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Mini Review

Phytomanagement: A Realistic Approach to Soil Remediating Phytotechnologies with New Challenges for Plant Science

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Abstract

Phytoremediation, the use of plants and associated microorganisms to eliminate environmental damage or threats posed by environmental pollution, never managed to live up to its expectations, because of long-term restrictions in land use. The recently developed phytomanagement bypasses this drawback by incorporating the aspect of economic revenue production into phytoremediation. Phytomanagement regards contaminated soils not as a problem but as an economic opportunity and a valuable resource that should be used sustainably. The product variety ranges from timber and pulp, over fodder and fertilizers up to pharmaceuticals. Phytomanagement could thus not only offer ecological benefits but offer also economic relief to communities that live near contaminated sites. Plant research could assist in achieving that goal by identifying new marketable plant species, by developing new crop management schemes (e.g. intercropping) and by developing new transgenic plants.

ABBREVIATIONS

EDTA: Ethylene Diamine Tetraacetic Acid; K_{ow}: Octanol-Water Partition Coefficient; PCB: Polychlorinated Biphenyl; TE: Trace Elements.

INTRODUCTION

Phytoremediation is defined as the use of green plants to remove pollutants from the environment or to render them harmless. Phytoremediation can be applied to both organic and inorganic pollutants, present in solid substrates, liquid substrates, and the air [1]. In the past years of phytoremediation development the following areas have been the main focus of research: phytoextraction (the removal of pollutants), rhizofiltration (their extraction from aqueous solution), phytotransformation (their metabolization and degradation) and phytostabilisation (their immobilization) [2].

Initial estimates of the phytoremediation market by Glass [3] considered phytoremediation to have a market potential worldwide of 34–54 billion US dollars. Virtually none of the market potential has been materialized. The reason for this lies in the fact that although it has very low operational costs, the phytoremediation process is often very time consuming thus, the costs or the loss of revenue (opportunity costs) from longer-term restrictions can be very high [4]. By adding value to the plants used for remediation and/or risk mitigation the opportunity costs can be reduced [5] and the time to decontaminate the soil becomes less important [6]. This is the concept of phytomanagement.

Phytoextraction: a dead end

The basic idea that plants can be used for environmental remediation is very old and cannot be traced to any particular source. This idea was possibly aided by the discovery of hyper accumulators by botanists throughout the centuries. By definition, a hyper accumulator must accumulate at least 100 mg kg^{-1} (0.01% dry wt.) Cd, As, 1000 mg kg^{-1} (0.1% dry wt.) Co, Cu, Cr, Ni or Pbor 10,000 mg kg^{-1} (1% dry wt.)Mn [7]. Unfortunately, the majority of the hyper accumulator species had slow growth and limited biomass production, thus they had an insufficient metal removal efficiency to remediate contaminated soils [8]. The next step was to use plants with high biomass plants such as tobacco, corn, sunflower etc., which however could not accelerate the extraction process [9,10], because these plants did not have the same propensity as the hyperaccumulators to accumulate TE. Thus, the increase of availability of TE to plant roots had become the key factor in deciding phytoextraction efficiency. This could be achieved with synthetic chelating agents such as ethylene diamine tetracetic acid (EDTA) which has already been used for more than 50 years to supply plants with micronutrients in both soil and hydroponics. Unfortunately, although the applied chelating agents were able to increase TE concentrations in plant shoots, a series of experiments showed that the mobilised metal fraction exceeded the actual plant uptake by 2-3 orders of magnitude [11,12], thus increasing the risk of further displacement in the depth, and even their leaching into groundwater or surface water [13-15]. A possible mean of avoiding the above mentioned drawbacks of synthetic APCAs seemed to be found when biodegradable chelating agents such as ethylene diamine disuccinate (EDDS) or nitrilotriacetic acid (NTA) were utilized. Many studies displayed a significant increase in TE uptake [16,17], they however did not investigate the TE leaching risk. It has also been shown that TE leaching by EDDS application can be very low, however if the EDDS rate is not high enough, the TE accumulated in plant shoots can be insufficient for an effective phytoremediation within an acceptable time frame[18]. Furthermore, although studies have shown that although TE leaching is lower compared to EDTA due to the degradation of EDDS [19] the degradation rates are still too low, [12,20] so that TE leaching could still occur. Additionally, the annual application of chelating agents, especially for time frames of 10-20 y can become very costly [13] and the production of biomass for economic revenue should be considered in order to compensate partially the operation cost[18]. Thus, phytoextraction has reached a point where the risks outweigh the benefits [11,21] and a change in strategy isnecessary. This has become also visible in the structural and conceptual development of phytoremediation companies in the last decade. Many companies which remediated solely by phytoextraction went out of business, while others teamed up with engineering companies. Companies such as Ecolotree have moved from phytoremediation into phytostabilisation (e.g. prevention of contaminant leaching), while others such as BioplantaInc. found additional sources of income, such as bioenergy or the extraction of active compounds from plants to boost profits.[2]

Phytotransformation: a promising start and successful applications

In the case of phytotransformation the progress was more promising. The importance of plant associated microorganisms in degrading/transforming organic pollutants and reaching the goal of irreversible conversion of pollutants into harmless substances was quickly seen [22]. This is especially important for hydrophobic organic pollutants such as polychlorinated biphenyl (PCB) with an octanol-water partition coefficient (K_{OW}) >4, where the uptake by plants is very low and the organic pollutants tend to adsorb to soil particles, and/or inside of root cell membranes limits thus limiting their transfer into the xylem. Plant species affect microbial community structure and composition in bulk soil, which subsequently has an influence on the degradation rate of targeted organic pollutants. In the case of PCB, Austrian pine (*Populusnigra*) and willow (*Salix caprea*) [23], as well as *N. Tabacum* [24] displayed high PCB degradation rates. For organic pollutants with Kow values of 1-4, such as trichloroethylene, which has a Kow of approximately 2.5 the loading of the xylem is very high. Trichloroethylene is absorbed, to a large extent volatilised, but also to some extent transformed and mineralized [25-27].

Phytostabilisation: a different focus

Owing to the limitations of phytoremediation, especially in the field of phytoextraction, the aim of reducing the risk arising from soil contaminants by inactivation and immobilization (phytostabilisation) through plant exudates, soil stabilisation and withdrawal of transpiration water through plant roots, [6] began to gain more prospective. This change of concept had resulted in different desired plant characteristics. In phytoextraction high accumulation efficiency was desired, whereas in phytostabilisation plants should preferably exclude the targeted contaminants. The success of the phytostabilisation concept has been demonstrated in studies, such as by Robinson et al. [28,29], where hybrid poplars enhanced evapotranspiration from a wood-waste, thus reducing B leaching. However, the concept was not yet complete, as the economic aspect was missing.

Phytomanagement: bringing the economics into phytoremediation

Phytomanagement does not see contaminated environmental compartments as a problem but rather as an opportunity to produce economic revenue by using them to produce mainly non-food products while mitigating the risk deriving from these soils/environmental compartments (Figure 1) [6]. Subsequently it would alleviate the pressure put on agricultural soil, which has nowadays to produce not only food but biofuels, bioplastics, biochar, paper and wood as well. Therefore, to maximise the potential of phytomanagement the utilized plant species, should a) have a low propensity to accumulate the contaminants of the site, b) not increase and preferably reduce the mobility of the contaminants and c) have a high socio-economic value and/or d) produce economic revenue.

The importance of the socio-economic value of the used plant species was also stressed by Pandey et al. [30], stating that plant species should be prioritized for green cover on fly ash dump sites in India, which could be used by local populations as fuel wood (*Prosopisjuliflora* (Sw.) DC. and *Acacianelotica* L), as fodder (*Cynodondactylon* (L.) Pers.) inreligious ceremonies or for making rope, baskets, broom, mats, and huts (*Typhalatifolia, Ipomoea carnea*).In other cases the target product may not have a direct social-economic value but it produce an economic revenue thus improving the livelihood of the surrounding people. Near Lille (France) large areas have been contaminated owing to smelter activity. These, areas were planted with poplars, willows and birches to prohibit the use of the contaminated area by the local population in order to mitigate the risk deriving from these areas, but are not used economically. The production of Zn-rich biochar intended as a slow release fertiliser could offer the people an income [31]. The same goes for the use of contaminated land for the production of bioenergy [32], and wood [33]. Verma et al. [34] showed new possibilities, which go beyond the common products. Their study showed that phytomanaged plants can be the source of several valuable aromatic chemical constituents, which are used in perfumery, pharmaceuticals, cosmetics and aromatherapy as well as toiletry products. Further possibilities are to combine phytomanagement with Se-biofortification as proposed by Banuelos et al. [35], thus providing growers with new and innovative and economical commodities such as Se-enriched forage for animals and vegetables for humans. Nevertheless, independent of the potential product bioaccumulation should

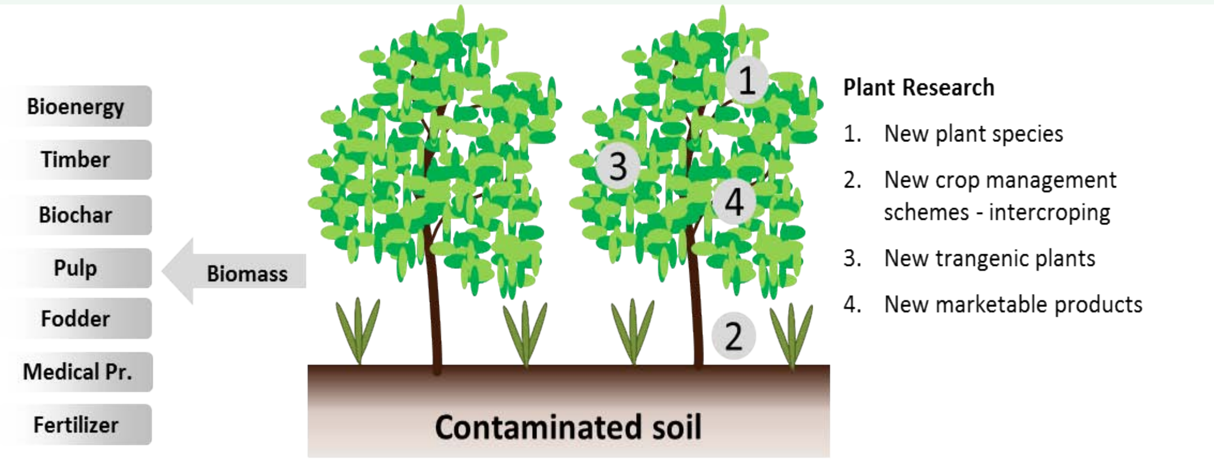

Figure 1 Possible products and new research areas in plant research in the frame of phytomanagement.

always be monitored to avoid risk on site through the deposition of contaminated biomass as well as for the consumers.

Furthermore, the economic revenue does not always have to come from products, ecosystem services such as providing a habitat for native animal species could also be seen as indirect economic revenue, as shown in the study at the Guadiamar Valley (SW Spain)[36]. The Guadiamar Green Corridor programme has the goal of providinga continuous vegetation belt for wildlife to migrate along the Guadiamar River basin between the Donana National Park in the South and the Sierra Morena mountains in the North. In the UK some fly ash deposit sites are regarded as locally valuable conservation areas for the dense birch/willow woodland with glades of orchids and ecological engineering the duration of succession on these sites may be reduced [37].

Not only has the choice of the plant species but also their biodiversity played an important role for the success of a phytomanagement project. During the development of phytoremediation, research was usually focused on the utilisation of one plant species (monocultures). Monocultures are however especially vulnerable when inadequate soils or stress conditions, such as drought and pathogens, are present. These issues should not be neglected as they are important in any sustainable system to guarantee its economic and ecological stability [4]. The use of multiple plant species can have also positive effects on the remediation of organic contaminated sites. It has the potential to increase soil degradation of PAH [38], PCB [39] or phthalic acid esters[40]. It can however also increase the uptake of trace elements such as Cd [39], which can be undesirable in the case of phytomanagement. For risk mitigation, by phytostabilisation of contaminated soil, the combined use of a few plant species might not be sufficient. In order to assure long-term sustainability, the goal should be the employment of species with different ecological functionality e.ggrasses may provide rapid growth while trees support a better soil protection againsterosion [41] as well as with contrasting life forms [42].

CONCLUSION

To make soil remediating/managing phytotechnologies viable they have to be linked to profitable production of biomass. Although, a multidisciplinary approach is required to make phytomanagement successful, research should be focused on the plant itself, in form of new plant species that can offer a variety of products, new crop management schemes as well as transgenic plants. Phytomanagement can offer socio-economically benefits by providing an alternative income to people who lost their livelihood because of the contamination.

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