



Phytoremediation as a Promising Method for the Treatment of Contaminated Sediments

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ABSTRACT

Dredging activities are necessary to maintain the navigation depth of harbors and channels. Additionally, dredging can prevent the loss of water bodies. A large amount of extracted sediments is produced around the world. Removed material is widely disposed at open seas or landfills. Much of the dredged material is polluted and is classified as unsuitable for open-sea disposal. In Sweden, many dredging activities are taking place nowadays like that in Oskarshamn harbor, Inre harbor Norrköping municipality and Malmfjärden bay in Kalmar. In this review, the potential of phytoremediation as a treatment method is discussed with focus on suggested methods for reusing the treated sediments. Recycling or reusing of dredged and treated sediments will preserve Earth natural resources as well as reduce diffusion of contaminants to the environment.

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INTRODUCTION

Shortage of resources is one of the main problems that are facing the future life on Earth. Natural resources have been excessively used in industrial, agricultural and other sectors without considering future needs [1]; therefore, societies need to employ an enhanced circular economy model in their daily activities by considering the lost valuables as wastes back to the circular economy as secondary resources. This will contribute towards the sustainability of the Earth's natural resources as well as protecting human health and the environment from the potential risks possessed by the dumped wastes.

Waste management regulations especially in cases of contaminated masses, urban development, lack of landfilling sites and spaces for new landfills and continuous increase in the produced wastes [2] demand environmental and economic innovative approaches to handle waste materials. These wastes contain valuables that should be extracted back into the circular economy. Metals, for instance, were and are still suffering from high consumptions along the industrial history that leads to both increasing the cost of mining from their primary sources and reducing their concentrations in these mines [3]. These elements are fundamental to the development of technological processes and economic growth.

Sediments have always been regarded as one of the final sinks of anthropogenic pollutants such as metals, hydrocarbons and other heterogeneous mixtures of organic and inorganic materials [4]. Land based actions, sewage, shipping and other activities contribute in contaminating the harbor sediments in different parts of the world. These pollutants are available to nekton, plankton and deposit feeders and, consequently, can enter the food chain through fish and other edible organisms and thus affect human health.[⁵]

Metals are among the common contaminants found in marine sediments owing to their non-biodegradable chemical forms. These metals bond to the sediments by absorption, precipitation and ion exchange reactions because of the heterogeneous geochemical composition of sediments [⁶]

Heavy metal contamination of sediments from both industrial and anthropogenic sources are alarming, to the point where it is regarded as a global crisis [7]. Previous studies have shown that suspended particles and sediments together account for more than 90% of heavy metal loads in aquatic environments [8, 9, 10]; which together with other persistent pollutants accumulate in organisms and bottom sediments [11]. Such an alarming situation calls for dedicated investigations of these materials. Investigations

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could enrich assessments of anthropogenic, industrial risks and impacts from waste along with effluent discharges into aquatic environments [7]; that would in turn inform policy making around regulation of such industrial discharges. Furthermore, such investigations could provide valuable information towards planning of sustainable methods of metal recovery into the circular economy.

The goal of this mini review is to highlight the state of the art of using phytoremediation for the treatment of contaminated sediments and discuss the potential end users for the treated sediments, which could contribute towards preservation of the Earth's natural resources as well as protecting human health and the environment.

PHYSIOCHEMICAL PROPERTIES

Sediment quality varies from place to place subject to the type of waste and effluent discharge, which is also influenced by availability and strength of environmental pollution legislation. Since they are the ultimate sinks of aquatic pollutants, sediments and their geo-physico-chemical characteristics are widely used as environmental indicators of pollution in aquatic environments [7, 11, 12, 13, 14]. Metals mobility and bioavailability in sediments is determined by the chemical form which include easily exchangeable ions, metal carbonates, oxides, sulphides, organometallic compounds and ions in crystal lattices of minerals [9, 15, 16]. These chemical forms are further influenced by physico-chemical properties of both the sediments and the aquatic system. Therefore, physico-chemical properties are important in evaluation of sediment quality, degree of contamination and magnitude of contaminants [7, 11, 12]. Sediment physico-chemical properties including pH, redox potential, particle size distribution, temperature, salinity, heavy metal concentration, texture, chemical form and fractional composition. These properties interact in different ways to yield a net increase, stability or decrease in heavy metal bioavailability and toxicity.

Factors influencing bioavailability and toxicity of metals and other elements have previously been grouped based on their phases (solid or aquatic) and on benthic organism properties (behavior and sensitivity) [9]. The solid phase comprises acid volatile sulfides (AVS), organic matter (OM) and sediment texture. AVS are an important metal-binding phase in sediments [17], and their formation is a result of sulfate reduction by sulfate reductive bacteria (SRB) under anaerobic conditions [18, 19]. AVS has been observed to increase with sediment depth [20, 21]; since its exposure to dissolved oxygen (DO) on surface sediments may result in its oxidization and eventual release of metals to more available forms [17]. An example of AVS operation is where the reduction of SO_4^{2-} by SRB in the presence of Fe^{2+} under

anoxic conditions yields crystalline FeS, from which the Fe^{2+} is later displaced by a divalent metal (Me^{2+}) to yield an insoluble metal sulfide [21, 22, 23, 24, 25]. In this way, toxic metals are made unavailable while the Fe^{2+} becomes available for more SO_4^{2-} reduction. Thus, AVS quantity is directly proportional to the bioavailability and toxicity of metals, where significant bioavailability and toxicity have been observed at low AVS levels [26] and lower bioavailability and toxicity at high AVS levels [17].

OM, otherwise quantified as TOC, is another crucial factor in sediment metal bioavailability. TOC decreases with sediment depth while metal solubility efficiency increases with decrease in sediment particle size [27, 28]. As such, elevated metal concentrations have been attributed to fine sediments with greater particulate organic carbon concentrations due to their affinity for metals [29]. It is also worth noting that humic substance concentration in sediment correlates with metals content [26]. They are responsible for metal binding in sediments by reducing metal bioavailability through formation of metal complexes with organic ligands [30, 31, 32]. However, aerobic breakdown of OM produces carbon dioxide which in turn enhances metals release via decalcification. Metal release is further enhanced after production of humic acid due to lower pH from the decomposition of higher OM [33, 34].

Aquatic phase factors, on the other hand, include pH, redox potential and salinity. As mentioned earlier about humic acid action on sediments, lower pH enhances metal releases through solubilization of sulfides, while extremely high pH leads to SRB inhibition, which further results in hampered AVS formation and reduced metal-binding capacity [35]. Generally, low pH weakens sediment metal association capacity whereas high pH stimulates adsorption and precipitation [28]. On the other hand, Redox potential, which is a measure of the electron availability, predicts the stability and bioavailability of heavy metals in sediments, where the oxidation rate of sulfides and the degradation of organic compounds are facilitated by an increase in redox potential. These results in an accelerated liberation of adsorbed or complexed metals [36]. Therefore, an increase in redox potential increases heavy metal bioavailability. Redox potential has further been linked to availability of nutrients in sediments as an interplaying factor. The presence of some nutrients such as nitrate and its action as a thermodynamic electron acceptor has the capability to increase redox potential [37], leading to an ultimate effect of increased heavy metal bioavailability. An additional aquatic phase factor interacting with solid phase factors is salinity. The growth and activity of SRB are inhibited by high salinity, resulting in reduced SO_4^{2-} reduction efficiency and thus a net increase in heavy metal bioavailability [15].

Therefore, heavy metal bioavailability and toxicity is a product of various complex interconnected factors. It is inadequate to single out one property like total metal concentration in the study of sediment physicochemical parameters and metal bioavailability. For instance, while total concentration of metals is a vital parameter in sediment assessments, it does not necessarily correlate with their toxicity and bioavailability always [23]. Instead, the interaction of different factors differently influences the bioavailability and toxicity of heavy metals in sediments. Bioaccumulation, on the other hand, has been observed to increase linearly with sediment metal total concentration, also mediated by different factors [38].

PHYTOREMEDIATION TREATMENT

The use of living plants to either extract and remove (known as phytoextraction), immobilize (phytostabilization) or degrade (phytodegradation) organic and inorganic contaminants is well known as phytoremediation method. This method is currently attracting more attention due to its economic efficiency compared to physicochemical and thermal methods [39]. According to Pittarello et al. [40] '*it is up to 25 times cheaper than chemical and thermal treatments*'. Furthermore, other factors such as social acceptance, environmental friendly and natural management options make this method more attractive [41]. Soil phytoremediation has been successfully identified as an effective method for the treatment of different contaminants like metals [42], oil hydrocarbon [43] and mixtures of these contaminants [42].

Different plants have been used and recommended as hyperaccumulator agents in soil phytoremediation projects depending on soil properties and pollutant physicochemical characteristics. In the case of sediments, studies on specifying hyperaccumulators are in the early stage. However, some attempts have been made and the results are promising. Doni et al. [44] investigated the use of *Paspalum vaginatum*, *Phragmites australis*, *Spartium junceum* with *P. vaginatum*, *Nerium oleander* along with *P. vaginatum* and *Tamarix gallica* also with *P. vaginatum* as phytoremediation agents to treat brackish sediments contaminated by a mixture of hydrocarbons and heavy metals. The 18 months experimental results showed that *Tamarix gallica* along with *P. vaginatum* achieved high removal of total petroleum hydrocarbons with 35 and 20% of Cd and Zn, respectively. Vervaeke et al. [45] on the other hand, displayed promising results in the extraction of Pb (41%), Zn (32%) and Cd (35%) from contaminated river sediments after planting period of 18 months.

Different parameters play important roles in the phytoremediation treatment of contaminated sediments. Redox potential and pH, for instance, influence the

mobility of trace elements due to the direct effect on the sorption and desorption of metals on the sediments binding sites [46]. Organic content is considered as another vital parameter due to the dual effect by either contributing to the mobility of metals in pore water when the pH is moving to basic levels or retaining the metals in sediments by the formation of metals-complexes [47]. In addition, sediments particle sizes and microorganisms should also be considered when proposing phytoremediation as a treatment method due to their direct contact with the roots zone and the biological mechanism of plants growth.

POTENTIAL END USERS

Around the world, several beneficial uses of sediments have been implemented. Productive and positive uses of dredged material including incorporation in commercial and industrial processes and wildlife habitat restoration [48]. In the construction industry, sediments have been employed to produce green construction materials which are obtained sustainably and are potentially profitable [49]. Punctual examples include the use of sediments as filling and composite material [48, 50] and as construction material to build roads [51, 52]. Moreover, sediments have also been successfully incorporated for production of bricks and blocks [53, 54, 55] and non-structural cement [56, 57, 58, 59].

Sediments can also be reused in fields different than construction. When sediments have a high level of nutrients and absence of pollutants, they can be employed in agricultural and soil conditioning purposes. Di Emidio [60] the possibility to reuse dredged sediments as an alternative low-cost impermeable barrier material to isolate and reclaim polluted sites and landfills. Finally, Mattei et al. [61] assessed the possibility to compost river sediments along with green waste. The research showed that the obtained manure could be employed as plant growing substrate.

CONCLUSIONS

Traditional sediment disposal methods are constrained by regulations and are unsuitable due to their possible contaminant pathways, lack of long-term stability, limited space capacity, costs and environmental compatibility. Finding new disposal routes for sediments have become a challenge for harbors. Implementing beneficial uses of sediments not only represents a proper way to eliminate sea dumping but also embodies adequate disposal which contributes to minimize the extraction of raw materials and to achieve sustainable management of sediments. Phytoremediation is regarded as the most cost-effective method in the treatment of

metals and hydrocarbon contaminants. According to different studies, this method showed promising results in the field of treating contaminated dredged sediments. However, more efforts are needed to specify the success of this method on the long-term perspective as well as in the treatment of high rate of contaminants.

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چکیده

فعالیت های لایروبی برای حفظ عمق ناوبری بندر و کانال ضروری است. علاوه بر این، گودبرداری می تواند لز از دست رفتن جسم آب جلوگیری کند. مقدار زیادی از رسوبات استخراج شده در سراسر جهان تولید می شود. مواد حذف شده به طور گسترده ای در دریاها یا آزاد یا دفن زباله ها دفع می شوند. بخش عمده ای از مواد غنی شده آلوده است و مناسب برای دفع در دریا در نظر گرفته شده است. در سوئد، بسیاری از فعالیت های لایروبی در حال حاضر در حال انجام است مانند در بندر Oskarshamn، بندر Inre Norrköping شهرداری و Malmfjärden خلیج در کالمار. در این بررسی، پتانسیل گیاهخواری به عنوان یک روش درمان با تمرکز بر روش های پیشنهاد شده برای استفاده مجدد از رسوبات مورد بحث قرار گرفته است. بازیافت و یا استفاده مجدد از رسوبات زراعی حفظ منابع طبیعی زمین و همچنین کاهش انتشار آلاینده ها به محیط زیست است.
