In past decades, to overcome HMs contamination problems, attention has been given to green and blue-green infrastructures. A green infrastructure (GI) is a deliberately cultivated system of natural and semi-natural zones and other environmental features that are constructed and accomplished to offer a wide range of ecosystem services' in rural and urban areas (Calvert et al., 2018). A blue-green infrastructure (BGI) is an extension to the concept of GI. The BGI also includes good water management restoring, or mimicking the natural water cycle, and is anticipated to be embraced at the industrial and local scale for the efficient closed-loop circulation of freshwater (Martinico-Perez et al., 2018). Both GI and BGI are essential for the sustainability, liability and healthfulness of any setting, whether natural or anthropogenic, as they provide numerous welfares and aid to the human and associated environment. These include sustainable tackling of the impact related to climate change, improving the aesthetic quality of the built environment air, water, and wastewater quality, protection and enhancement of the biodiversity, and offering places for relaxation, physical activity, and play (Calvert et al., 2018; Martinico-Perez et al., 2018). These sustainable infrastructures can also contribute to air remediation through OPs canopy, capturing the particulate matter with deposited HMs using leaves, fruits, wood, and flowers surfaces (Schreck et al., 2012). Further, these OPs canopies growing in urban areas act as competent collectors of re-suspended dust and can also be used as air bio-monitors and bio-indicators (Lajayer et al., 2019).

The special OPs for HMs (Cd, Pb, Zn, and Ni) with accumulation potential are *Acer negundo* L. (Common name: Boxelder maple), *Ailanthus altissima* (Mill.) Swingle (Common name: Tree of heaven), *Fraxinus angustifolia* Vah l. (Common name: Desert ash), and *Robinia pseudoacacia* L. (Common name; Black locust) and hence the canopy of such plants can reduce the HMs exposure to other living organisms. Use of GI and BGI, like constructed wetlands, have been well reported to remediate HMs in soil, water, and wastewater (del Carmen Durán-Domínguez-de et al., 2018; Sandoval et al., 2019). It is not only achieved by the plant uptake or stabilization, but also by the plant litter. Plant litter acts as a bio-sorbent and includes debris, cellulose, cutin, fibres, lignin, pectin, suberin, and wax, that perform sorption of metal ions (Vithanage et al., 2012).

A better understanding of GI/BGI and HMs tolerant OPs can also benefit the grey infrastructures, which are the conventionally used wastewater treatment facilities, at industrial and domestic scale (Qi et al., 2019). These grey infrastructures contribute to the current 60% of urban surfaces, primarily pavements and roofs. The usage of OPs, in both GI and BGI, will be encouraged in future, with the enhancement in living standards and cities. Unfortunately, minimal attention has been given to this possibility. The existing limited freshwater and clean soil resources are already stressed due to climatic changes and an increase in the human population (Ha et al., 2018). The chances are high that for sustaining the growth and maintenance of GI and BGI, irrigation with treated wastewater or greywater would be needed. The exposure to contaminated dust due to automobile and pedestrian can affect the performance of OPs in GI and BGI (Wang and Zhou, 2005). Previously reported HMs tolerant OPs (Table 2) and the new OPs would be the key players in such infrastructures.

Industries are among the potent site that is known to cause significant anthropogenic pollution of limited freshwater bodies. According to sustainable development goal (SDG) 6.6, protection and restoration of water ecosystems is a must by 2020. In the scenario of developing countries, the physicochemical method is not feasible; due to applicability limitation, the problem associated with rejects dispersal and high capital cost (Aziz et al., 2008). Utilization and optimization of alternate technologies are essential to achieve SDG 6.4, i.e. reducing, eliminating, and minimizing the improper disposal. Hence finding an appropriate combination of plants, that can withstand the harsh conditions, is one of the challenges needed to be addressed earlier, for the successful delivery, management, and planning in an uneven picture of GI and BGI. Therefore, green infrastructure benefits must be maximized whilst being mindful of the cost of delivery and maintenance. For industrial wastewater, where the concentration of HMs, level of salinity, fluctuation of pH, and amounts of dissolved solids are relatively high, it is impossible to use OPs directly in GI and BGI for treatment of wastewater. Similarly, the domestic wastewater also needs to be characterized, as the most prominent issues with domestic wastewater usage are the higher biological oxygen demand, chemical oxygen demand, total suspended solids, and total dissolved solids. It is first essential to characterize the wastewater; if needed, the wastewater can be pre-treated using physicochemical methods. It can even be diluted, before irrigation of OPs and OTs. No matter which design model is used for municipal sewage, the area of horizontal flow constructed wetlands is usually about 5 m^2 Population Equivalent^{-1}. It is recommended that the respective inflow loads of 6 g m^{-2} day^{-1} and 20 g m^{-2} day^{-1} should be maintained to achieve the outflow BOD_5 and TSS concentration of 30 mg L^{-1} (Vymazal, 2010). Further, the OPs and OTs can also be used in GI and BGI for nutrient removal in the final stages of the wastewater treatment system, as the polishing step (Marín-Muñiz et al., 2020).

The OPs, after HMs phytoremediation, can be used for utilitarian purposes from the harvested vegetation and flower (Nakbanpote et al., 2016). The biomass produced can be used for valuable products like pot plants and cut flowers. Further, flower cuttings can be sold in flowers shop, while their essential oils and fragrant wood can be used for perfume and air freshener production. There is no previous report on HMs exposure through the perfumes obtained from OPs cultivated on HMs contaminated matrices. Based on the absence of HMs in essential oils of medicinal and aromatic plants, it can be hypothesized that the perfumes produced from parts of OPs using the distillation methods are free from HMs and can be safely promoted with no risk to human health (Lajayer et al., 2017; Raza et al., 2019). Although there is no documented evidence for the presence of HMs in essential oils obtained from OPs, there is still the need to prove this with the help of concrete scientific evidence after thorough experimentation on OPs-HMs system. Optimistically, OPs can generate considerable revenue by selling cut flowers, produced after exposure and cultivation on HMs containing matrices by utilizing the brownfields. The application of OPs in the field can be distributed into four phases, with key checkpoints at each step.

3.1. Phase 1: Initial site assessment

During this phase, necessary information related to site and matrices to be treated. The parameters included for monitoring included the contained site's total related chemistry, as it varies from one place to another. It must be performed to effectively account and quantify the different constituents that can interfere with one another and plants. The quantification of chemical composition will help select prospective OPs and OTs. Further, it can also assist the expected changes in the composition of soils rhizosphere microbes. The plant parameters that can be checked include plant biomass, height, and covered vegetative area. The most practical biochemical status of OPs and OTs, while in the field include the plant pigments (chlorophyll contents). To evaluate the aesthetic quality index of visual quality can be created. A model quality index ranged from 1 to 5, indicating non-commercial to outstanding quality. Based on leaf discolouration, leaf necrosis, defoliation, and flowering are presented in supplementary table 1.

3.2. Phase 2: Off-site testing and pilot-scale optimization

After identifying the site's elemental composition, soil status, and selection of potent OPs, the design of a constructed wetland system must be finalized. It can be performed in lab-controlled conditions. As the state is controlled the status of design system upset can be estimated. The parameters that can be noted include the changes in temperature, flow rate, water chemistry (including biological oxygen demand, total suspended solids, total dissolved solids, organics', and inorganics' composition). Through early testing, these parameters, a robust and predictable treatment is possible though construed wetland. This activity can be extrapolated toward field application and can help enhance the accuracy of initial size estimates for the full-scale treatment wetlands. The pilot-scale optimization checklist is presented in supplementary table 2.

3.3. Phase 3: On-site execution and performance monitoring

Through the findings of phases 1 and 2, an on-site prototype of the constructed wetland should be is designed at a small scale, to test the system workability. Through this, the final detailed optimization, according to the site, can be made. If needed, any changes in the design can be introduced before constructing the full-scale system.

3.4. Phase 4: Operational full-scale system

At phase 4, with the trail of phase 1, 2, and 3, a well-designed, appropriately sized constructed wetland can be established to achieve the desired goals. For a full-scale operational system, there is the need to provide acclimatization time to plant and microbes to achieve wetland maturation. Throughout this phase, regular monitoring is needed. It is performed to assess the efficiency and reduce the risk of divergences from the optimal treatment design. As the design system upsets were considered earlier at prototype scales, a decision matrix should also be maintained for the adaptive constructed wetland management.

4. Methods to improve the tolerance of ornamental plants

The alteration in soil structure using soil amendments affects the tolerance and phytoremediation competence for HMs in the OPs. Based on the previous finding, there have been many methods adopted to improve the tolerance potential of OPs against HMs, and similar techniques can be tested for the OPs (Table 3). The soil conditions, changes in plant-microbe interactions, transgene introduction into plants, synthetic chelator use, and associating phytoremediation with other treatment methods have been investigated extensively (Lajayer et al., 2019; Liu et al., 2017). The schematic representation of how these methods can contribute to the improvement in the tolerance of OPs is presented in Figure 1, further detailed discussion on each process is conferred individually, in the proceeding section.

4.1. Use of soil conditioners

4.1.1. Biochar

Biochar is manufactured by thermal degradation under limited oxygen availability using organic feedstock, including plant material, manure, rumen, and sludge (Jegajeevagan et al., 2016). Due to biochar's physicochemical properties, like high pH and carbon content, large surface area, and functional groups, it’s amendment in soil results in modified soil microbial population, soil fertility, carbon sequestration, and improved soil physical properties (Iqbal et al., 2019). The composition and remediation capacity of biochar depend on the feedstock, pyrolysis temperature, and post-production modifications (Sanchez-Monedero et al., 2018). The application of biochar on various plants can behave differentially (positively, negatively, or neutrally). Further, there are legislations (in Europe) that do not allow the land application (Fascella, 2015), resulting in most of the lab-scale studies (Zhang et al., 2016).

4.1.2. Compost

Compost is one of the commercially available soil conditioners produced using a variety of organic materials typically produced after long aerobic decomposition at thermophilic ranges. These materials include plant fibres and debris, sludge, animal corpses, slaughter remain, and material rich in organic matter (Ngo and Cavagnaro, 2018). Compost has been widely used as a soil additive for ornamental plants. Its application is reported to promote the growth of *Calendula officinalis* L. (Common name: Marigold), *Petunia hybrida* L. (Common name: Petunia), and *Nicotiana alata* L. (Common name: Jasmine tobacco) (Gerats et al., 2005; Khan et al., 2019ab). It promotes the soil aeration by reducing the soil compaction, moisture retention, nutrient release, and reducing the mobility of contaminants like hydrocarbon and heavy metals (García-Delgado et al., 2019; Hussain et al., 2018). It has been reported to show synergistic positive effects on plant and soil parameters (Egene et al., 2018; Gong et al., 2018).

4.1.3. Peat-moss

Peat moss is one of the major soil conditioners produced commercially (Ángeles-Argáiz et al., 2016). It is produced by incomplete anaerobic decomposition of plants (typically *Sphagnum* and *Carex*) at low temperature, nutrient and pH (Bourgeois et al., 2018; Preston et al., 2012).

It shows a slow degradation rate in soil, higher water holding and cation exchange capacity, high porosity, and low bulk density (Kern et al., 2017). Due to the acidic properties in the soil, it increases the HMs soil mobility (Lee et al., 2015), which can help improve the metal uptake within OPs capable of phytoextraction. It's ever-growing demand and cost are linked with environmental problems (Méndez et al., 2017). The use of peat moss alone should not be promoted and should be blended with other soil conditioners, or alternative materials should be used.

4.1.4. Biosolids, vermicompost and fertilizers

Coir dust, manufactured with mesocarp tissue or coconut husk, is very cheap biosolid (Etim et al., 2016). It has been found to improve the plant growth, and experiments have shown that it can adsorb the HMs like Ni, Cu, and Zn (Swarnalatha and Ayoob, 2016). Vermicompost produced with the help of worms (notably red wiggler and white worms) mediated composting process and promotes plant growth. Mani et al., (2015) reported that with vermicompost and sulphur combined application on Pb-polluted soil, improvement of photosynthetic pigments and higher Pb phytoextraction by *Chrysanthemum indicum* L. was achieved. Alteration in the soil parameters, by augmentation of nutrients, can also promote plant tolerance. The phosphate addition resulted in higher arsenic uptake up to 265% in *Pteris vittata* (Common name: Chinese brake) (Cao et al., 2003). *Carpobrotus rossii* (Common name: Karkalla), an Australian native Cd hyperaccumulator, when grown in the presence of chemical N fertilizers and manure, showed improved shoot biomass, while with manure application reduction in Cd availability in soil was reported (Liu et al., 2016). Another study reported that NPK fertilizer significantly increased the cadmium uptake in *Cosmos sulphurous* (Common name: Sulfur cosmos) and *Cosmos bipinnata* (Common name: Mexican aster), in comparison to the control (Zhou et al., 2018). However, biofertilizers are more beneficial and sustainable than synthetic and chemical fertilizers, as they offer more macro and micronutrients to plants (Liu et al., 2017).

4.2. Use of synthetic chelators and organic compounds

Synthetic chelators can also be used to study the influence of HMs on OPs growth (Habiba et al., 2015). The synthetic chelators were reported to negatively impact plant growth and rhizospheric microbial populations (Kalyvas et al., 2018). The use of DTPA (Diethylene triamine penta-acetic acid), EDTA (Ethylene diamine tetra-acetic acid), EGTA (ethylene glycol tetra-acetic acid), and SDS (Sodium dodecyl sulphate) is widespread to influence HMs mobility within plant or retention in soil. The co-application of synthetic chelators instantaneously amplifies environmental contamination (Sarwar et al., 2017).

Cui et al. (2007) studied the impact of sodium EDTA, oxalic acid, tartaric acid and citric acid, on the growth of *Zinnia elegans* Jacq. (Common name: Youth-and-age). They identified that the development of *Z. elegans* was better when equimolar exogenous chelators were provided concerning the metal concentrations. Similarly, the use of EDTA enhanced the Cd uptake in four ornamental plants, *Althaea rosea* (Common name; Hollyhock), *Lonicera japonica* (Common name; Japanese honeysuckle), *Salvia virgate* (Common name; Southern meadow sage), and *Dahlia hybrida* (Common name; Dahlia) (Cay et al., 2016). Khan et al. (2019a) reported that EDTA with *P. hybrida* significantly increased the HMs uptake (Cd, Cr, Cu, Ni, and Pd), but the higher uptake reduced plant's aesthetics and growth. Similarly, to improve the performance of OPs in HMs stressed environment use of citric acid, salicylic acid, humic acid, and fulvic acids as a bio-stimulant has also been discussed in detail by Canellas et al. (2015) and Wei et al. (2018). The use of synthetic chelators needs to be investigated with the OPs to conclude how OPs will behave when exposed to synthetic chelator and HMs.

4.3. Influence of microbial factors on soil nutrient cycling and plant HMs tolerance

One of the potential soil quality indicators is the soil microbial population and their activities (Graham et al., 2021). Plants are highly dependent on the microbiological process that mediate the mineralization of organic matter and convert them to readily available nutrients (Khan et al., 2017b). The microbial population is responsible for producing organic acids like humic acid and fulvic acids though bio-decomposition of organic matter. The produced organic acids act as a bio-stimulants for the plant growth as proposed by Wei et al. (2018). Hence, in natural and engineered biological remediation systems, a diverse and health soil microbial population plays a determinant role in managing a stable reserve of carbon and nitrogen, maintained by rapid biological decomposition living and dead organic materials (He et al., 2010). A detailed review of this matter was published by Chen et al. (2003), where the importance of actinomycetes, bacteria and fungi in biological C and N fixation was discussed in detail. Apart from nutrients cycling the microorganism, notably bacteria and fungi, play an active role in biological remediation and improve the plant tolerance against metal exposure (Khan et al., 2016ab). The proceeding section discusses the role of bacteria and fungi and mediating the reduction of HMs stress to plants.

4.3.1. Bacteria

Microorganisms can influence the mobility and bioavailability of HMs in the soil (Arshad et al., 2017). They utilize different methods, including accumulation, acidification, bio-sorption, chelation, complexation, methylation, and redox reactions (Lin et al., 2018; Liu et al., 2017). Arshad et al. (2017) reported that the combined use of biochar with bacterial consortia of *Bacillus cereus* and *Pseudomonas japonica*, resulted in a reduction of Cr(VI) to Cr(III). This reduced phytotoxicity of Cr in *Triticum aestivum* L. (Common name: Wheat). It can be inferred that bacterial augmentation can play a significant role in increasing or decreasing the HMs mobility within the ornamental plants. In another study with *Helianthus annuus* (Common name: Sunflower) the addition of bacterial strains *Ralstonia eutropha* and *Chrysiobacterium humi* lead to a significant reduction in the plant weight loss due to the zinc and cadmium exposure (67 and 64%, respectively) (Marques et al., 2013). Another study with *Orychophragmus violaceus* (Common name: Chinese violet cress) reported that the bio-augmentation rescued the bacterial diversity by 83%, which was reduced due to soil contamination with Cd and Zn (He et al., 2010). Properties like production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase minimises ethylene production in the plant. Further, the synthesis of plant auxins like indole-3-acetic acid (IAA), solubilization of phosphate in soil, and siderophore production can also influence plants' HMs uptake. Bioaugmentation of such bacterial strains with OPs will improve their potential against the HMs tolerance, uptake and accumulation (Roquigny et al., 2017). Lin et al. (2018) reported that the application of phosphate solubilizing bacteria (PSB) with *Wedelia trilobata* (Common name: Singapore daisy), improved plant growth, enhanced Cu adsorption and transportation within the plant. They further concluded that the PSB was tolerant of Cu contamination in soil, even at elevated levels. Heavy metal tolerant bacterial strains can also promote the performance of ornamental plants. Zn tolerant bacterial strains *Bacillus subtilis, Bacillus cereus, Flavobacterium sp.,* and *Pseudomonas aeruginosa* promoted the *Orychophragmus violaceus's* (Common name: Chinese violet) the physiological status and metal uptake by (He et al., 2010). The strain *Flavobacterium* sp. with *O. violaceus* showed highest Zn accumulation in shoot and root than the non-inoculated plants.

Similarly, the inoculation of bacterial consortia, consisting of *Rhizobium leguminosarum, Bacillus simplex*, *Luteibacter sp.*, and *Variovorax sp.*, improved shoot (59%) and root (56%) biomass of *Lathyrus sativus* L. (Common name: grass pea) under Pb stress in the hydroponic system. Higher Pb translocation in shoot and root (39 and 47%, respectively) was observed, compared to the non-inoculated plant. All strains were capable of initiating root nodulation, synthesis of IAA, siderophore production, phosphate stabilization. Hence, an inference can be made that the use of bacterial strains can improve the growth of OPs, and due to the scarcity of data in this domain, more research is needed.

4.3.2. Fungi

Aspergillus, Mucor, Penicillium, and *Trichoderma* genera of filamentous fungi are well known for their ability to tolerate heavy metal stress (Tiwari and Lata, 2018). The use of arbuscular mycorrhizae (ABM) and ectomycorrhizae (ECM) fungi can influence plant growth. Further, it can also affect the HMs mobility within in rhizosphere and different plant compartments (Lajayer et al., 2019; Liu et al., 2017). Like bacteria, Fungi are found ubiquitously in the environment and are reported to improve biomass and yield of associated plants, by mitigating the biotic and abiotic stress, improving the plant nutrient availability, providing barrier and tolerance to the contaminants. They also compete and inhibit potential pathogenic micro-organism within plant and rhizosphere (Khan et al., 2017ab). The symbiotic relationship between ABM and plants reduces HM toxicity and uptake by sequestering the HM in fungi (Lajayer et al., 2019). Khan et al. (2017) reported that *Glomerella truncate* and *Phomopsis fukushii* inoculation with *Solanum nigrum* L. increased the Cd tolerance of the plant at high concentrations (25 mg Cd kg^{-1} sand DW). The methods of HMs complexation were also reported for the fungal strains that can promote plant growth. It is achieved using organic compounds and immobilization through chemical bonding to the cell wall (Khan et al., 2017; Luo et al., 2014). One such study was conducted by Tabrizi et al. (2015), in which *Calendula officinalis* L. was cultivated with ABM fungi (*Glomus mossea* and *G. intraradices*). The results indicated higher Pb and Cd accumulation in root and shoot than the plant with no association. Fungal associations with plants are also reported to trigger the gene expression pattern of plants. Still, there is a lack of research in this domain, and further investigation is needed to defend this claim.

4.4. Introduction of the transgene in OPs

One of the most crucial aspects of maintaining a good phytoremediation strategy is the genotype of the plant. Most of HM accumulation characteristics, tolerance, translocation, and compartmentalization are dependent on it (Lajayer et al., 2019). The HMs metabolism is a complex mechanism reliant on the biotic and abiotic surroundings. Transformation of plants using transgenes is one of the popular options to overcome HM stress and toxicity (Koźmińska et al., 2018). Table 4 discussed the transgenic OPs reported for HMs remediation or tolerance. Strategies commonly adopted include transformation with genes responsible for uptake, translocation, stabilization, compartmentalization, and sequestration of HMs. Such modification leads to making plants capable of producing higher biomass, fast-growing, increased tolerance and resistance to multiple HMs (Koźmińska et al., 2018; Lajayer et al., 2019).

In OPs introduction of tolerance, genes can confer higher tolerance. The study conducted by Wu et al. (2011) summarized that *Petunia hybrida*, transformed with an *Arabidopsis CAX1* variant (*CAXcd*) was capable of tolerating and accumulating higher levels of Cd (2.5 times higher), than the control plants. Another approach to improve the tolerance of OPs is the introduction of bacterial/fungal catabolic or plant growth-promoting genes. The transformation of *Petunia hybrida* with bacterial genes 1-aminocyclopropane deaminase (ACC) and tryptophan/indole-3-acetic acid monooxygenase resulted in better biomass and height of transgenic compared to the wild control plants (Zhang et al., 2008). The addition of these genes can lead to fruitful results with other plants, as the biomass is a limiting factor in most phytoremediation studies. Another scheme that can be used for the transformation of OPs is introducing genes coding for metal chelators called phytochelatins (Koźmińska et al., 2018).

Depending on the source of gene and model used, one of the issues that can arise upon the transformation of OPs with PCs from other plants is that PCs' expression and production can affect the HMs transpiration and compartmentalization significantly in the transgenics. The transformation of *Populus tomentosa* Carr. (Common name: Poplar plant) phytochelatin synthase (*PtPCS*) gene into *Nicotiana tabacum* L. resulted in lower Cd translocation into the aerial parts of *PtPCS* transgenics (Chen et al., 2015). Contrary to this, Shukla et al. (2013) reported that the transformation of *Ceratophyllum demersum* L. (Common name: Coontail) phytochelatin synthase ($CdPCS_1$) in *Arabidopsis* plant improved Cd and As accumulation and uptake. Co-overexpression of multiple genes responsible for metal homeostasis in OPs can also be interesting, and by this approach, a potential hyperaccumulator can be obtained (Koźmińska et al., 2018).

It was proven by the findings of Zhao et al. (2014). According to them, co-expression of a *Phragmites australis* (Common name: Reed) glutamyl cysteine synthetase gene (*PaGCS*) with

P. australis PC synthase (*PaPCS*) in *Festuca arundinacea* (Common name: Tall Fescue) improved the PCs activity, and due to co-expression of both genes, the double transgenic plant of *F. arundinacea* performed higher Cd translocation and accumulation, in comparison to the wild-type and single gene transformed plants (Zhao et al., 2014).

5. Case studies related to OPs & OTs mediated HMs remediation

The field application of OPs for removing HMs is practised in a different part of the world. The results and response of these applications remained encouraging. For instance, flowering OPs belonging to *Canna, Iris, Heliconia, and Zantedeschia* were reported to improve the efficiency of constructed wetland up to 30% compared with constructed wetland without flowering OPs (Sandoval et al., 2019). While in some places OPs show limited or no positive impact of phytoremediation. To overcome this issue, the synergistic application, along with the method explained in Table 3. One such study was conducted in Alborz city, Iran. It was found that the simultaneous addition biosolids, collected from the Tehran based urban wastewater treatment plants, along with cow manure significantly improves the growth and HMs (Ni, Pb, and Zn) accumulation capacity of *Helianthus annuus* L. (Yazdanbakhsh et al., 2020). These resulted were also supported by the previously conducted study by Mukhtar et al., (2010).

Chengli et al., (2020) reported a case study for the impacts of OPs on the soil heavy metal pollution (Cd, Cr, Cu, Pb and Zn) in Kaifeng City, China. The studied OPs included *Argyranthemum frutescens, Chrysanthemum morifolium, Dendranthema morifolium,* and *Tagetes patula.* It was proposed that the use of OPs benefited Kaifeng city's environment as these OPs helped in daily dust retention, released oxygen released and fixed carbon dioxide content per day, which is increased by increasing the OPs cultivation density. The OPs showed the following absorption capacity: Cr> Cd > Pb > Zn > Cu, with *C. morifolium* showing the best response.

Aquatic and terrestrial OPs can be used to remove nutrient and heavy metals (Cr, Pb, Cd) in the wastewater. *Iris pseudacorus* L. and *Acorus gramineus* Soland (Common name: Japanese sweet flag) were considered terrific selections for managing composite-polluted urban wastewater (Zhang et al., 2007). The availability of freshwater is expected to get scarce in the urban centre, and hence using greywater ornamental plants will be cultivated. This greywater can contain the nutrient and thus promote plant growth. Shaharoona et al., (2019) conducted one such study in Oman. It was found that 28% of respondents use wastewater for irrigation, as it is believed that it can help improve plants growth and yield due to the nutrient richness. This trend will surely be rise further, as more people are shifting to urban and suburban areas, with time.

Polianthes tuberosa (Common name: Teberose) was used by Singh and Srivastava, (2016) for the removal of HMs (Cu, Zn, Ni, Al, Pb, and Fe) from domestic wastewater in horizontal subsurface flow constructed wetland. It was discovered that HMs concentrations followed the following biological concentration factor trend Al $\gg$ Zn > Cu > Ni > Pb > Fe. Further, the compartmentalization was highest in roots, followed by rhizomes, leaves, and inflorescence, respectively. It is a way wastewater can be treated, and the flower cuttings and potted OPs can be sold to generate revenue. Similarly, HMs contaminated CWs can also be subjected to treatment using OPs. Aquatic OPs *Pontederia cordata* (Common name: Pickerelweed) has been reported as a prospective OPs the phytoremediation of Cd contaminated wetlands, sequestering 50–77% of the Cd^{2+} in the plant roots (Xin et al., 2020).

The OPs and OTs can be used to study the fluctuations in HMs of a region. Sevik et al., (2020) reported a study in which HMs (Pb, Co, and Fe) concentrations tree rings (the inner and outer bark) of Cedar tree (*Cedrus sp*.) cut by the end of 2016, in Kastamonu province, Turkey. It was done to perform a retrospective investigation of atmospheric HMs in 2016. It was found that the HMs were in higher concentration in the road-facing bark than in the inward-facing bark. Hence, OTs' collected biomass can also be used to study the impact of HMs and particulate matter on human health (Manzoor et al., 2016). Turkyilmaz et al., (2019) also proposed the same outcomes in a case study conduct in Ankara, Turkey, by analysing HMs deposition in *Quercus laevis* rings.

6. Challenges and future perspective of OPs mediated HMs phytoremediation

In the recent decade, the picture of soil as an inert solid matrix that passively presents its services to the ecosystem's abiotic and biotic components has been changed. It is recognized as the dynamic matrix, having complex biological, chemical, and physical interactions, which play an essential role in shaping the microbial diversity, the fate of a nutrient and contaminant by regulating the biogeochemical cycles and affecting human, animals, and plants (Khan et al., 2019c). Hence soil plays a significant role in the overall ecological processes in science and engineering, well recognized in the academic and professional world (Cecchin et al., 2017). Similarly, water is also recognized as a dynamic body (Rinke et al., 2019). The removal of HMs with biological methods, notably, phytoremediation has received much attention in recent decades. Heavy metals are non-degradable, and if no attention is given to this, the xenobiotic concentration of HMs will end up into one of the environmental compartments (Tiwari and Lata, 2018). Many methods can be adapted to implement successful phytoremediation of HMs contaminated site using OPs, which were discussed previously in section 4 of this review. Still, certain obstacles should be kept into consideration while designing the OPs mediated phytoremediation. Several strategies have been successfully applied to generate plants which can grow in metal contaminated soils and accumulate or tolerate metal stress.

The notable challenges and their prospects for successful remediation or recreational strategy using OPs for the HMs contaminated site are summarized in Figure 2. The most crucial factor in phytoremediation is the potential plant's choice (Thakur and Sharma, 2016). The response of plants to HMs is highly variable, as different factors play a significant role in it, which included ecotype of plant, and specific HM tolerance. Furthermore, the tolerance against one metal is not sure whether the same plant can tolerate other HMs. That’s why many selected HMs accumulators, and hyperaccumulators failed at the field and industrial scale (Sharma et al., 2016; Thakur and Sharma, 2016). Rigorous screening for tolerance against HMs and site-specific parameters is needed for successful implementation of phytoremediation. The site-specific parameters that should be considered include temperature, water availability, soil conditions, HMs contamination levels, presence of other contaminants, and economic factors.

Further, the impact of plant-microbe associations concerning ornamental plants has not been investigated in-depth, in previous studies. Another challenge is to overcome the problem of heterogeneous contamination of the contaminated sites. The fruitfulness of HMs remediation with OPs should be tested against multi HMs. With this strategy, a minimal depiction of the original site can be achieved, while these findings' output will become more practical. The same idea was also proposed by Thakur and Sharma (2016). They suggested that for successful phytoremediation in field conditions, each site's complexity should be considered, as the choice of plant and associated axillary things varies with site conditions.

The selection of the phytoremediation process is also critical. It is essential as the end-product can carry a higher level of HMs if the used plant was an HM hyperaccumulator. The HMs are non-degradable so; a secondary HMs stabilization process is needed. The inappropriate disposal of the harvested plants can raise environmental concerns due to the high load of HMs (Aftab et al., 2020). The secondary process that can be adopted includes pyrolysis, where the plant residues can be converted into catalytic carbon, as reported by Álvarez-Mateos et al. (2019). They converted *Jatropha curcas* L. (Common name: Jatropha) biomass, generated after the process of phytoremediation of the highly contaminated mining site, into catalytic carbon by the process of pyrolysis. Production of biochar from residues of OPs caused after HMs phytoremediation is also reported. *Silphium perfoliatum* L. (Common name: Cup plant) containing high levels of Cd, Pb, and Zn was successfully converted into biochar, that stabilized the already absorbed HMs, and HMs were further stabilized through adsorption to produced biochar (Du et al., 2019).

Metal(liod) recovery and valorisation can also be used for the stabilization of HMs. Eze and Harvey (2018) reported the phytoremediation of As containing soil (200 mg kg^{-1}) with the help of *Pteris cretica* (Common name: Cretan brake fern). The biomass is used to produce valuable As products (including As nanoparticles (NPs), and magnesium arsenate). Another attractive alternative that can be used is phytomining. In phytomining, the HMs containing plant parts can be converted into bio-ores, which is achieved by the controlled combustion of plant residues of the harvested plants resulting in ash's energy production and formation (Ali et al., 2013). The resulting ash can be used for metal recovery and recovered metals and metalloids can produce green NPs. A study conducted by Keshavarzi et al. (2018) reported Au ion bio-reduction to Au NPs, using three different varieties, Nikshahri, Hamedani, and Yazdi, of Iranian *Medicago sativa* (Common name: Alfalfa). They found that at pH 4.7 with a three mM Au ion concentration Hamedani variety was best for green production of Au NPs. In another study, Gul et al., (2020) evaluated the extraction and recovery of Pb using *Pelargonium hortoum* (Common name: Garden geranium). Flowers of OPs also have economic value as they can be sold (Khan et al., 2020a; Mushtaq et al., 2020). They can also be used to produce essential oils for fragrances (Lajayer et al., 2019). To date, no report supports the presence of HMs in OPs essential oil and further research in this domain is also needed. Participation of professional belonging to environmental, and landscape science and stakeholders, including enterprises and responsible authorities is essential. This mutual collaboration will result in positive outcomes in the provision of sustainable results from clean-up missions and practical employment of more environmentally friendly technologies with close to zero emissions that are important in the scope of minimizing climate change problems.

7. Post-phytoremediation management legislations for the harvested OPs biomass

One primary consideration needed for the final and effective utilization biomass produced after the HMs remediation. It requires the development of biomass management acts and policies after phytoremediation. As suggested by Song and Park (2017), the first stage is to prohibit the use of toxic residues in compost. For this, there are many instruments and legal codes around the world. Among the notable examples of acts that mention control mobility of hazardous waste, includes “Hazardous Substances Rules, 2003” in Pakistan, “Hazardous and Other Wastes (Management and Trans-boundary Movement) Rules, 2016” in India, “Wastes Control Act (Act Number 13038)” in South Korea, “Urban Waste Water Treatment Directive (91/271/EEC)” and “Sewage Sludge Directive (86/278/EEC)” in Europe, and “Solid Waste Disposal Act (Public law 89-272)” in USA. However, none of these acts or laws specifically concerned with post-remediation biomass. It is therefore vital to improve the management of contaminated biomass additional legislation should be considered.

Further, the promotion of post-remediation biomass usage proven safe for consumption, as per the first-stage policy measures, is the second measure needed to be implemented for effective policymaking and execution. Therefore, any government must set out obligation through national environmental quality standards (NEQS). These NEQS can prevent phytoremediation biomass related secondary pollution, cut the cycle of toxic pollutants, and promote close-loop cycling of biomass using environmentally acceptable and sustainable methods.

8. Recommendations

As the OPs mediated HMs phytoremediation is dual advantageous, for both recreational and remediational purposes, interdisciplinary nature research must be done, to identify the depth of knowledge and to improve the overall process. Extensive screening of OPs in needed to find HMs tolerant, accumulator, and hyperaccumulators. The use of biological (natural and synthetic) and chemical amendment must be exposed with OPs for HMs phytoremediation. The OPs currently used (commonly and extensively), plants belonging to *Asteraceae, Liliaceae, Nicotiana, Nymphaeaceae, Petunia,* and *Rosaceae,* must be exposed first their agronomic practice are well developed. The results contribute to the knowledge of phytoremediation and reduce the risk of economic loss to the horticulture market of the studied plants.

A well in-depth risk assessment is needed to be conducted to quantify the benefits or shortcomings of OPs over other crop and previously used plants. A cost-benefit analysis will be beneficial to quantify the efficacy of OPs in phytoremediation and applicability of green technologies. The better understanding of metal, soil, microbes, and plant roots the key four rhizosphere players will quantify the improvement or negative impacts of HM-OPs interaction. The current knowledge of plant HMs exposure must be extended from single HM exposure to multiple HMs conditions, as in real condition the site is contaminated with numerous contaminants. The OPs have shown promising results when cultivated on synthetic wastewater. Ornamental Plants like *Celosia argentea* L., *Catharanthus roseus* (L.) G. Don, *Petunia hybrida* L., *Nicotiana alata* L. are among the example of few recently tested plant against such heterogenous HMs contaminated wastewater (Iqbal et al., 2019; Khan et al., 2019b: Mushtaq et al., 2020).

In vitro testing system should be established to preserve the time required to test potential OPs, which can tolerate/remediate the contaminate(s). These include tissue culture, plant enzymes and extracts, components of live plants, and soilless media like hydroponics. Such systems allow quick characterization of plants for their effectiveness in tolerating, accumulating, or degradation of contaminant(s). A few examples are presented in Table 5. Further, OPs must be tested for other pollutants like hydrocarbons, pesticides, dyes, antibiotics, and persistent organics. The OPs *Acorus calamus* performed remediation of soil co-contaminated with cadmium and polycyclic aromatic hydrocarbons (Jeelani et al., 2017). Similarly, Chandanshive et al., (2018) reported efficient removal of dyes from textile wastewater, stabilising HMs (Cd, As, Pb and Cr) using *Tagetes patula*, *Aster amellus*, *Portulaca grandiflora* and *Gaillardia grandiflora.* The potential of OPs extends to the removal of antibiotics. Li et al., (2020) reported that *Mirabilis jalapa* L. and *Tagetes patula* L. are favourable OPs intended to remediate alkaline soil co-contaminated with Cd and tetracycline.

The International Union of Pure and Applied Chemistry and other forums must address to update the definition of HMs and prepare the periodic table according to HMs toxicity. Unfortunately, trace metals do not fit for Cd, Ni, and Pb in the current scenario, as they are not needed even in the minute concentration by plant and animal. At the same time, terms can be used with some reservation for Cu and Cr. Duffus (2002) also proposed a periodic table classification based on the understanding of the chemical basis of toxicity and toxic effects to be predicted.

9. Conclusions

The use of OPs brings dual benefits, remediational and recreational at the same time, so their use must be promoted when designing the HMs phytoremediation strategy. They offer a reduced risk of biomagnification as compared to the crop plants. This work focused on the mechanisms of HMs toxicity to plants, the possibility of using OPs in HMs phytoremediation, and methods to improve their growth in field conditions. The most critical factor for HMs phytoremediation is selecting native OPs; this will reduce the time required for initial screening. It is important to note that HM-OPs interaction can reduce OPs growth and biomass, which can be improved with the use of soil conditioners, appropriate OPs-microbe interactions, and the introduction of transgenes, or/and use of synthetic and organic compounds. These substitutions will improve plant growth by HMs compartmentalization, sequestering, and detoxification. It is achieved through a range of enzymatic and non-enzymatic antioxidants, reducing the toxicity to aerial parts and plants' roots. Further, the detailed mechanisms of HMs toxicity, sequestering and compartmentalization using OPs with other amendments are needed to be investigated. The risk assessment associated with the valuable products formed by OPs grown on HMs contaminated site; specifically pot plants, cut flowers, and essential oils, is another crucial thing that is needed is to perform.

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References

Abbas, A.M., Abd-Elmabod, S.K., El-Ashry, S.M., Soliman, W.S., El-Tayeh, N., Castillo, J.M., 2019. Capability of the invasive tree *Prosopis glandulosa* Torr. to remediate soil treated with sewage sludge. Sustainability 11, 2711.

Aftab, N., Saleem, K., Khan, A., Butt, T., Mirza, C., Hussain, J., Farooq, G., Tahir, A., Yousaf, S., Zafar, M., 2020. *Cosmos sulphureus* Cav. is more tolerant to lead than copper and chromium in hydroponics system. Int J Environ Sci Technol 2020, 1-10.

Ahmad, M., Hussain, M., Saddiq, R., Alvi, A., 2007. Mungbean: a nickel indicator, accumulator or excluder? B Environ Contam Tox 78, 319-324.

Ai, T.N., Naing, A.H., Yun, B.-W., Lim, S.H., Kim, C.K., 2018. Overexpression of RsMYB1 enhances anthocyanin accumulation and heavy metal stress tolerance in transgenic *Petunia*. Front Plant Sci 9, 1388.

Alaboudi, K.A., Ahmed, B., Brodie, G., 2018. Phytoremediation of Pb and Cd contaminated soils by using sunflower (*Helianthus annuus*) plant. Ann Agric Sci 63, 123-127.

Ali, H., Khan, E., Sajad, M.A., 2013. Phytoremediation of heavy metals—concepts and applications. Chemosphere 91, 869-881.

Alirzayeva, E., Neumann, G., Horst, W., Allahverdiyeva, Y., Specht, A., Alizade, V., 2017. Multiple mechanisms of heavy metal tolerance are differentially expressed in ecotypes of *Artemisia fragrans*. Envrion Pollut 220, 1024-1035.

Álvarez-Mateos, P., Alés-Álvarez, F.-J., García-Martín, J.F., 2019. Phytoremediation of highly contaminated mining soils by *Jatropha curcas* L. and production of catalytic carbons from the generated biomass. J Environ Manage 231, 886-895.

Ángeles-Argáiz, R.E., Flores-García, A., Ulloa, M., Garibay-Orijel, R., 2016. Commercial Sphagnum peat moss is a vector for exotic ectomycorrhizal mushrooms. Biol Invasions 18, 89-101.

Angelova, V.R., Grekov, D.F., Kisyov, V.K., Ivanov, K.I., 2015. Potential of lavender (*Lavandula vera* L.) for phytoremediation of soils contaminated with heavy metals. Int J Biol Biomol Agric Food Biotechnol Eng 9, 465-472.

Arbolino, R., Carlucci, F., De Simone, L., Ioppolo, G., Yigitcanlar, T., 2018. The policy diffusion of environmental performance in the European countries. Ecol Indic 89, 130-138.

Arshad, M., Khan, A.H.A., Hussain, I., Anees, M., Iqbal, M., Soja, G., Linde, C., Yousaf, S., 2017. The reduction of chromium (VI) phytotoxicity and phytoavailability to wheat (*Triticum aestivum* L.) using biochar and bacteria. Appl Soil Ecol 114, 90-98.

Aziz, H.A., Adlan, M.N., Ariffin, K.S. 2008. Heavy metals (Cd, Pb, Zn, Ni, Cu and Cr (III)) removal from water in Malaysia: Post treatment by high quality limestone. Bioresource Technol 99, 1578-1583.

Barouchas, P.E., Akoumianaki-Ioannidou, A., Liopa-Tsakalidi, A., Moustakas, N.K., 2018. Effects of Vanadium and Nickel on Morphological Characteristics and on Vanadium and Nickel Uptake by Shoots of Mojito (*Mentha*× *villosa*) and Lavender (*Lavandula anqustifolia*). Not Bot Horti Agrobo 47, 487-492.

Bourgeois, B., Rochefort, L., Bérubé, V., Poulin, M., 2018. Response of plant diversity to moss, *Carex* or *Scirpus* revegetation strategies of wet depressions in restored fens. Aquat Bot 151, 19-24.

Brewer, C.E., Hall, E.T., Schmidt-Rohr, K., Laird, D.A., Brown, R.C., Zygourakis, K., 2017. Temperature and reaction atmosphere effects on the properties of corn stover biochar. Environ Prog Sustain Energy 36, 696-707.

Caldelas, C., Bort, J., Febrero, A., 2012. Ultrastructure and subcellular distribution of Cr in *Iris pseudacorus* L. using TEM and X-ray microanalysis. Cell Biol Toxicol 28, 57-68.

Calvert, T., Sinnett, D., Smith, N., Jerome, G., Burgess, S., King, L., 2018. Setting the standard for green infrastructure: The need for, and features of, a benchmark in England. Plan Pract R 33, 558-573.

Canellas, L.P., Olivares, F.L., Aguiar, N.O., Jones, D.L., Nebbioso, A., Mazzei, P., Piccolo, A., 2015. Humic and fulvic acids as biostimulants in horticulture. Sci Hortic 196, 15-27.

Cano-Ruiz, J., Galea, M.R., Amorós, M., Alonso, J., Mauri, P., Lobo, M.C., 2020. Assessing Arundo donax L. in vitro-tolerance for phytoremediation purposes. Chemosphere 252, 126576.

Cao, X., Ma, L.Q., Shiralipour, A., 2003. Effects of compost and phosphate amendments on arsenic mobility in soils and arsenic uptake by the hyperaccumulator, *Pteris vittata* L. Envrion Pollut 126, 157-167.

Cárdenas-Aguiar, E., Gascó, G., Paz-Ferreiro, J., Méndez, A., 2017. The effect of biochar and compost from urban organic waste on plant biomass and properties of an artificially copper polluted soil. Int Biodeter Biodegr 124, 223-232.

Cay, S., 2016. Enhancement of cadmium uptake by *Amaranthus caudatus*, an ornamental plant, using tea saponin. Environ Monit Assess 188, 320.

Cay, S., Uyanik, A., Engin, M.S., 2016. EDTA supported phytoextraction of Cd from contaminated soil by four different ornamental plant species. Soil Sediment Contam 25, 346-355.

Cay, S., Uyanik, A., Engin, M.S., Kutbay, H.G., 2015. Effect of EDTA and tannic acid on the removal of Cd, Ni, Pb and Cu from artificially contaminated soil by *Althaea rosea* Cavan. Int J Phytoremediat 17, 568-574.

Cazalis, V., Loreau, M., Henderson, K., 2018. Do we have to choose between feeding the human population and conserving nature? Modelling the global dependence of people on ecosystem services. Sci Total Environ 634, 1463-1474.

Cecchin, I., Reddy, K.R., Thomé, A., Tessaro, E.F., Schnaid, F., 2017. Nanobioremediation: Integration of nanoparticles and bioremediation for sustainable remediation of chlorinated organic contaminants in soils. Int Biodeter Biodegr 119, 419-428.

Chandanshive, V.V., Kadam, S.K., Khandare, R.V., Kurade, M.B., Jeon, B.-H., Jadhav, J.P., Govindwar, S.P., 2018. In situ phytoremediation of dyes from textile wastewater using garden ornamental plants, effect on soil quality and plant growth. Chemosphere 210, 968-976.

Chen, Y., Liu, Y., Ding, Y., Wang, X., Xu, J., 2015. Overexpression of *PtPCS* enhances cadmium tolerance and cadmium accumulation in tobacco. Plant Cell Tiss Org 121, 389-396.

Chengli, Z., Jing, Q., Weiping, Z., Yuchen, L., Shaoyu, W., Jingchao, L., Zhiyong, G., Jianhua, M., Chaosheng, Z., 2020. Study on the remediation effect and environmental benefits of ornamental plants on heavy metal soil: A case study of Kaifeng City *Chrysanthemum*. Environ Chem 7, 1883-1893.

Chirakkara, R.A., Reddy, K.R., 2015. Biomass and chemical amendments for enhanced phytoremediation of mixed contaminated soils. Ecol Eng 85, 265-274.

Coelho, L.C., Bastos, A.R.R., Pinho, P.J., Souza, G.A., Carvalho, J.G., T Coehlo, V.A., Oliveira, L.C.A., Domingues, R.R., Faquin, V., 2017. Marigold (*Tagetes erecta*): The potential value in the phytoremediation of chromium. Pedosphere 27, 559-568.

del Carmen Durán-Domínguez-de, M., Navarro-Frómeta, A.E., Bayona, J.M., 2018. Greenhouse Gas Emissions and Treatment Performance in Constructed Wetlands with Ornamental Plants: Case Studies in Veracruz, Mexico María Elizabeth Hernández-Alarcón and José Luis Marín-Muñiz, Artificial or Constructed Wetlands. CRC Press, pp 171-185.

Du, J., Zhang, L., Ali, A., Li, R., Xiao, R., Guo, D., Liu, X., Zhang, Z., Ren, C., Zhang, Z., 2019. Research on thermal disposal of phytoremediation plant waste: Stability of potentially toxic metals (PTMs) and oxidation resistance of biochars. Process Safety Environ 125, 260-268.

Duffus, J.H., 2002. “Heavy metals” a meaningless term? (IUPAC Technical Report). Pure Appl Chem 74, 793-807.

Egene, C.E., Van Poucke, R., Ok, Y., Meers, E., Tack, F., 2018. Impact of organic amendments (biochar, compost and peat) on Cd and Zn mobility and solubility in contaminated soil of the Campine region after three years. Sci Total Environ 626, 195-202.

El-Naggar, N.E.-A., Hamouda, R.A., Mousa, I.E., Abdel-Hamid, M.S., Rabei, N.H., 2018. Statistical optimization for cadmium removal using *Ulva fasciata* biomass:

Characterization, immobilization and application for almost-complete cadmium removal from aqueous solutions. Sci Rep 8, 12456.

Etim, U., Umoren, S., Eduok, U., 2016. Coconut coir dust as a low cost adsorbent for the removal of cationic dye from aqueous solution. J Saudi Chem Soc 20, S67-S76.

Eze, V.C., Harvey, A.P., 2018. Extractive recovery and valorisation of arsenic from contaminated soil through phytoremediation using *Pteris cretica*. Chemosphere 208, 484-492.

Fascella, G., 2015. Growing substrates alternative to peat for ornamental plants: Soilless culture-Use of substrates for the production of quality horticultural crops. IntechOpen, pp 51-54

García-Delgado, C., Fresno, T., Rodríguez-Santamaría, J., Diaz, E., Mohedano, A., Moreno-Jimenez, E., 2019. Co-application of activated carbon and compost to contaminated soils: toxic elements mobility and PAH degradation and availability. Int J Environ Sci Te 16, 1057-1068.

Gill, S.S., Tuteja, N., 2011. Cadmium stress tolerance in crop plants: probing the role of sulfur. Plant Signal Behav 6, 215-222.

Gong, X., Li, S., Sun, X., Wang, L., Cai, L., Zhang, J., Wei, L., 2018. Green waste compost and vermicompost as peat substitutes in growing media for geranium (*Pelargonium zonale* L.) and calendula (*Calendula officinalis* L.). Sci Hortic 236, 186-191.

Goswami, S., Das, S., 2016. Copper phytoremediation potential of *Calandula officinalis* L. and the role of antioxidant enzymes in metal tolerance. Ecotox Enivron Safe 126, 211-218.

Guarino, F., Conte, B., Improta, G., Sciarrillo, R., Castiglione, S., Cicatelli, A., Guarino, C., 2018. Genetic characterization, micropropagation, and potential use for arsenic phytoremediation of *Dittrichia viscosa* (L.) Greuter. Ecotox Enivron Safe 148, 675-683.

Ha, T., Dieperink, C., Otter, H.S., Hoekstra, P., 2018. Governance conditions for adaptive freshwater management in the Vietnamese Mekong Delta. J Hydrol 557, 116-127.

Haase, D., 2015. Reflections about blue ecosystem services in cities. Sustaina Water Qual Ecol 5, 77-83.

Habiba, U., Ali, S., Farid, M., Shakoor, M.B., Rizwan, M., Ibrahim, M., Abbasi, G.H., Hayat, T., Ali, B., 2015. EDTA enhanced plant growth, antioxidant defense system, and phytoextraction of copper by *Brassica napus* L. Environ Sci Pollut R 22, 1534-1544.

He, C.Q., Tan, G., Liang, X., Du, W., Chen, Y., Zhi, G., Zhu, Y., 2010. Effect of Zn-tolerant bacterial strains on growth and Zn accumulation in *Orychophragmus violaceus*. Appl Soil Ecol 44, 1-5.

Huang, J., Yang, Z., Li, J., Liao, M.a., Lin, L., Wang, J., Yang, Y., Liang, D., Xia, H., Wang, X., 2017. Cadmium accumulation characteristics of floricultural plant *Cosmos bipinnata.* Chem Ecol 33, 807-816.

Hussain, F., Hussain, I., Khan, A.H.A., Muhammad, Y.S., Iqbal, M., Soja, G., Reichenauer, T.G., Yousaf, S., 2018. Combined application of biochar, compost, and bacterial consortia with Italian ryegrass enhanced phytoremediation of petroleum hydrocarbon contaminated soil. Environ Exp Bot 153, 80-88.

Iqbal, A., Mushtaq, M.U., Khan, A.H.A., Nawaz, I., Yousaf, S., Iqbal, M., 2019. Influence of *Pseudomonas japonica* and organic amendments on the growth and metal tolerance of *Celosia argentea* L. Environ Sci Pollut R, 27:24671–24685

Jeelani, N., Yang, W., Xu, L., Qiao, Y., An, S., Leng, X., 2017. Phytoremediation potential of *Acorus calamus* in soils co-contaminated with cadmium and polycyclic aromatic hydrocarbons. Sci Rep 7, 8028.

Jegajeevagan, K., Mabilde, L., Gebremikael, M.T., Ameloot, N., De Neve, S., Leinweber, P., Sleutel, S., 2016. Artisanal and controlled pyrolysis-based biochars differ in biochemical composition, thermal recalcitrance, and biodegradability in soil. Biomass Bioenerg 84, 1-11.

Jiang, Y., Jiang, S., Li, Z., Yan, X., Qin, Z., Huang, R., 2019. Field scale remediation of Cd and Pb contaminated paddy soil using three mulberry (*Morus alba* L.) cultivars. Ecol Eng 129, 38-44.

Jin, Z., Li, J., Li, Y., 2015. Interactive effects of arbuscular mycorrhizal fungi and copper stress on flowering phenology and reproduction of *Elsholtzia splendens*. PloS One 10, e0145793.

Kalve, S., Sarangi, B.K., Pandey, R.A., Chakrabarti, T., 2011. Arsenic and chromium hyperaccumulation by an ecotype of *Pteris vittata*–prospective for phytoextraction from contaminated water and soil. Curr Sci, 100, 888-894.

Kalyvas, G., Tsitselis, G., Gasparatos, D., Massas, I., 2018. Efficacy of EDTA and Olive Mill Wastewater to Enhance As, Pb, and Zn Phytoextraction by *Pteris vittata* L. from a Soil Heavily Polluted by Mining Activities. Sustainability 10, 1962.

Kern, J., Tammeorg, P., Shanskiy, M., Sakrabani, R., Knicker, H., Kammann, C., Tuhkanen, E.-M., Smidt, G., Prasad, M., Tiilikkala, K., 2017. Synergistic use of peat and charred material in growing media–an option to reduce the pressure on peatlands? J Environ Eng Landsc Manage 25, 160-174.

Keshavarzi, M., Davoodi, D., Pourseyedi, S., Taghizadeh, S., 2018. The effects of three types of alfalfa plants (*Medicago sativa*) on the biosynthesis of gold nanoparticles: An insight into phytomining. Gold Bulletin 51, 99-110.

Khan, A.H.A., Anees, M., Arshad, M., Muhammad, Y.S., Iqbal, M., Yousaf, S., 2016a. Effects of illuminance and nutrients on bacterial photo-physiology of hydrocarbon degradation. Sci Total Environ 557, 705-711.

Khan, A.H.A., Ayaz, M., Arshad, M., Yousaf, S., Khan, M.A., Anees, M., Sultan, A., Nawaz, I., Iqbal, M., 2019c. Biogeochemical cycle, occurrence and biological treatments of polycyclic aromatic hydrocarbons (PAHs). Iran J Sci Technol A 43, 1393-1410.

Khan, A.H.A., Butt, T.A., Mirza, C.R., Yousaf, S., Nawaz, I., Iqbal, M., 2019a. Combined application of selected heavy metals and EDTA reduced the growth of *Petunia hybrida* L. Sci Rep 9, 4138.

Khan, A.H.A., Kiyani, A., Cheema, A.S., Tareen, U., Nawaz, I., Iqbal, M., Yousaf, S., 2020a. Integrative Application of Soil Conditioners and Bio-augmentation for Enhanced Heavy Metal Stabilization from Wastewater and Improved Growth of *Nicotiana alata* L. and *Petunia hydrida* L. J Plant Growth Regul, 1-14.

Khan, A.H.A., Nawaz, I., Qu, Z., Butt, T.A., Yousaf, S., Iqbal, M., 2020b. Reduced growth response of ornamental plant *Nicotiana alata* L. upon selected heavy metals uptake, with co-application of ethylenediaminetetraacetic acid. Chemosphere 241, 125006.

Khan, A.H.A., Nawaz, I., Yousaf, S., Cheema, A.S., Iqbal, M., 2019b. Soil amendments enhanced the growth of *Nicotiana alata* L. and *Petunia hydrida* L. by stabilizing heavy metals from wastewater. J Environ Manage 242, 46-55.

Khan, A.H.A., Tanveer, S., Alia, S., Anees, M., Sultan, A., Iqbal, M., Yousaf, S., 2017b. Role of nutrients in bacterial biosurfactant production and effect of biosurfactant production on petroleum hydrocarbon biodegradation. Ecol Eng 104, 158-164.

Khan, A.H.A., Tanveer, S., Anees, M., Muhammad, Y.S., Iqbal, M., Yousaf, S., 2016b. Role of nutrients and illuminance in predicting the fate of fungal mediated petroleum hydrocarbon degradation and biomass production. J Environ Manage 176, 54-60.

Khan, A.R., Waqas, M., Ullah, I., Khan, A.L., Khan, M.A., Lee, I.-J., Shin, J.-H., 2017a. Culturable endophytic fungal diversity in the cadmium hyperaccumulator *Solanum nigrum* L. and their role in enhancing phytoremediation. Environ Exp Bot 135, 126-135.

Khandare, R.V., Kabra, A.N., Kurade, M.B., Govindwar, S.P., 2011. Phytoremediation potential of Portulaca grandiflora Hook.(Moss-Rose) in degrading a sulfonated diazo reactive dye Navy Blue HE2R (Reactive Blue 172). Bioresource Technol 102, 6774-6777.

Komives, T., Gullner, G., 2006. Dendroremediation: the use of trees in cleaning up polluted soils, Phytoremediation Rhizoremediation. Springer, pp 23-31.

Koźmińska, A., Wiszniewska, A., Hanus-Fajerska, E., Muszyńska, E., 2018. Recent strategies of increasing metal tolerance and phytoremediation potential using genetic transformation of plants. Plant Biotechnol Rep 12, 1-14.

Lajayer, B.A., Ghorbanpour, M., Nikabadi, S., 2017. Heavy metals in contaminated environment: Destiny of secondary metabolite biosynthesis, oxidative status and phytoextraction in medicinal plants. Ecotox Enivron Safe 145, 377-390.

Lajayer, B.A., Moghadam, N.K., Maghsoodi, M.R., Ghorbanpour, M., Kariman, K., 2019. Phytoextraction of heavy metals from contaminated soil, water and atmosphere using ornamental plants: mechanisms and efficiency improvement strategies. Environ Sci Pollut R 2019, 1-17.

Lam, E.J., Gálvez, M.E., Cánovas, M., Montofré, Í.L., Keith, B.F., 2018. Assessment of the adaptive capacity of plant species in copper mine tailings in arid and semiarid environments. J Soil Sediment 2018, 1-14.

Lan, X.-Y., Yang, B., Yan, Y.-Y., Li, X.-Y., Xu, F.-L., 2018. Resistance mechanisms and their difference between the root and leaf of *Microsorum pteropus*–A novel potential aquatic cadmium hyperaccumulator. Sci Total Environ 616, 480-490.

Lange, B., Ent, A., Baker, A.J.M., Echevarria, G., Mahy, G., Malaisse, F., Meerts, P., Pourret, O., Verbruggen, N., Faucon, M.P., 2017. Copper and cobalt accumulation in plants: a critical assessment of the current state of knowledge. New Phytol 213, 537-551.

Lee, S.-J., Park, J.H., Ahn, Y.-T., Chung, J.W., 2015. Comparison of heavy metal adsorption by peat moss and peat moss-derived biochar produced under different carbonization conditions. Water Air Soil Pollut 226, 9.

Levizou, E., Antoniadis, V., Papatheodorou, S., 2016. Without exceeding the limits: industrial soil rich in Zn and Cd has no effect on purslane and lettuce but promotes geranium growth. Environ Earth Sci 75, 1256.

Li, D., Gao, Q., Xu, L., Pang, S., Liu, Z., Wang, C., Tan, W., 2017. Characterization of glutathione S-transferases in the detoxification of metolachlor in two maize cultivars of differing herbicide tolerance. Pestic Biochem Phys 143, 265-271.

Li, X., Zhu, W., Meng, G., Guo, R., Wang, Y., 2020. Phytoremediation of alkaline soils co-contaminated with cadmium and tetracycline antibiotics using the ornamental hyperaccumulators *Mirabilis jalapa* L. and *Tagetes patula* L. Environ Sci Pollut 27, 14175–14183.

Lin, M., Jin, M., Xu, K., He, L., Cheng, D., 2018. Phosphate-solubilizing bacteria improve the phytoremediation efficiency of *Wedelia trilobata* for Cu-contaminated soil. Int J Phytoremediat 20, 813-822.

Liu, J., Xin, X., Zhou, Q., 2017. Phytoremediation of contaminated soils using ornamental plants. Environ Rev 26, 43-54.

Liu, W., Zhang, C., Hu, P., Luo, Y., Wu, L., Sale, P., Tang, C., 2016. Influence of nitrogen form on the phytoextraction of cadmium by a newly discovered hyperaccumulator *Carpobrotus rossii*. Environ Sci Pollut R 23, 1246-1253.

Luo, Z.-B., Wu, C., Zhang, C., Li, H., Lipka, U., Polle, A., 2014. The role of ectomycorrhizas in heavy metal stress tolerance of host plants. Environ Exp Bot 108, 47-62.

Mahmood, T., 2010. Phytoextraction of heavy metals-the process and scope for remediation of contaminated soils. Soil Environ, 29, 91-109.

Majed, N., Real, M., Isreq, H., Akter, M., Azam, H.M., 2016. Food Adulteration and Bio-Magnification of Environmental Contaminants: A Comprehensive Risk Framework for Bangladesh. Front Environ Sci 4, 34.

Maleki, M., Ghorbanpour, M., Kariman, K., 2017. Physiological and antioxidative responses of medicinal plants exposed to heavy metals stress. Plant Gene 11, 247-254.

Mani, D., Kumar, C., Patel, N., Sivakumar, D., 2015. Enhanced clean-up of lead-contaminated alluvial soil through *Chrysanthemum indicum* L. Int J Environ Sci Te 12, 1211-1222.

Manzoor, M., Gul, I., Silvestre, J., Kallerhoff, J., Arshad, M., 2018. Screening of indigenous ornamental species from different plant families for Pb accumulation potential exposed to metal gradient in spiked soils. Soil Sediment Contam 27, 439-453.

Manzoor, M., Khan, A.H.A., Ullah, R., Khan, M.Z., Ahmad, I., 2016. Environmental epidemiology of cancer in South Asian population: risk assessment against exposure to polycyclic aromatic hydrocarbons and volatile organic compounds. Arab J Sci Eng 41, 2031-2043.

Marín-Muñiz, J.L., Hernández, M.E., Gallegos-Pérez, M.P., Amaya-Tejeda, S.I., 2020. Plant growth and pollutant removal from wastewater in domiciliary constructed wetland microcosms with monoculture and polyculture of tropical ornamental plants. Ecol Eng 147, 105658.

Marques, A.P., Moreira, H., Franco, A.R., Rangel, A.O., Castro, P.M., 2013. Inoculating *Helianthus annuus* (sunflower) grown in zinc and cadmium contaminated soils with plant growth promoting bacteria–Effects on phytoremediation strategies. Chemosphere 92, 74-83.

Marsik, P., Podlipna, R., Vanek, T., 2017. Study of praziquantel phytoremediation and transformation and its removal in constructed wetland. J Hazard Mater 323, 394-399.

Martínez, M., Bernal, P., Almela, C., Vélez, D., García-Agustín, P., Serrano, R., Navarro-Aviñó, J., 2006. An engineered plant that accumulates higher levels of heavy metals than *Thlaspi caerulescens*, with yields of 100 times more biomass in mine soils. Chemosphere 64, 478-485.

Martinico-Perez, M.F.G., Schandl, H., Fishman, T., Tanikawa, H., 2018. The Socio-Economic Metabolism of an Emerging Economy: Monitoring Progress of Decoupling of Economic Growth and Environmental Pressures in the Philippines. Ecol Econ 147, 155-166.

Masrati, G., Dwivedi, M., Rimon, A., Gluck-Margolin, Y., Kessel, A., Ashkenazy, H., Mayrose, I., Padan, E., Ben-Tal, N., 2018. Broad phylogenetic analysis of cation/proton antiporters reveals transport determinants. Nat Commun 9, 4205.

Meindl, G.A., Ashman, T.-L., 2013. The effects of aluminum and nickel in nectar on the foraging behavior of bumblebees. Envrion Pollut 177, 78-81.

Méndez, A., Cárdenas-Aguiar, E., Paz-Ferreiro, J., Plaza, C., Gascó, G., 2017. The effect of sewage sludge biochar on peat-based growing media. Biol Agric Hortic 33, 40-51.

Miao, Q., Yan, J., 2013. Comparison of three ornamental plants for phytoextraction potential of chromium removal from tannery sludge. J Mater Cycles Waste 15, 98-105.

Mukhtar, S., Bhatti, H.N., Khalid, M., Haq, M.A.U., Shahzad, S.M., 2010. Potential of sunflower (*Helianthus annuus* L.) for phytoremediation of nickel (Ni) and lead (Pb) contaminated water. Pak J Bot 42, 4017-4026.

Murik, O., Tirichine, L., Prihoda, J., Thomas, Y., Araújo, W.L., Allen, A.E., Fernie, A.R., Bowler, C., 2019. Downregulation of mitochondrial alternative oxidase affects chloroplast function, redox status and stress response in a marine diatom. New Phytol 221, 1303-1316.

Mushtaq, M., Iqbal, A., Nawaz, I., Mirza, C., Yousaf, S., Farooq, G., Ali, M., Khan, A., Iqbal, M., 2020. Enhanced uptake of Cd, Cr, and Cu in *Catharanthus roseus* (L.) G. Don by *Bacillus cereus*: application of moss and compost to reduce metal availability. Environ Sci Pollut Res 27, 39807-39818.

Nakbanpote, W., Meesungnoen, O., Prasad, M., 2016. Potential of ornamental plants for phytoremediation of heavy metals and income generation, Bioremediation and Bioeconomy. Elsevier, pp 179-217.

Ngo, H., Cavagnaro, T., 2018. Interactive effects of compost and pre-planting soil moisture on plant biomass, nutrition and formation of mycorrhizas: a context dependent response. Sci Rep 8, 1509.

Nguyen, A., Le, B.V., Richter, O., 2020. The Role of Mangroves in the Retention of Heavy Metal (Chromium): A Simulation Study in the Thi Vai River Catchment, Vietnam. Int J Env Res Pub He 17, 5823.

Nirola, R., Megharaj, M., Aryal, R., Naidu, R., 2016. Screening of metal uptake by plant colonizers growing on abandoned copper mine in Kapunda, South Australia. Int J Phytoremediat 18, 399-405.

Pandey, V.C., Souza-Alonso, P., 2019. Market opportunities: in sustainable phytoremediation, Phytomanagement of Polluted Sites. Elsevier, pp 51-82.

Pardo, T., Rodríguez-Garrido, B., Saad, R.F., Soto-Vázquez, J.L., Loureiro-Viñas, M., Prieto-Fernández, Á., Echevarria, G., Benizri, E., Kidd, P.S., 2018. Assessing the agromining potential of Mediterranean nickel-hyperaccumulating plant species at field-scale in ultramafic soils under humid-temperate climate. Sci Total Environ 630, 275-286.

Pilipović, A., Zalesny Jr, R.S., Rončević, S., Nikolić, N., Orlović, S., Beljin, J., Katanić, M., 2019. Growth, physiology, and phytoextraction potential of poplar and willow established in soils amended with heavy-metal contaminated, dredged river sediments. J Environ Manage 239, 352-365.

Pourret, O., 2018. On the necessity of banning the term "Heavy Metal" from the scientific literature. Sustainability 10, 2879.

Prapagdee, B., Wankumpha, J., 2017. Phytoremediation of cadmium-polluted soil by *Chlorophytum laxum* combined with chitosan-immobilized cadmium-resistant bacteria. Environ Sci Pollut R 24, 19249-19258.

Preston, M.D., Smemo, K.A., McLaughlin, J.W., Basiliko, N., 2012. Peatland microbial communities and decomposition processes in the James Bay Lowlands, Canada. Front Microbiol 3, 70.

Qi, J.-D., He, B.-J., Wang, M., Zhu, J., Fu, W.-C., 2019. Do grey infrastructures always elevate urban temperature? No, utilizing grey infrastructures to mitigate urban heat island effects. Sustain Cities Soc 46, 101392

Ramana, S., Biswas, A., Ajay, Singh, A., Srivastava, S., Naqvi, A., 2016. Potential of Mestha (*Hibiscus sabdarifa*) for Remediation of Soils Contaminated with Chromium. J Nat Fibers 13, 597-602.

Ramana, S., Biswas, A.K., Singh, A.B., Ajay, Ahirwar, N.K., Subba Rao, A., 2015. Tolerance of ornamental succulent plant crown of thorns (*Euphorbia milli*) to chromium and its remediation. Int J Phytoremediat 17, 363-368.

Ramírez, A., García, G., Werner, O., Ros, R.M., 2020. In vitro lead tolerance and accumulation in three *Chrysanthemum* cultivars for phytoremediation purposes with ornamental plants. Int J Phytoremediat, 22, 1-12.

Raza, A., Khan, A.H.A., Nawaz, I., Qu, Z., Yousaf, S., Ali, M.A., Sayal, A.U., Iqbal, M., 2019. Evaluation of arsenic-induced stress in *Dahlia pinnata* Cav.: morphological and physiological response. Soil Sediment Contam 28, 716-728.

Redfern, L.K., Gunsch, C.K., 2016. Endophytic phytoaugmentation: treating wastewater and runoff through augmented phytoremediation. Ind Biotechnol 12, 83-90.

Rinke, K., Keller, P.S., Kong, X., Borchardt, D., Weitere, M., 2019. Ecosystem Services from Inland Waters and Their Aquatic Ecosystems, Atlas of Ecosystem Services. Springer, pp 191-195.

Roquigny, R., Novinscak, A., Biessy, A., Filion, M., 2017. Pseudomonadaceae: From biocontrol to plant growth promotion, Rhizotrophs: Plant Growth Promotion to Bioremediation. Springer, pp 39-68.

Sanchez-Monedero, M., Cayuela, M., Roig, A., Jindo, K., Mondini, C., Bolan, N., 2018. Role of biochar as an additive in organic waste composting. Bioresource Technol 247, 1155-1164.

Sandoval, L., Zamora-Castro, S.A., Vidal-Álvarez, M., Marín-Muñiz, J.L., 2019. Role of Wetland Plants and Use of Ornamental Flowering Plants in Constructed Wetlands for Wastewater Treatment: A Review. Appl Sci 9, 685.

Sarwar, N., Imran, M., Shaheen, M.R., Ishaque, W., Kamran, M.A., Matloob, A., Rehim, A., Hussain, S., 2017. Phytoremediation strategies for soils contaminated with heavy metals: Modifications and future perspectives. Chemosphere 171, 710-721.

Saxena, G., Purchase, D., Mulla, S.I., Saratale, G.D., Bharagava, R.N., 2019. Phytoremediation of heavy metal-contaminated sites: eco-environmental concerns, field studies, sustainability issues, and future prospects. Rev Environ Contam Toxicol 249, 71-131.

Schreck, E., Foucault, Y., Sarret, G., Sobanska, S., Cécillon, L., Castrec-Rouelle, M., Uzu, G., Dumat, C., 2012. Metal and metalloid foliar uptake by various plant species exposed to atmospheric industrial fallout: mechanisms involved for lead. Sci Total Environ 427, 253-262.

Seregin, I., Kozhevnikova, A., Zhukovskaya, N., Schat, H., 2015. Cadmium tolerance and accumulation in Excluder *Thlaspi arvense* and various accessions of hyperaccumulator *Noccaea caerulescens*. Russ J Plant Physiol 62, 837-846.

Sevik, H., Cetin, M., Ozel, H.B., Akarsu, H., Cetin, I.Z., 2020. Analyzing of usability of tree-rings as biomonitors for monitoring heavy metal accumulation in the atmosphere in urban area: a case study of cedar tree (*Cedrus sp*.). Environ Monit Assess 192, 23.

Shaharoona, B., Al-Ismaily, S., Al-Mayahi, A., Al-Harrasi, N., Al-Kindi, R., Al-Sulaimi, A., Al-Busaidi, H., Al-Abri, M., 2019. The role of urbanization in soil and groundwater contamination by heavy metals and pathogenic bacteria: A case study from Oman. Heliyon 5, e01771.

Shang, C., Wu, T., Huang, G., Wu, J., 2019. Weak sustainability is not sustainable: Socioeconomic and environmental assessment of Inner Mongolia for the past three decades. Resour Conserv Recy 141, 243-252.

Sharma, S.S., Dietz, K.J., Mimura, T., 2016. Vacuolar compartmentalization as indispensable component of heavy metal detoxification in plants. Plant Cell Environ 39, 1112-1126.

Shim, D., Kim, S., Choi, Y.-I., Song, W.-Y., Park, J., Youk, E.S., Jeong, S.-C., Martinoia, E., Noh, E.-W., Lee, Y., 2013. Transgenic poplar trees expressing yeast cadmium factor 1 exhibit the characteristics necessary for the phytoremediation of mine tailing soil. Chemosphere 90, 1478-1486.

Shukla, D., Kesari, R., Tiwari, M., Dwivedi, S., Tripathi, R.D., Nath, P., Trivedi, P.K., 2013. Expression of *Ceratophyllum demersum* phytochelatin synthase, *CdPCS1*, in *Escherichia coli* and *Arabidopsis* enhances heavy metal(loid)s accumulation. Protoplasma 250, 1263-1272.

Silva, F.A., Guirgis, A., Thornburg, R.W., 2018. Nectar analysis throughout the Genus *Nicotiana* suggests conserved mechanisms of nectar production and biochemical action. Front Plant Sci 9, 1100.

Singh, M., Srivastava, R.K., 2016. Feasibility of using tuberose (*P. tuberosa* L.) in horizontal subsurface flow constructed wetland for heavy metal removal from domestic wastewater. Environ Prog Sustain 35, 125-132.

Sricoth, T., Meeinkuirt, W., Saengwilai, P., Pichtel, J., Taeprayoon, P., 2018. Aquatic plants for phytostabilization of cadmium and zinc in hydroponic experiments Environ Sci Pollut R 25, 14964-14976.

Swarnalatha, K., Ayoob, S., 2016. Adsorption studies on coir pith for heavy metal removal. Int J Sustain Eng 9, 259-265.

Tabrizi, L., Mohammadi, S., Delshad, M., Moteshare Zadeh, B., 2015. Effect of arbuscular mycorrhizal fungi on yield and phytoremediation performance of pot marigold (*Calendula officinalis* L.) under heavy metals stress. Int J Phytoremediat 17, 1244-1252.

Taheri-Dehkordi, A., Khandan-Mirkohi, A., Kafi, M., Salami, S.A., 2018. Exploring and optimising the conditions for virus-induced gene silencing in an ornamental tobacco, *Nicotiana alata*. J Hortic Sci Biotechnol 93, 377-384.

Tang, S.-r., Xi, L., 2002. Accumulation of chromium by *Commelina communis* L. grown in solution with different concentrations of Cr and L-histidine. J Zhejiang Uni-Sc A 3, 232-236.

Tauqeer, H.M., Ali, S., Rizwan, M., Ali, Q., Saeed, R., Iftikhar, U., Ahmad, R., Farid, M., Abbasi, G.H., 2016. Phytoremediation of heavy metals by *Alternanthera bettzickiana*: growth and physiological response. Ecotox Enivron Safe 126, 138-146.

Thakur, S., Sharma, S.S., 2016. Characterization of seed germination, seedling growth, and associated metabolic responses of *Brassica juncea* L. cultivars to elevated nickel concentrations. Protoplasma 253, 571-580.

Tiwari, S., Lata, C., 2018. Heavy metal stress, signaling, and tolerance due to plant-associated microbes: an overview. Front Plant Sci 9, 452.

Turkyilmaz, A., Sevik, H., Isinkaralar, K., Cetin, M., 2019. Use of tree rings as a bioindicator to observe atmospheric heavy metal deposition. Environ Sci Pollut Res 26, 5122-5130.

Vallejo, V.A., Tychonievich, J., Lin, W.-K., Wangchu, L., Barry, C.S., Warner, R.M., 2015. Identification of QTL for crop timing and quality traits in an interspecific *Petunia* population. Mol Breeding 35, 2.

Van der Ent, A., Baker, A.J., Reeves, R.D., Pollard, A.J., Schat, H., 2013. Hyperaccumulators of metal and metalloid trace elements: facts and fiction. Plant Soil 362, 319-334.

Vita, G., Hertwich, E.G., Stadler, K., Wood, R., 2019. Connecting global emissions to fundamental human needs and their satisfaction. Environ R Lett 14, 014002.

Vithanage, M., Dabrowska, B.B., Mukherjee, A.B., Sandhi, A., Bhattacharya, P., 2012. Arsenic uptake by plants and possible phytoremediation applications: a brief overview. Environ Chem Lett 10, 217-224.

Vymazal, J., 2010. Constructed wetlands for wastewater treatment. Water 2, 530-549.

Wan, X., Lei, M., Chen, T., Tan, Y., Yang, J., 2017. Safe utilization of heavy-metal-contaminated farmland by mulberry tree cultivation and silk production. Sci Total Environ 599, 1867-1873.

Wang, X.-F., Zhou, Q.-X., 2005. Ecotoxicological effects of cadmium on three ornamental plants. Chemosphere 60, 16-21.

Watharkar, A.D., Khandare, R.V., Kamble, A.A., Mulla, A.Y., Govindwar, S.P., Jadhav, J.P., 2013. Phytoremediation potential of Petunia grandiflora Juss., an ornamental plant to degrade a disperse, disulfonated triphenylmethane textile dye Brilliant Blue G. Environ Sci Pollut R 20, 939-949.

Wei, S., Xu, L., Dai, H., Hu, Y., 2018. Ornamental hyperaccumulator *Mirabilis jalapa* L. phytoremediating combine contaminated soil enhanced by some chelators and surfactants. Environ Sci Pollut R 25, 29699-29704.

Wenzel, W., Bunkowski, M., Puschenreiter, M., Horak, O., 2003. Rhizosphere characteristics of indigenously growing nickel hyperaccumulator and excluder plants on serpentine soil. Envrion Pollut 123, 131-138.

Wu, M., Luo, Q., Zhao, Y., Long, Y., Liu, S., Pan, Y., 2018. Physiological and biochemical mechanisms preventing Cd toxicity in the new hyperaccumulator *Abelmoschus manihot*. J Plant Growth Regul 37, 709-718.

Wu, Q., Shigaki, T., Williams, K.A., Han, J.-S., Kim, C.K., Hirschi, K.D., Park, S., 2011. Expression of an *Arabidopsis* Ca2+/H+ antiporter CAX1 variant in *Petunia* enhances cadmium tolerance and accumulation. J Plant Physiol168, 167-173.

Wu, Q., Shigaki, T., Williams, K.A., Han, J.-S., Kim, C.K., Hirschi, K.D., Park, S., 2011. Expression of an *Arabidopsis* Ca2+/H+ antiporter CAX1 variant in *Petunia* enhances cadmium tolerance and accumulation. J Plant Physio l168, 167-173.

Xin, J., Ma, S., Li, Y., Zhao, C., Tian, R., 2020. Pontederia cordata, an ornamental aquatic macrophyte with great potential in phytoremediation of heavy-metal-contaminated wetlands. Ecotox Environ Safe 203, 111024.

Yadav, P., Kaur, R., Kanwar, M.K., Bhardwaj, R., Sirhindi, G., Wijaya, L., Alyemeni, M., Ahmad, P., 2018. Ameliorative Role of Castasterone on Copper Metal Toxicity by Improving Redox Homeostasis in *Brassica juncea* L. J Plant Growth Regul 37, 575–590

Yazdanbakhsh, A., Alavi, S.N., Valadabadi, S.A., Karimi, F., Karimi, Z., 2020. Heavy metals uptake of salty soils by ornamental sunflower, using cow manure and biosolids: a case study in Alborz city, Iran. Air Soil Water Res 13, 1178622119898460.

Yu, Z., Zhou, Q., 2009. Growth responses and cadmium accumulation of *Mirabilis jalapa* L. under interaction between cadmium and phosphorus. J Hazard Mater 167, 38-43.

Yue, Y., Cui, L., Lin, Q., Li, G., Zhao, X., 2017. Efficiency of sewage sludge biochar in improving urban soil properties and promoting grass growth. Chemosphere 173, 551-556.

Zhang, D., Yan, M., Niu, Y., Liu, X., van Zwieten, L., Chen, D., Bian, R., Cheng, K., Li, L., Joseph, S., 2016. Is current biochar research addressing global soil constraints for sustainable agriculture? Agr Ecosyst Environ 226, 25-32.

Zhang, X., Gao, B., Xia, H., 2014. Effect of cadmium on growth, photosynthesis, mineral nutrition and metal accumulation of bana grass and vetiver grass. Ecotox Enivron Safe 106, 102-108.

Zhang, X.-b., Peng, L., Yang, Y.-s., Chen, W.-r., 2007. Phytoremediation of urban wastewater by model wetlands with ornamental hydrophytes. J Environ Sci 19, 902-909.

Zhang, Y., Liu, J., 2011. Transgenic alfalfa plants co-expressing glutathione S-transferase (GST) and human CYP2E1 show enhanced resistance to mixed contaminates of heavy metals and organic pollutants. J Hazard Mater 189, 357-362.

Zhang, Y., Zhao, L., Wang, Y., Yang, B., Chen, S., 2008. Enhancement of heavy metal accumulation by tissue specific co-expression of iaaM and ACC deaminase genes in plants. Chemosphere 72, 564-571.

Zhao, C., Xu, J., Li, Q., Li, S., Wang, P., Xiang, F., 2014. Cloning and characterization of a *Phragmites australis* phytochelatin synthase (PaPCS) and achieving Cd tolerance in tall fescue. Plos One 9, e103771.

Zheljazkov, V.D., Craker, L.E., Xing, B., 2006. Effects of Cd, Pb, and Cu on growth and essential oil contents in dill, peppermint, and basil. Environ Exp Bot 58, 9-16.

Zhou, G., Guo, J., Yang, J., Yang, J., 2018. Effect of fertilizers on Cd accumulation and subcellular distribution of two cosmos species (*Cosmos sulphureus* and *Cosmos bipinnata*). Int J Phytoremediat 20, 930-938.

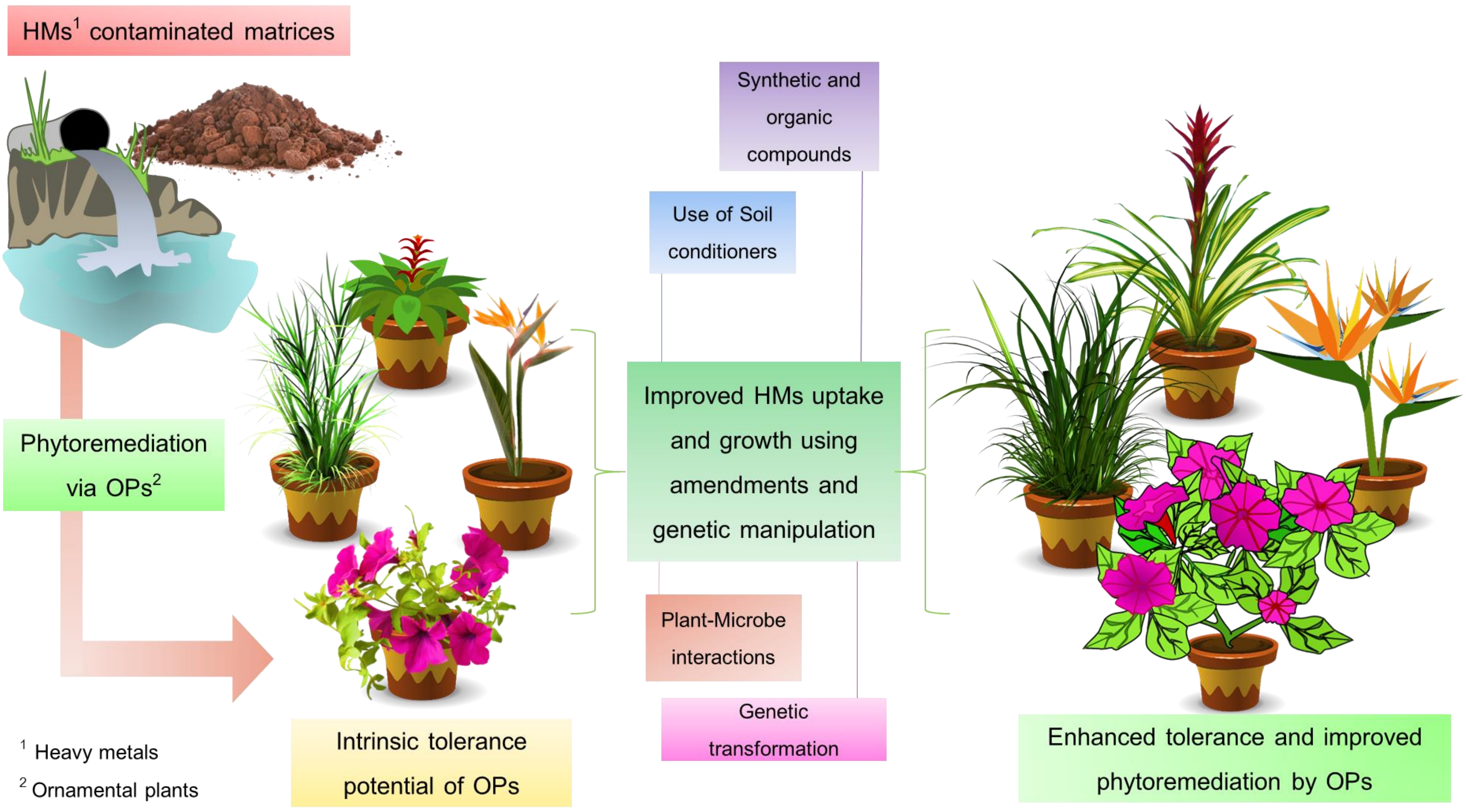

Figure 1. Use of ornamental plants for phytoremediation and methods to improve the response and tolerance, with incremented HMs uptake.

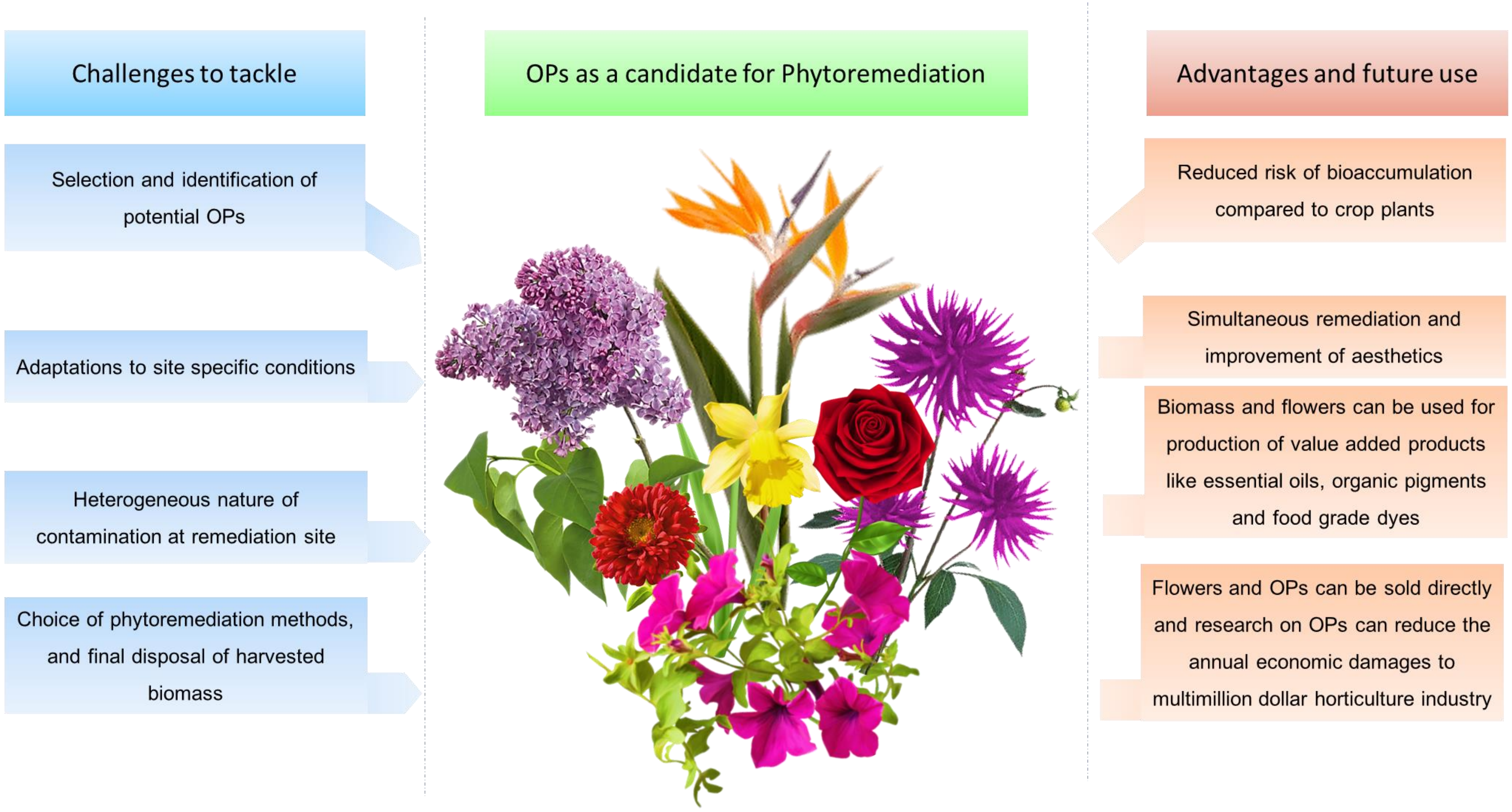

Figure 2. Challenges and future perspectives of phytoremediation with ornamental plants