

Mechanism of Hydroponic Plants to Purify Wastewater

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Contributor: Chao Mai , Amin Mojiri , Swaminathan Palanisami , Ali Altaee , Yuhan Huang , John L. Zhou

As the global population reaches eight billion, large quantities of wastewater (domestic, industrial, livestock) need to be treated in an efficient, green, and environmentally friendly manner. Wastewater hydroponics technology (HP) can efficiently remove various pollutants (conventional and emerging pollutants, heavy metals, and microorganisms) and create economic benefits. The principle of hydroponic wastewater purification is phytoremediation, which is a low-cost and solar-powered natural cleaning technology. Plants assist in the removal of pollutants in a variety of ways, including phytoextraction, phytovolatilization, phytodegradation, and rhizofiltration.

hydroponics

phytoremediation

wastewater purification

hydroponic plants

1. Introduction

Water is crucial for sustainable human and socio-economic development, energy and food production, ecosystem stability, and human survival. It also plays a central role in climate change adaptation and serves as a critical link between society and the environment. With rapid population and economic growth, large quantities of urban, industrial, and livestock wastewater are generated daily. According to the UN Water Sustainable Development Goal report, 44% of household wastewater worldwide remains untreated [1].

Domestic wastewater may contain potential pollutants, including detergents from bathrooms, food scraps and oils from kitchens, and excrement from toilets. As a result, it can contain pathogens, nutrients, and organic matter [2]. In recent years, the water industry has placed greater emphasis on treating and recycling wastewater due to social and environmental pressures. However, high-strength industrial wastewater still contains numerous persistent organic contaminants and inorganic pollutants, as well as heavy metals, presenting significant challenges to environmental safety [3]. In agriculture, the widespread use of chemical fertilizers and pesticides to enhance crop yields and livestock quality poses a significant threat to surface and groundwater [1].

Globally, 80% of wastewater is discharged into the environment without adequate treatment. As a result, approximately 1.8 billion people are exposed to fecal-contaminated drinking water sources, putting them at risk of diseases such as cholera, dysentery, typhoid, and infections of the spinal cord, as well as the risk of polio [4].

In addition to the direct harm caused by bacteria and viruses in water, heavy metal pollution poses another threat to human health. Lead (Pb), for instance, can adversely affect the human nervous system, particularly leading to learning deficits and a decline in IQ among infants and young children [5]. Arsenic (As) can seriously affect human

skin and internal organs and cause various malignant tumors [6]. Chromium (Cr(VI)) facilitates UV-induced skin cancer [7].

Cadmium (Cd) has the potential to cause osteomalacia and osteoporosis, leading to severe damage to the liver, kidneys, reproductive system, and cardiovascular system. It is also recognized as a carcinogen, contributing to the development of cancer [8]. Furthermore, emerging contaminants such as cosmetics, pharmaceuticals, personal care products, and microplastics have been identified in wastewater treatment plants and natural water sources worldwide. These contaminants cannot be effectively eliminated, and may even be detected in drinking water, posing potential risks such as endocrine disorders, birth defects, developmental disorders, and impacts on fertility and reproductive health in humans [9][10]. Additionally, these pollutants can promote malignancy and increase the resistance of bacterial pathogens. In order to minimize potential harm to humans and ecosystems resulting from wastewater, various physical, chemical, and biological wastewater treatment technologies have been developed [11].

Among them, popular approaches widely used for wastewater treatment and resources recovery include adsorption by activated carbon and biochar, advanced oxidation processes (such as photocatalysis), biological methods (such as constructed wetlands-CWs), and hybrid methods based on membrane technology. These methods offer different treatment performances, depending on the specific requirements and characteristics of the wastewater being treated [12][13]. However, these technologies often suffer from the issue of high implementation and maintenance costs [14]. For instance, the production cost of biochar and filtration membranes is significant, resulting in higher overall investment and operational expenses [15]. Additionally, certain treatment technologies can generate significant amounts of by-products or residues. If these by-products or residues are not properly treated, they can result in secondary pollution. For example, in the case of biochar or membranes used for adsorption or filtration, recycling or appropriate treatment is necessary to ensure their harmlessness and prevent any negative environmental impact [16]. Advanced oxidation processes often require the addition of oxidants and catalysts, which can also produce by-products [17]. Furthermore, some technologies have strict operating conditions and environmental requirements, which can make widespread adoption challenging. For instance, cultivating microorganisms for biofiltration requires a significant amount of time [18], while membrane technology requires pressure control to prevent clogging, fouling, or rupture [19]. Therefore, it is crucial to identify a method that is easy to implement, involves low investment and operating costs, and offers economic value through by-products. Hydroponic systems have gained significant attention for their ability to support plant growth in controlled environments. This soil-less method of plant cultivation utilizes water-based nutrient solutions to provide plants with the essential elements they need for healthy development. Hydroponics offers several advantages, including efficient resource utilization, optimal nutrient uptake, and higher crop yields compared to traditional soil-based farming. Beyond its application in conventional agriculture, hydroponic systems also hold great potential for wastewater treatment. Wastewater hydroponics is one such method, which is derived from traditional hydroponics. Traditional hydroponics involves growing plants without soil utilizing mineral nutrient solutions [20]. This method serves as an excellent alternative to mitigate the drawbacks of soil media, which consume substantial amounts of freshwater and fertilizers. In traditional hydroponics, nutrients are directly delivered to the plant roots, providing optimal conditions for plant growth and ensuring consistent yields [21]. Wastewater hydroponics, however, employ

wastewater instead of traditional hydroponic nutrient solutions, allowing for wastewater purification while simultaneously obtaining economically valuable by-products [22].

2. Mechanism of Hydroponic Plants to Purify Wastewater

The principle of hydroponic wastewater purification is phytoremediation, which is a low-cost and solar-powered natural cleaning technology. Plants assist in the removal of pollutants in a variety of ways, including phytoextraction, phytovolatilization, phytodegradation, and rhizofiltration (Figure 1). Phytoextraction refers to the absorption and transport of pollutants by plant roots from soil or water. Phytoextraction occurs either through metal hyperaccumulators or fast-growing plants for continuous extraction or application of acidifying chemical $(\text{NH}_4)_2\text{SO}_4$ to enhance plant uptake and transport of metals [23]. In addition, phytomining is a special method of phytoextraction with excellent commercial potential, which utilizes the absorption and accumulation of metals by plants to extract and accumulate noble metals from dispersive sources. This technology is widely used to recover nickel from contaminated land [24]. Dinh et al. [25] summarized nearly two decades of research on the phytomining, enrichment, and extraction of various precious metals, especially gold and silver. They believed that, in the case of depleted reserves, phytomining is a promising approach to recover noble metals from low-grade ores or secondary resources. However, this technology is only aimed at polluted soil, industrial wastewater, or mine wastewater that may also contain a large quantity of precious metals. So far, there is no relevant research on this type of wastewater hydroponics. Moreover, given the significant rise in rare earth prices and industrial demand in recent years, the utilization of phytomining for extracting rare earth elements has yet to be extensively explored and implemented in practical applications. This approach holds great promise as a sustainable and eco-friendly method for extracting rare earth elements from both wastewater and ores [25][26].

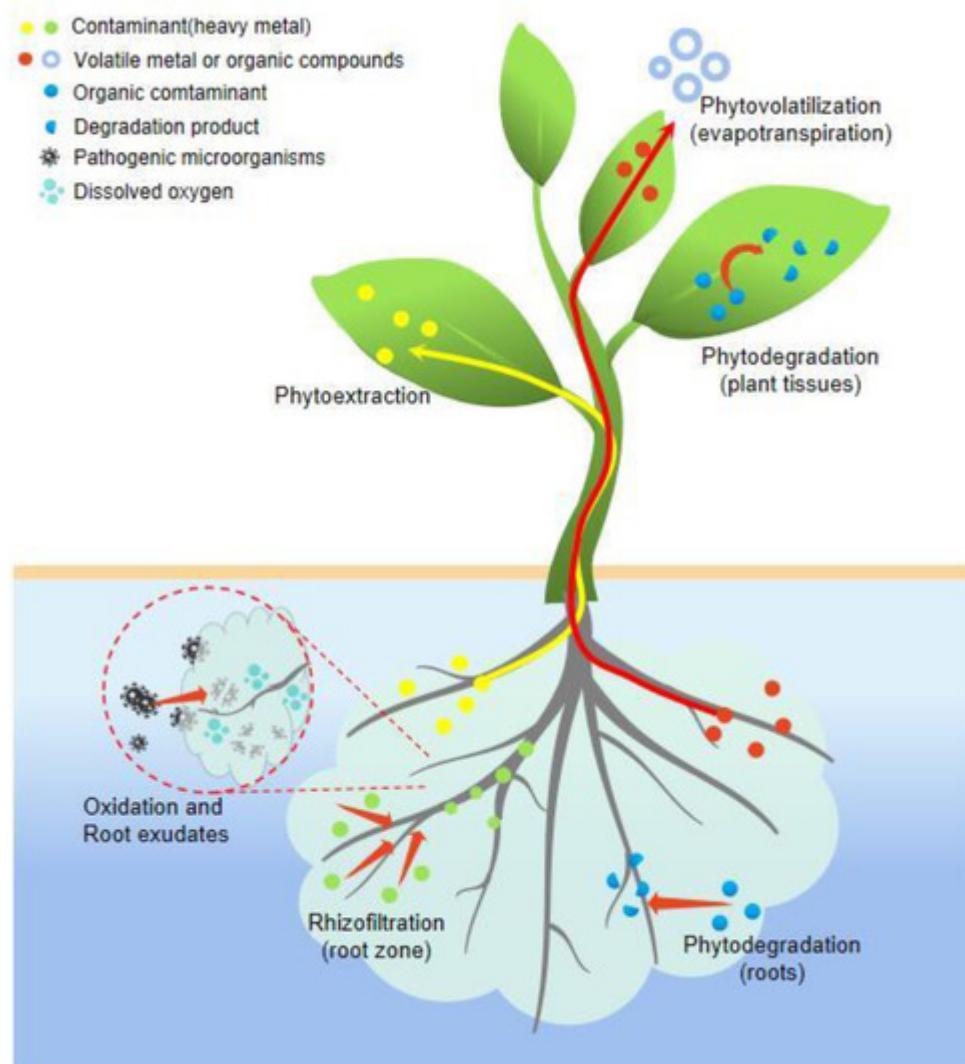


Figure 1. Schematic diagram of phytoremediation processes in wastewater hydroponics.

Phytovolatilization means that plants absorb pollutants through their roots and convert them into gaseous states, which are then released into the atmosphere through plant evapotranspiration. This technique has been used to remediate metal contamination (i.e., mercury (Hg) and Selenium (Se)) with volatile properties. For example, selenium can be volatilized by conversion to dimethyl selenide $[(CH_3)_2Se]$ [27][28]. Groundwater contaminated with volatile organic compounds, such as perchloroethylene and trichloroethylene, can also be remediated with this technology. This passive repair technique costs much less than traditional repair techniques [29].

Phytodegradation involves the direct degradation of organic pollutants through the release of enzymes from roots or through metabolic activities within plant tissues. During plant degradation, organic pollutants are taken up by roots and metabolized in plant tissues into less toxic substances. As with plant extraction and volatilization, plant uptake generally occurs only when the solubility and hydrophobicity of the contaminant are within acceptable limits. Phytodegradation has been observed to remediate some organic pollutants, such as chlorinated solvents and herbicides [30].

Rhizosphere filtration is primarily used to remediate contaminants in water by adsorbing or precipitating contaminants to plant roots or by absorbing contaminants around the root zone of plants [31][32][33]. Wastewater hydroponics mainly uses this technology to repair heavy metals and radioactive pollutants [34].

Chanu and Gupta [35] investigated the ability of hydroponic water spinach to remove Pb from wastewater and found that plant roots accumulated higher concentrations of Pb relative to stems and leaves, which had the ability to retain and limit the transport of heavy metals from roots to stems. A similar response was observed for copper in the same plant by Khumanleima Chanu and Gupta [36]. Two other studies also showed that the plant could be propagated by fragmentation, where uncontaminated parts can be excised and regenerated in uncontaminated media and new batches of wastewater can be reprocessed. Once growth has resumed, contaminant-rich necrotic fractions can be safely disposed of. Garousi et al. [37] evaluated the tolerance and accumulation of selenium in hydroponic sunflowers. The selenium content in the plants increased significantly with increasing selenium concentration. Chlorophyll a and b in the plants were not damaged after three weeks of selenium exposure up to 3 ml/L, which shows that the selenium of sunflower has high tolerance and absorption capacity, and selenium is easily transferred from the roots to the shoots. In addition to studying a single heavy metal, researchers also conducted a series of experiments on the ability of hydroponic plants to absorb various mixed heavy metals. *Helianthus annuus* can simultaneously absorb As, Cd, Cr, nickel (Ni), and Fe, and a significant increase of the As and Cd enrichment phenomenon was observed [38]. *Iris sibirica* can tolerate and accumulate Pb, cobalt (Co), and Ni, and the bioaccumulation factor of Pb is greater than one, indicating that it has a good phytoremediation potential for Pb and can be used for the remediation of mineral wastewater [39]. Researchers also used sunflower to absorb and accumulate radioactive elements, Cd, plutonium (Pu) [40], uranium (U) [41], and radon-222 [42].

Regarding the elimination of pathogens, a growing body of literature indicates that plant roots play a significant role [43][44][45][46][47]. The first mechanism involves oxidation. Through radial oxygen loss [48], plants release oxygen into the rhizosphere via their root system, thereby increasing the dissolved oxygen concentration in that area. However, as most intestinal bacteria are facultative or obligate anaerobes, the presence of aerobic conditions poses a significant threat to their survival [49][50][51]. Previous studies have demonstrated that aeration for 2 h resulted in an 8–10-fold increase in the bacterial mortality rate [52]. Moreover, the utilization of artificial aeration systems in hydroponic methods such as deep water culture and floating raft culture can enhance the removal efficiency of *E. coli* [53][54]. Another mechanism involves the release of root exudates by plants, which possess antimicrobial properties [55]. Earlier research has revealed that root exudates from plants like *Scirpus lacustris* and *Phragmites australis* have the ability to eliminate fecal *E. coli* and other pathogenic bacteria [56]. Recent studies have highlighted the secretion of proteins called lectins by plants, which enable the binding of pathogens to the root surface and cause damage to their structure [57]. Additionally, plants can secrete specific defense proteins to counteract infection by harmful bacteria [58]. For example, sweet basil roots secrete rosmarinic acid to combat *Pseudomonas aeruginosa* infection [59].

Comparison between Wastewater Hydroponics and Constructed Wetlands

Similar to wastewater hydroponic systems, CWs are widely used in sewage purification through microbial degradation, plant absorption, and substrate filtration due to their low treatment costs and stable operation. By simulating natural wetlands, CWs utilize the triple synergistic effects of natural ecosystems in physical, chemical, and biological states to achieve sewage purification. Thus, plants and media are the key elements in applying CWs in sewage treatment. However, there are many differences between wastewater hydroponic systems and CWs. Wastewater hydroponics are shallow wastewater treatment systems that typically treat low-intensity polluted wastewater. CWs are usually deep-water treatment systems, which can be used to treat landfill leachate, usually as the secondary or tertiary treatment stage of wastewater treatment plants [60].

CWs use a large number of media fillers to settle, filter, adsorb, and trap important pollutants in sewage [61]. With the accumulation of contaminants, many non-degradable solids enter the CW system. At the same time, microbial metabolism produces colloidal sludge with high water content and low density, resulting in a gradual decrease in the porosity of the filling layer, blocking the water flow channel, and ultimately affecting the effectiveness of treatment and operating life of the CW [32][33]. Wastewater hydroponic systems, on the other hand, use almost no media filtration, which means there is no risk of system clogging, thereby extending system life.

Hydroponic systems are mostly set up in a greenhouse environment or condition. Greenhouses protect crops from harsh weather (extreme temperatures, extreme rainfall, and strong winds) and pests, providing favorable climatic conditions for plant growth. In contrast, most of the CWs are outdoors, and purification performance varies with the seasons [62]. In winter, plants may wither and release nutrients, causing secondary pollution.

There are still a lot of uncertainties about the economics of these two technologies. A notable feature of hydroponics compared to CWs is that crops or flowers with a higher economic value can be used to remediate wastewater. The harvested vegetables, fruits, and flowers can generate sizable economic benefits. In recent years, the development of vertical farming has made it possible for hydroponic wastewater treatment technology to require less space, and it can also be implemented on-site. The yield of hydroponic crops is several times higher than that of traditional soil-based planting [63]. However, high initial investment requirements and huge energy consumption also significantly affect the economics of this technology. In contrast, CWs also require a specific initial investment, and a suitable location needs to be selected for site construction. However, the whole system has low energy consumption and simple operation. The CW itself can be used as a natural habitat and flood control facility, which can improve the aesthetic significance of suburban and rural areas, but the economic benefits are not obvious [60].

Based on the characteristics of the two technologies, Gong et al. [64] attempted a combination of CW and hydroponic vegetable (HV) systems to test the purification effect. The four systems tested included HV, subsurface flow constructed wetland (SFCW), HV followed by SFCW (HV/SFCW), and SFCW followed by HV (SFCW/HV). Among them, the HV/SFCW system achieved the best performance, by removing 39.1% COD, 61.1% TN, and 55% TP. They therefore suggested that HV/SFCW was most suitable for rural sewage tail water treatment.

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