Application and Development of Bioadsorption Technology for Heavy Metals in Biomass Composting

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Abstract. Biomass composting is a fundamental method for recovering resources from organic waste. However, the accumulation of heavy metals in its raw materials has turned into a crucial bottleneck that impedes the safe application of products. Bioadsorption technology, which is environmentally friendly, cost-effective, and highly efficient, has come to be a key approach to deal with heavy metal contamination in compost. This paper comprehensively examines the sources and migration risks of heavy metals in biomass compost, analyzes the mechanisms of bioadsorption, types of adsorbents, and the regulatory effects of compost environmental factors. It also summarizes the practical applications and cost-benefit analyses of different adsorbents, points out existing technical bottlenecks such as the limited reusability of adsorbents and the unstable adsorption efficiency in complex compost systems, and puts forward optimization directions and future trends. In particular, integrating bioadsorbents with functional microbial agents is anticipated to boost the efficiency of heavy metal immobilization, and developing scalable adsorbent regeneration technologies will enhance the economic feasibility of large-scale composting. The findings are intended to offer theoretical support and practical references for the governance and safe application of heavy metal pollution in compost.

1 Introduction

Biomass composting takes organic waste, like livestock manure and agricultural straw, and turns it into soil amendments that are rich in organic matter. This process plays a really important part in encouraging sustainable agriculture to develop. Nevertheless, if heavy metals that are concentrated within the compost materials make their way into the soil via the compost product, these heavy metals might not merely upset the soil's ecology and fertility, but they could also get into the food chain as a result of being absorbed by crops. In the end, this could put human health in danger. More specifically, consuming agricultural products that are contaminated with heavy metals over a long period of time can lead to kidney damage as well as neurological disorders. Among these, arsenic (As) especially has a very high risk

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of causing cancer [1]. As for cadmium (Cd) contamination, it notably suppresses the photosynthesis process in crops such as wheat, causing the grain yield to decrease by around 10% to 20% [2]. According to statistics, roughly 20% of China's arable land is polluted by heavy metals, and biomass compost happens to be one of the key sources of agricultural pollution [3].

To tackle this particular challenge, bioadsorption technology has surfaced as a viable solution to help alleviate the issue of heavy metal pollution within compost. The reason being its advantageous traits of being environmentally friendly as well as cost-effective. This specific approach mainly relies on microorganisms and various biomass materials, employing them as adsorbents. These adsorbents work by immobilizing heavy metals through means such as surface functional group complexation and ion exchange mechanisms. As an example, modified biomass materials like cotton stalk powder have shown to possess relatively high adsorption capacities when it comes to numerous heavy metal ions [4]. Biochar, endowed with a well-developed porous structure along with an abundance of surface functional groups, is capable of not only efficiently adsorbing heavy metals but also enhancing the physicochemical properties of the soil [5]. Research findings suggest that when biochar is combined with green manure compost, it can further decrease the mobility as well as the bioavailability of heavy metals present in the soil [6].

However, the extensive application of this particular technology is still confronted with quite a few bottlenecks. To begin with, adsorbents do not possess adequate stability when it comes to the high-temperature conditions that are typical of composting, which range from 50 to 70 ℃, as well as the fluctuating pH levels within the composting process, which can vary between 4.0 and 9.0. Moreover, conventional adsorbents tend to show rather poor selectivity with regard to specific heavy metals, and this poor selectivity puts a limit on their remediation efficiency in situations where there is complex pollution. Apart from these, the relatively high costs involved in the preparation and application of modified adsorbents also act as a restriction, preventing their more widespread adoption. Hence, conducting a systematic review of the research advancements in bioadsorption technology, making clear its underlying mechanisms, the outcomes of its applications, and the existing challenges it faces, is of great importance for the purpose of optimizing and promoting its practical implementation. This review is intended to offer theoretical references for ensuring the safe utilization of biomass composting.

2 The source of heavy metals in compost and its environmental risk

2.1 Main source

The primary route through which heavy metals enter the system is via livestock and poultry manure. In the context of large-scale breeding operations, the feed additives containing copper and zinc are not entirely absorbed by the animals. Instead, these unabsorbed elements are expelled alongside the manure and subsequently accumulate. Should the soil at the breeding site become polluted, the heavy metals present in it would mix with the manure, thereby further increasing the overall load of heavy metals.

Moreover, urban sludge itself inherently contains heavy metals like cadmium and lead. Directly mixing it with compost leads to an increase in the overall heavy metal content within the system, thereby giving rise to potential risks.

2.2 Types and structural characteristics of biosorbents

Microbial adsorbents, with Bacillus subtilis, Pseudomonas, Aspergillus niger, and Chlorella serving as typical examples, have a key advantage. Their cell walls are made up of polysaccharides and proteins, which are abundant in active functional groups like hydroxyl and carboxyl groups. These components can directly bind to heavy metal ions such as Cd^{2+}, Pb^{2+}, and AsO_4^{3-} via strong interactions, including complexation and ion exchange, thus enabling targeted adsorption [7]. This mechanism depends solely on the inherent cellular structure of microorganisms, necessitating no extra modification for effective adsorption. This intrinsic ability constitutes the core competitiveness of microbial adsorbents in targeted heavy metal treatment.

Plant-based adsorbents, with corn stalk and orange peel being used as reference materials, exhibit different mechanisms. The unmodified corn stalk has a minimal amount of hydroxyl groups within its cellulose and hemicellulose structures, which only allows for a weak binding of Cd^{2+} and results in a low adsorption capacity [8]. On the other hand, orange peel is naturally rich in pectin and has numerous carboxyl groups that form strong complexes with Pb^{2+}, showcasing excellent adsorption performance. This indicates that the adsorption mechanisms of plant-based adsorbents are fundamentally restricted by their structural composition. When they are unmodified, their functional groups are inadequate to accomplish effective adsorption. It is only when the raw materials intrinsically contain specific functional groups such as pectin that they can display optimal adsorption performance. This clarifies why plant-based adsorbents, although widely available, still have limited performance when unmodified.

Modified biomass adsorbents have a key principle, which is to actively optimize their structural features by means of chemical modification. Alkaline modification can break down the cellulose fibers in straw, and it can increase the amount of functional groups by 20% to 30%. This, in turn, enhances the ability to adsorb Cd^{2+} through stronger complexation [3]. When biochar is modified with nano Fe_3O_4, it can achieve a really large specific surface area of 500 to 800 m^2/g. At the same time, it introduces magnetic active sites, which boost the ability to adsorb arsenic (As) by more than 50% due to coordination effects [9]. Compared to the first two types of adsorbents, the mechanism of modified biomass adsorbents is like an active upgrade of the 'inherent structural adsorption' mechanism. It artificially increases the number of functional groups, introduces active sites, and expands the specific surface area. This fundamentally improves the strength and efficiency of adsorption. Therefore, it stands out as the most hopeful technical path in the field of bioadsorbents.

2.3 The regulation of environmental factors in composting

In a composting environment, factors such as temperature, pH value, organic matter, and moisture content can significantly regulate the adsorption efficiency of heavy metals. The principle lies in that they can exert influence on aspects such as the structure of the adsorbent, the form presented by heavy metals, and the activity of microorganisms.

Temperature is a crucial regulatory element. Biochar shows great efficiency in adsorbing Pb^{2+} at room temperature, whereas high temperatures notably decrease the adsorption capacity of unmodified lignin-based adsorbents. The structural stability of modified adsorbents results in a considerably smaller reduction in capacity [10]. Even though high temperatures suppress bacterial activity, thermotolerant fungi remain stable – this is a common feature seen in microbial adsorption during the high-temperature stage of composting. This underscores the significance of modification techniques and thermotolerant microorganisms in managing temperature fluctuations.

The precise regulation of pH directly determines adsorption efficiency. When pH is between 6.0 and 7.0, biochar achieves an adsorption rate of 85%-95% for Pb^{2+}, while the rate drops sharply below pH 4.0 [4]. For example, arsenic (As) exists as the easily adsorbable AsO_4^{3-} in acidic conditions but transforms into the less adsorbable AsO_3^{3-} under alkaline conditions. This demonstrates the universal principle of pH influencing heavy metal forms and adsorption behavior, highlighting the pivotal role of pH in adsorption performance.

Organic matter as well as moisture content need to be regulated in a coordinated manner. When there is an excessive amount of organic matter, it will compete with the adsorbents for heavy metals. However, when the organic matter is at an optimal level, it can promote the growth of microorganisms and improve the efficiency of adsorption, which is a common situation in compost systems. On the other hand, if the moisture content is too high, it will lead to the agglomeration of adsorbents and decrease in aeration, thus suppressing the activity of microorganisms [11]. It is crucial to maintain this balance in order to achieve effective adsorption.

3 Application status and typical cases of bioadsorption technology

3.1 Application of different adsorbents

Within microbial adsorbents, Bacillus subtilis, with its concentration ranging from 10^8 to 10^9 CFU per gram, was added in an amount of 1% to 2% into pig manure compost. This addition managed to achieve cadmium adsorption rates that fell within the range of 75% to 85%, as well as lead adsorption rates that were between 80% and 90% [12]. On another note, when a composite microbial consortium—which consisted of Bacillus, Pseudomonas, and Aspergillus niger—was put into use in chicken manure-stubble compost, the efficiency of adsorption for numerous heavy metals went up by 10% to 15% in comparison to the situations where only single-strain treatments were employed [13]. This clearly shows the advantageous effects of synergy that microbial consortia can bring about.

Modified biomass adsorbents were created by adding nano-modified biochar in the range of 2% to 3% to vegetable waste compost. As a result, the removal rates for Pb reached between 80% and 90%, while the removal rates for Cd were within the range of 75% to 85%. Moreover, the recovery rate of the adsorbent was also quite high, being between 85% and 95% (Gol-Soltani et al., 2024). This clearly shows that the approach possesses not only remarkable adsorption performance but also considerable potential for resource recovery, thus rendering it a technological method of great value.

3.2 Application effect and cost assessment

Modified biomass adsorbents performed the most impressively, among which nano-modified biochar displayed a notably high efficiency in the removal of Pb and Cd, thus becoming the preferred option for large-scale applications [9]. Microbial adsorbents showed relatively stable performance, and the composite microbial communities had obvious synergistic advantages, rendering them appropriate for situations involving mixed heavy metals [12]. Unmodified plant-based adsorbents, although their removal rates were somewhat limited, were extremely cost-effective and fit well for low-cost composting.

Most adsorbents can enhance compost quality, but nano-modified adsorbents require precise dosage control to prevent pH imbalance [11]. Although the initial cost of modified adsorbents is higher, their cost-effectiveness improves significantly after recycling [4], making them more viable for widespread adoption.

4 Existing problems and development trends

4.1 Core bottlenecks in technology application

In real composting situations, the unpredictability of adsorbents is still the key obstacle. The unaltered microbial adsorbents have really low survival chances when the temperature is high in the composting process. It’s hard for them to keep working for a long time. Even the modified straw-based ones start to lose their useful parts bit by bit as composting goes on. This makes their ability to absorb keep getting worse and worse. It stops the technology from being used practically for a long time.

Moreover, the low selectivity associated with adsorption stands out as a considerable problem. The majority of currently available adsorbents do not possess specific affinity towards multiple heavy metals. In compost, common ions such as Cu^{2+} and Zn^{2+} are prone to interfering with the target heavy metals. This phenomenon of “non-specific adsorption” notably undermines the accuracy of treatment, rendering it challenging to satisfy the requirements posed by intricate pollution situations.

4.2 Directions for technical optimization

To address the dual limitations of stability and selectivity, functionalization of adsorbents provides a direct and effective optimization strategy. By introducing specific functional groups through surface modification or loading onto porous carriers, this approach not only enhances the adsorbent's selectivity for target heavy metals but also improves its stability in extreme composting environments, thereby fundamentally resolving this core issue.

In addition, the combination technology is the key means to break through the limitation of single technology. The combination of bioadsorption, chemical passivation and microbial remediation can achieve the synergistic effect of "adsorption-fixation-degradation", which can not only improve the removal rate of heavy metals, but also reduce the interference to the composting process. The practical value of this combination mode is significantly better than that of single technology.

At the same time, the integrated design of composting process and adsorption process is indispensable. According to the environmental characteristics of different stages of composting, the timing and process parameters of adsorbent addition can be adjusted to ensure the adsorption effect and reduce energy consumption, making the technology application more economical and operable.

4.3 Future development trends

In the long term, the elucidation of mechanisms based on molecular biology as well as targeted modifications will take center stage in technological advancements. By employing genetic engineering, one can enhance the performance of microbial adsorbents or control the pathways of heavy metal transformations, which could lead to a remarkable improvement in adsorption efficiency. This marks a crucial breakthrough for the technological progress in the future.

The development of intelligent adsorption systems is full of potential. These systems combine real-time sensor monitoring with big data prediction, which allows for precise dosing of adsorbents. It can prevent under-dosing or over-dosing, and reduce labor costs, making the technology more efficient and accurate.

The industrialization of green and low-cost adsorbents is an essential requirement for implementing this technology. By using agricultural waste to prepare adsorbents and optimizing the modification process to lower energy consumption, as well as recovering resources from discarded adsorbents, we can address environmental problems and cut costs at the same time, thereby achieving a "win-win" scenario for both environmental protection and the economy. This represents the ultimate developmental objective of bioadsorption technology.

5 Conclusion

Composting is the core obstacle of resource utilization of organic waste, and bioadsorption technology is the key treatment path with its environmental compatibility and cost advantage. In practice, the treatment efficiency of modified biomass adsorbent and composite microbial agent is the best, and the removal rate of heavy metals is more than 70%, which is significantly better than that of unmodified materials.

However, the large-scale application of this technology still faces challenges including insufficient stability, low selectivity, and high costs. The effectiveness of composite pollution treatment and long-term stability also require further validation. I believe functionalized modified adsorbents represent the core development direction. Future efforts should focus on developing high-temperature resistant and highly selective materials, as well as optimizing integrated process control. Through these breakthroughs, the technology will provide more reliable support for the safe implementation of compost resource utilization.

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