water

MDPI

Review

Wastewater Hydroponics for Pollutant Removal and Food Production: Principles, Progress and Future Outlook

Chao Mai [1], Amin Mojiri [2,*], Swaminathan Palanisami [1], Ali Altaee [1], Yuhan Huang [1] and John L. Zhou [1,*]

[1] Centre for Green Technology, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia; chao.mai@student.uts.edu.au (C.M.); swaminathan.palanisami@alumni.uts.edu.au (S.P.); ali.altaee@uts.edu.au (A.A.); yuhan.huang@uts.edu.au (Y.H.)

[2] School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

* Correspondence: amin.mojiri@gmail.com (A.M.); junliang.zhou@uts.edu.au (J.L.Z.)

Abstract: 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. This paper aims to systematically review the principles, applications, and limitations of wastewater hydroponics technology in the context of pollution and nutrient removal. Unlike constructed wetlands, wastewater hydroponics has been proven to be effective in removing pollutants through small-scale in situ restoration. For instance, the average removal of COD, total nitrogen (TN), total phosphorus (TP), copper (Cu), and zinc (Zn) was more than 70%, 60%, 80%, 64.2%, and 49.5%, respectively. However, HP technology still has the disadvantages of high energy consumption, complex control parameters, and low public acceptance of using wastewater for planting crops. Therefore, further research is needed to reduce system energy consumption. In addition, hybrid technologies, such as two-stage hydroponics that use aquatic plants (algae or aquatic floating weeds) to recycle pollutant-containing wastewater nutrients for hydroponics, should be further developed.

Keywords: food crops; hydroponics; phytoremediation; pollutant removal; wastewater purification

check for updates

Citation: Mai, C.; Mojiri, A.; Palanisami, S.; Altaee, A.; Huang, Y.; Zhou, J.L. Wastewater Hydroponics for Pollutant Removal and Food Production: Principles, Progress and Future Outlook. *Water* **2023**, *15*, 2614. https://doi.org/10.3390/w15142614

Academic Editor: José Alberto Herrera-Melián

Received: 11 June 2023
Revised: 15 July 2023
Accepted: 17 July 2023
Published: 19 July 2023

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]. In addition, the effects of different types of wastewater in hydroponic experiments are rarely examined.

Therefore, this review aims to discuss the process mechanism in wastewater hydroponic systems, compare the wastewater hydroponics and CWs systems, review the progress of wastewater hydroponic experiments in recent years, and propose future research directions.

2. Wastewater Hydroponic Process

2.1. Nutrient Solutions

In wastewater hydroponics, the nutrients present in wastewater serve as essential elements for plant growth. These nutrient solutions must contain a significant amount of macro elements, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S), as well as trace amounts of microelements, such as iron (Fe), boron (B), manganese (Mn), zinc (Zn), and copper (Cu). According to [23], these essential elements are classified based on their relative concentrations in plant tissues, with the order being N > K > Ca > Mg > P > S > Fe > B > Mn > Zn > Cu. Therefore, insufficient nutrients in the wastewater can hinder crop growth. Studies have indicated that irrigating crops with treated wastewater can lead to yield reductions of nearly 50% compared to commercial nutrient solutions, due to the low nutrient concentrations in the wastewater [24–27]. Additionally, the chemical composition of wastewater nutrients can vary significantly, including variations in micro and macro nutrient content, pH levels, pollutants, and pathogens, depending on the wastewater source and treatment processes.

2.2. Wastewater Hydroponics

Generally, wastewater hydroponics can be categorized into open systems (where the nutrient solution is used only once) and closed systems (where the nutrient solution is recirculated). The open hydroponic system, also known as static solution culture, involves the simple application of the nutrient solution without considering the potential risks of plant infection or increased salinity resulting from recycling the solution. There are two types of open systems: deep water culture and floating raft culture. In a deep water culture (Figure 1a), plants are grown in pots with a growth medium, and the bottom of the pots are immersed in the nutrient solution, allowing some roots to be submerged, while others remain in the air [28]. In a floating raft culture (Figure 1b), plants are grown on a rigid Styrofoam raft that floats on a pool of nutrient solution. Both methods require aeration of the nutrient solution to prevent oxygen deficiency in the plant roots, which could inhibit cellular respiration [29]. Based on the experience in commercial hydroponics, the deep-water aquaculture system is recommended as a potential cultivation method for lettuce and other leafy vegetables. It offers simplicity, ease of operation, shorter crop duration, economic feasibility, high yield, and high-quality produce [30].

A closed hydroponic system, which is also called a continuous flow solution culture, can save more water and fertilizers than an open system. The nutrient film technique (Figure 1c) is the most common closed hydroponic system. In this system, the nutrient solution is pumped through the growing zone and flows over the plant roots. The water-saving effect of this system has been confirmed by many studies. The authors of [31] studied the recycling of hydroponic wastewater to grow cucumbers in greenhouses and found that the reuse of wastewater reduced water consumption by 33%, resulting in savings of 59% N, 25% P, and 55% K. One potential problem of closed hydroponic systems may be the accumulation of salt ions, mainly Na and chlorine (Cl). The increase in salt concentration leads to a decrease in plant photosynthesis and transpiration rates, a reduction in plant weight, and an apparent toxicity effect caused by Cl [32]. During the initial period of elevated salinity, root growth is rapidly and severely affected, with significant damage to older leaves observed after a few days, followed by mass death of older leaves after a few weeks [33]. Trajkova et al. [34] found that the cucumber yield in the nutrient solution with Na concentration of 31.0 mM was significantly lower than that of the standard solution with Na concentration of 1.23 mM. However, Grewal et al. [31] found that cucumber yields were not affected by salinity accumulation. They believed that the Na content of the drainage water reused for irrigation could not have been increased, because approximately 67% of the cucumber crop irrigation was from a fresh nutrient solution made with drinking water. In addition, not all plants are affected by high salinity. Sweet basil has been tested to have no effect on plant yield and quality at high NaCl concentrations (up to 30.0 mol/m^3) and low P concentrations (0.1 mol/m^3) [35]. The selection of wastewater hydroponic system depends on whether the effluent quality meets safe discharge standards, with particular attention paid to the removal of heavy metals and emerging pollutants.

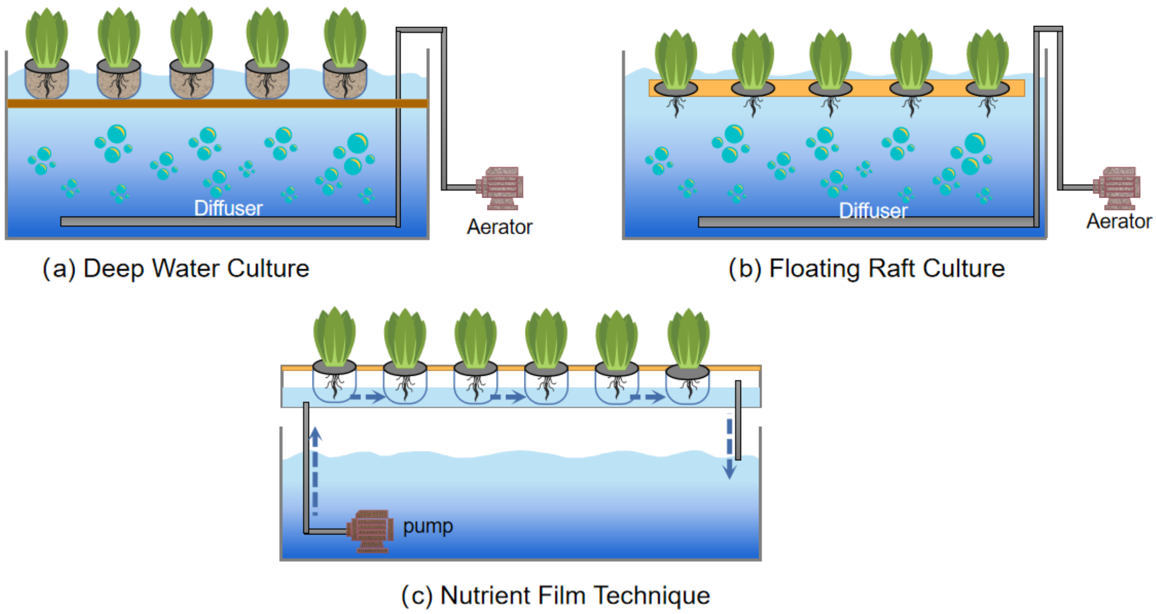

Figure 1. Typical types of wastewater hydroponic systems.

2.3. Hydroponic Plants

Commercial hydroponics are suitable for growing various fruits and vegetables using corresponding cultivation techniques [36]. Wastewater hydroponics is not recommended for growing vegetable species that use plant roots and stems as edible parts, because the roots and stems of the plants are in direct contact with wastewater. In addition to vegetable farming, wastewater hydroponics can also be used for flower farming. Damasceno et al. [37] irrigated gerbera with treated domestic wastewater in four volumes: 0%, 25%, 50%, and 75%, mixed with chemical fertilizers. The results showed that fertilizer-only irrigation produced only 6.1% more flowers than wastewater-only irrigation. The combination of mineral fertilizers and treated wastewater favored gerbera's growth and leaf development, and the harvested flowers were of higher quality.

3. 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 2). 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 $(NH_4)_2SO_4$ to enhance plant uptake and transport of metals [38]. 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 [39]. Dinh et al. [40] 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 [40,41].

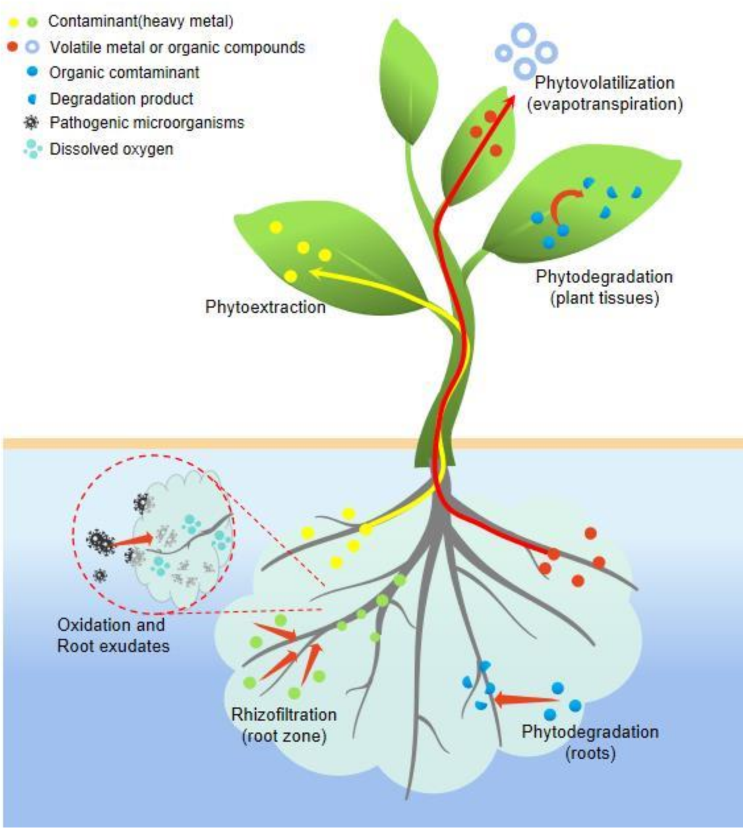

Figure 2. Schematic diagram of phytoremediation processes in wastewater hydroponics.

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 [$(CH_3)_2Se$] [42,43]. 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 [44].

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 [45].

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 [46–48]. Wastewater hydroponics mainly uses this technology to repair heavy metals and radioactive pollutants [49].

Chanu and Gupta [50] 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 [51]. 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. [52] 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 [53]. *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 [54]. Researchers also used sunflower to absorb and accumulate radioactive elements, Cd, plutonium (Pu) [55], uranium (U) [56], and radon-222 [57].

Regarding the elimination of pathogens, a growing body of literature indicates that plant roots play a significant role [58–62]. The first mechanism involves oxidation. Through radial oxygen loss [63], 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 [64–66]. Previous studies have demonstrated that aeration for 2 h resulted in an 8–10-fold increase in the bacterial mortality rate [67]. 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* [68,69]. Another mechanism involves the release of root exudates by plants, which possess antimicrobial properties [70]. 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 [71]. 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 [72]. Additionally, plants can secrete specific defense proteins to counteract infection by harmful bacteria [73]. For example, sweet basil roots secrete rosmarinic acid to combat *Pseudomonas aeruginosa* infection [74].

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 [75].

CWs use a large number of media fillers to settle, filter, adsorb, and trap important pollutants in sewage [76]. 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 [47,48]. 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 [77]. 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 [78]. 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 [75].

Based on the characteristics of the two technologies, Gong et al. [79] 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.

4. Hydroponics Performance in Pollutant Removal from Wastewater

Based on the type of wastewater and hydraulic retention time, wastewater hydroponics can be divided into domestic, industrial, and animal husbandry wastewater. As shown in Tables S1 and S2, the plant species, hydroponic system type, and hydraulic retention time (HRT) selected in each case are different, so there are considerable differences in the wastewater treatment results.

Figure 3 shows the removal performance in domestic wastewater. When hydroponics are used to treat domestic sewage, the HRT ranges from 3 h to two weeks, the removal rate of TN is greater than 60%, the average removal rate of COD is 70%, and the removal rate of TP is greater than 80% over 4 to 8 days. When treating industrial and livestock wastewater using hydroponics (Figure 4), the HRT is significantly longer than that of domestic sewage (up to 67 days), and the relationship between the removal effect of many elements and the HRT is not apparent.

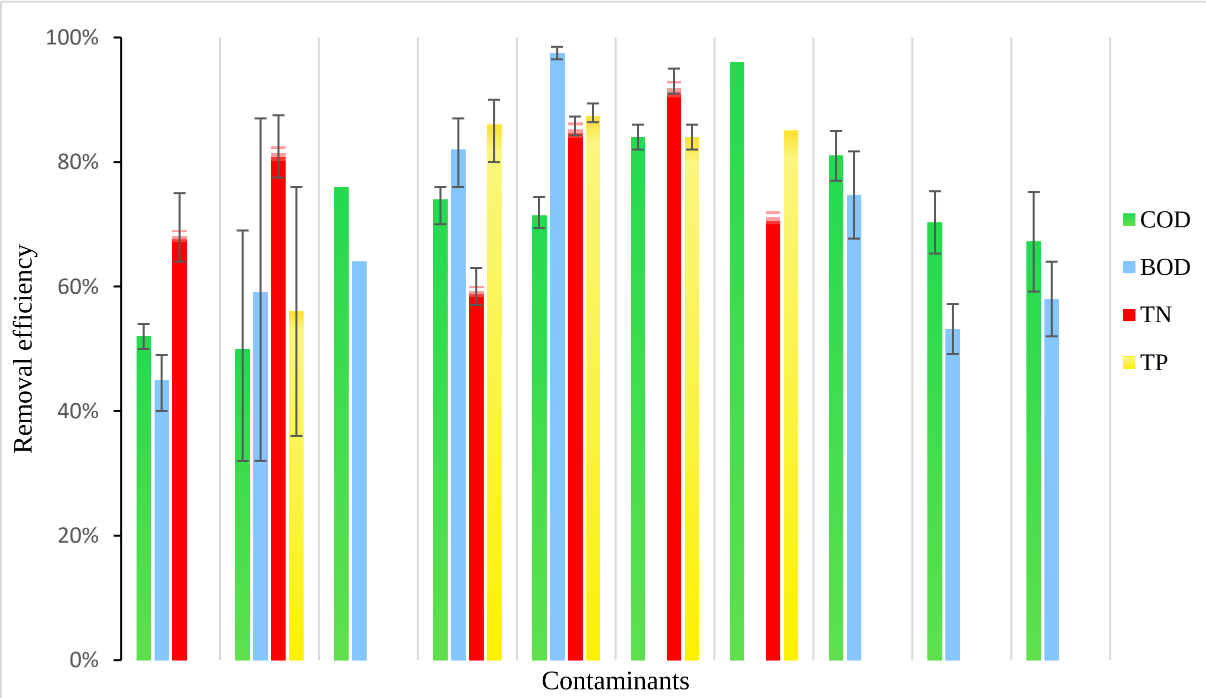

Figure 3. Hydroponic performance in the removal of pollutants from domestic wastewater. The following references have been used to draw the graph: [75,80–86].

At the same time, there are also significant differences in the treatment effects of different plants under the same conditions. The TN removal rate reached 98% for umbrella palm, but only 39% for vetiver [87].

Water quality indicators representing the treatment performance were also different. The conventional water quality parameters include N, P, COD, biochemical oxygen demand (BOD), total suspended solids (TSS), total dissolved solids (TDS), and total organic carbon (TOC). To protect public health, it is important to pay attention to the detection of *E. coli* when using vegetables as hydroponic plants. In the effluent of wastewater hydroponic vegetables, Ndulini et al. [86] found that the removal rate of fecal coliforms was up to 93% when the HRT was 8 days. In the leaves of hydroponic lettuce, *E. coli* and fecal coliforms were not detected in treated greywater, treated post-hydrothermal liquefaction wastewater, or wastewater treatment plant (WWTP) effluents [88–90]. The results indicate that it is possible to grow leafy vegetables in hydroponic systems with treated wastewater; however, particular attention needs to be paid to the risk of microbial contamination during irrigation and harvesting. In addition, hydroponic plants can also remove heavy metals while absorbing nutrients. Davamani et al. [91] found that the removal rates of lead and cadmium in paper board mill effluent were 54% and 33%, respectively after 40 days, due to the affinity of vetiver to lead. Jin et al. [92] found that, after 20 days of hydroponic spinach using swine wastewater, the removal rates of Cu(II) and Zn(II) reached 64.29% and 49.53%, respectively, and the water quality met the national discharge standard for livestock wastewater in China.

In terms of plant selection, wastewater hydroponics mostly use small herbaceous and aquatic plants (Table 1), which have a short growth cycle and strong adaptability. Economic value is also one of the key considerations in wastewater hydroponics. Most of the selected plants can be used for food, medical treatment, animal feed, and ornamental purposes.

Table 1. Common plants in wastewater hydroponics and their uses.

Name	Category	Use	Reference
Spinach	Leafy green flowering plant	Food	[92,93]
Romaine lettuce	Annual plant	Food	[81,93]
Bidens pilosa L	Herbaceous flowering plant	Food and medicine	[86]
Amaranthus hybridus	Annual flowering plant	Food, medicine, ornamental	
Chrysopogon zizanioides	Perennial bunchgrass	Skincare, animal feed, perfumery, medicine	[75,85,87,91,94]
Water lettuce	Aquatic plants	Animal feed, medicine	[75]
Giant salvinia	Aquatic fern	Cancer research	
Water hyacinth	Perennial aquatic plant	Bioenergy, food, medicine	[75,80,95]
Nephthytis podophyllum	Evergreen herbaceous plant	Ornamental	[82]
Ipomoea aquatica	Semi-aquatic, tropical plant	Food, animal feed, medicine	[83]
Pointed cabbage	Biennial plant	Food	[96]
Typha latifolia	Perennial herbaceous plant	Food and medicine	[97]
Umbrella palm	Grass-like plant	Ornamental	[87]
Ramie	Perennial herbaceous plant	Textile	[98]
Citrullus colocynthis	Desert viny plant	Food and medicine	[99]

WTPs are typically designed to remove suspended solids and oxygen demand (COD, BOD_5), they cannot completely remove organic pollutants from wastewater, especially trace contaminants such as pharmaceutical components, which include analgesics, antibacterials, antibiotics, antidepressants, anti-inflammatory drugs, antipyretics, lipid-lowering drugs, antidiabetic drugs, and sedatives. These pharmaceutical ingredients constitute emerging pollutants to water bodies. Many studies have been conducted to remove emerging contaminants using hydroponics, and the plants and removal rates reported in the relevant literature are summarized in Table 2.

Table 2. Plants and removal rates reported for emerging pollutants.

Pharmaceutical Ingredients	Plant	Exposure Concentration	Period (Days)	Removal Efficiency	References
Antidiabetic II medicine (Metformin)	*Typha latifolia*	6.45 mg/L 32.29 mg/L	28	74.0 ± 4.1% 81.1 ± 3.3%	[84]
Blood lipid regulator (Carbamazepine)	*Scirpus validus*	0.5 mg/L	21	54–64%	[100]
Analgesic (Naproxen)				80–94% (30–42% by photodegradation)	
Anti-inflammatory (Diclofenac)				85–98% (73–77% by photodegradation)	
Blood lipid regulator (Clofibric acid)				41–73%	
Stimulant drug (Caffeine)	*I. pseudacorus*		2	100%	[101]
Opioid analgesic (Codeine)		24×10^{-6} mg/L		93%	
Antidepressant (Citalopram)		84×10^{-6} mg/L		87%	
X-ray contrast agent (Iopromide)	*Typha latifolia*	15.8 mg/L	28	87%	[102]
Anti-inflammatory and analgesic (Aspirin)	*Brassica juncea*	4–180 mg/L	28	90%	[103]
Antibiotic (Tetracycline)		5–225 mg/L	24	71%	
Antibiotic (Ciprofloxacin)	*Chrysopogon zizanioides*	10 mg/L	7	93%	[85]
Antibiotic (Tetracycline)				97%	

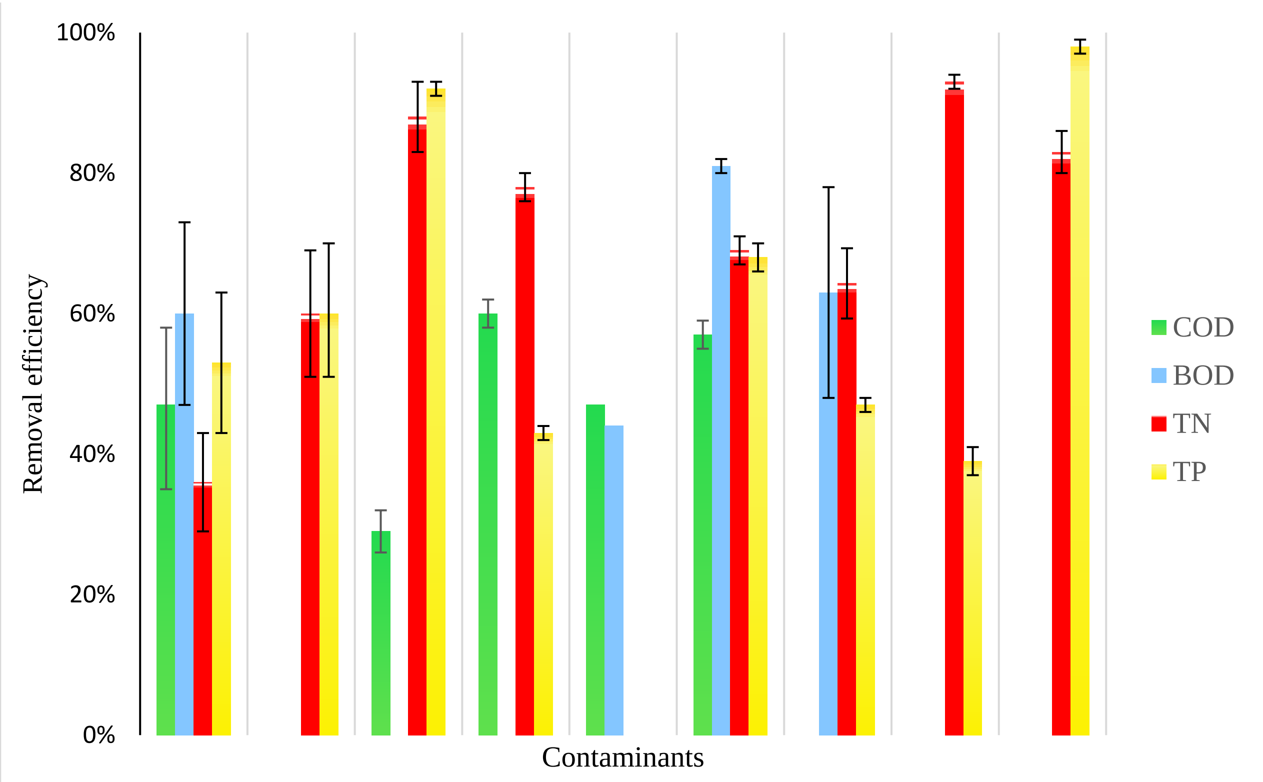

Figure 4. Hydroponic performance in the removal of pollutants from industrial and livestock wastewater. The following references have been used to draw the graph: [87,91,92,94,98,99].

Several studies have examined the kinetics of removing pollutants from hydroponic plants and have found that the process follows first-order kinetics, meaning that the rate of pollutant removal is related to the initial concentration. Interestingly, different experiments have yielded conflicting conclusions. Cui and Schröder [84] discovered that metformin was more effectively removed from nutrient solutions at lower treatment concentrations compared to higher concentrations. Similarly, negative correlations between initial concentration and removal efficiency were observed in hydroponic experiments using *Typha* spp. to remove carbamazepine, and in constructed wetlands employing *C. alternifolius* to remove four pharmaceutically active compounds [104,105]. However, Zhang et al. [100] found a positive correlation between the initial spiked concentration of carbamazepine and its removal efficiency. This finding aligns with findings by Enyoh and Isiuku [106], who observed the same phenomenon in the removal of 2,4,6-trichlorophenol by *Canna indica*. Furthermore, some studies have reported that the removal rate is independent of the influent concentration, but positively correlated with temperature.

Emerging pollutants taken up by plants through their roots are translocated to different parts of the plants, causing them to be detected in the stems, leaves, and fruits, and root vegetables pose a higher risk of exposure to humans than leafy vegetables in heterogeneously polluted environments [84,107–109]. These organic pollutants may be partially or wholly degraded, metabolized, or transformed into less toxic compounds or even inorganics. However, research on the transformation of medicinal components by plants is limited. For instance, metformin (MET), a widely used drug for treating type 2 diabetes worldwide, is frequently detected in surface water monitoring events. *Typha latifolia*, a plant species, has been found to convert MET into methyl biguanide (MBG) in a hydroponic environment. However, MBG accounts for only a small portion of the overall MET conversion, and further studies are needed to explore other conversion products [84]. It is important to note that new compounds formed during the transformation of intermediates may be more environmentally toxic than the original compounds (Yan et al., 2020). For example, a study on the removal of carbamazepine with four wetland plants discovered that an intermediate metabolite (acridine) was more toxic than the parent compound [110]. Additionally, the safe disposal of plants after harvest also requires further research [111].

5. Advantages and Limitations of Wastewater Hydroponics

Wastewater hydroponics offers several advantages as a green process for wastewater treatment. Firstly, it relies on natural processes such as adsorption, biodegradation, and phytoremediation, making it environmentally friendly. Secondly, it serves a dual purpose of treating wastewater while enabling the growth of crops and plants that can potentially be used for human consumption, provided sufficient precautions and quality control measures are in place. Additionally, the process is highly versatile, allowing for various configurations, dimensions, types of plants, and operational parameters (e.g., hydraulic retention time). Moreover, this method requires minimal maintenance once it has been properly established.

However, wastewater hydroponics have significant limitations. Wastewater hydroponic systems are highly dependent on the power supply to support plant growth. Power consumption is needed for lighting, as well as various sensors to monitor hydroponic parameters, and this power is often provided by the grid. Some studies have proposed the use of microbial electrochemical systems, such as microbial fuel cells, to collect and store the bioelectricity generated by bacterial metabolism for the lighting, monitoring, and pumping power requirements in hydroponic systems [112,113]. Although this method can increase the removal efficiency of pollutants and reduce greenhouse gas emissions while supplementing electric energy, the high initial investment, difficult control, and overly complex systems restrict the application of this method [114].

It has been observed that the wastewater treatment effectiveness and crop yield in wastewater hydroponic systems are influenced by various factors, including environmental conditions (such as temperature, pH, electrical conductivity (EC), light intensity, and duration) and hydroponic system parameters (such as wastewater type and strength, plant and substrate type, aeration duration, nutrition retention time, and irrigation system). Among these factors, hydraulic retention time (HRT) is a key parameter that determines the rate of pollutant removal.

The public's acceptance of wastewater cultivation for edible crops is also one of the key factors that determine the economics of wastewater hydroponics. A survey of parents of high school children in Greece found that 60% had a positive attitude towards wastewater reuse, but 77% voted against the use of wastewater in greenhouse vegetables [115]. In Brazil, a questionnaire survey of 356 people on wastewater reuse showed that 30% of the people believed that the reuse of treated water within the scope of normative standards for irrigation of raw food (vegetables, fruits, and vegetables) may bring health problems, and 20% thought that the same water used to irrigate rice, beans, and corn would also cause health problems [116]. A similarly sized survey in Belgium showed that 11% of the respondents would not eat vegetables grown from treated wastewater, even if the water quality had been rigorously tested [117]. In Qatar, a larger survey (1352 people) on the reuse of industrial wastewater showed that 74% of the respondents did not accept the reuse of industrial wastewater. The respondents were worried that the pollutants in the wastewater could not be completely removed, and also expressed concerns regarding the possible risks of long-term use of wastewater [118].

The concerns about food irrigated with wastewater are not unfounded, as numerous studies have found that pathogens can enter crops through the roots, with the highest concentrations typically found in the root system. Moreover, hydroponic plants pose a greater risk of pathogen entry compared to soil-grown plants [119]. Hirneisen and Kniel [120] observed the internalization of Hepatitis A Virus (HAV) and Murine Norovirus (MNV) in spinach and green onions under hydroponic conditions, whereas no viruses were found in soil cultivation systems. Under hydroponic conditions, both human norovirus and animal caliciviruses can enter through the roots of lettuce and be transmitted to sprouts and leaves [121]. Studies have demonstrated that plants can serve as alternative hosts for pathogens. For example, salmonella can enter edible plants while still retaining its toxicity to animals [119]. Once these pathogens enter the internal tissues of plants, they cannot be removed through surface cleaning, and currently, there is no research on disinfection methods specifically targeting pathogens that have been internalized in plants. Therefore, it is recommended to use ornamental or non-edible crops for wastewater hydroponics. In addition to growing crops directly in wastewater, microalgae or duckweed can be used to recycle nutrients from wastewater. Microalgae are photosynthetic organisms that can thrive in wastewater by utilizing nutrients and organic compounds. Numerous studies have examined the use of microalgae for wastewater treatment. For instance, Li et al. [122] investigated the cultivation of chlorella using municipal wastewater and observed that, after 14 days, the algae removed 93.9% of ammonia, 89.1% of total nitrogen (TN), and 80.9% of total phosphorus (TP). Similar cultivation periods and treatment results were reported in studies involving microalgae treatment of landfill leachate and mine wastewater [123,124]. Duckweed, on the other hand, is a small, rapidly growing aquatic plant that floats on the water surface. It exhibits a high protein content, and its biomass can double in 16 to 24 h. Duckweed is relatively easy to handle, harvest, and process. Notably, compared to algae, it is simpler to harvest duckweed in large quantities because it does not require time- and energy-consuming centrifugation or membrane filtration steps [125]. Regarding wastewater treatment, duckweed demonstrates a similar efficacy to microalgae. In a pilot-scale study conducted by El-Shafai et al. [126], it was found that duckweed, during the warm season (with a hydraulic retention time of 15 days), could remove 98% of ammonia, 85% of total kjeldahl nitrogen (TKN), and 78% of TP from domestic wastewater. In winter, it took eight weeks for duckweed to remove 83.7% and 89.4% of TN and TP, respectively, from swine wastewater [127]. Therefore, both microalgae and duckweed exhibit relatively stable recovery efficiencies for wastewater nutrients. Future research can explore their use in nutrient recovery from wastewater, followed by the conversion of the harvested biomass into a nutrient solution for hydroponics. This approach can enhance water quality treatment performance and avoid direct contact between sewage and crops.

6. Conclusions

While the field of hydroponics has achieved significant success in commercial applications, research in the field of wastewater hydroponics is still limited. A literature review indicates that various aquatic and terrestrial plants can effectively treat different types of wastewater, including domestic, industrial, and livestock waste. Wastewater hydroponics, through phytoremediation, offers the potential to remove heavy metals, microorganisms, emerging pollutants, and conventional pollutants. However, there are several limitations to this approach. The average removal rates of COD, total nitrogen (TN), total phosphorus (TP), copper (Cu), and zinc (Zn) were found to be more than 70%, 60%, 80%, 64.2%, and 49.5%, respectively. The efficiency of wastewater hydroponic systems is influenced by various operating parameters, such as influent concentration, pH, plant selection, light duration, and hydraulic retention time (HRT). Furthermore, there is currently no standardized evaluation index for assessing the effectiveness of pollutant removal in wastewater hydroponics. Therefore, determining optimal operating parameters is crucial to ensure high pollutant removal and efficient utilization of wastewater hydroponic systems. In contrast to large-scale hydroponics in constructed wetlands, most wastewater hydroponics experiments are still limited to laboratory-scale trials. Immature technology, along with high energy consumption and capital investment, restricts the scale and economic feasibility of wastewater hydroponics. Future research should focus on developing and utilizing alternative green energy sources, such as solar energy, to reduce energy costs.

While scientific reports have not detected *E. coli* or helminth eggs in vegetables grown from wastewater, public concerns about potential bacterial contamination persist. Therefore, it is crucial to establish stringent procedures throughout the entire process of wastewater hydroponics to prevent vegetable contamination during planting and harvesting stages.

Pre-treating specific wastewater to remove toxic chemicals like heavy metals and *E. coli* is necessary.

7. Future Perspective

Routine analysis of harvested vegetables should be conducted to detect any exceedance of food safety standards, which would require proper disposal. Additionally, instead of directly using wastewater for crop cultivation, fast-growing aquatic plants like microalgae or duckweed can be utilized to sustainably recycle nutrients in wastewater. The harvested biomass can then serve as a nutrient solution for hydroponic crops. This approach, known as the 'double hydroponic' method, may present a new direction for future advancements in wastewater hydroponics. In addition, alternative green energy sources should be developed and utilized, such as solar energy, to reduce energy consumption and operational costs. This technology could also determine optimal parameters for pollutant removal, including influent concentration, pH levels, plant selection, light duration, and hydraulic retention time (HRT). Standardized evaluation indices for accurate comparisons and optimization should be established. In summary, wastewater hydroponics hold great potential for addressing the continuous generation of large volumes of wastewater and the subsequent water scarcity crisis. However, further improvement and development is necessary to fully realize this potential.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15142614/s1, Table S1: Removal performance in domestic wastewater-based hydroponics; Table S2: Removal performance in industrial and livestock wastewater-based hydroponics.

Author Contributions: Conceptualization, C.M. and J.L.Z.; investigation, C.M. and S.P. and A.M.; resources, A.A., Y.H. and J.L.Z.; writing—original draft preparation, C.M., A.M. and J.L.Z.; writing—review and editing, C.M. and S.P.; supervision, J.L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The first author acknowledges the China Scholarship Council (CSC) for the financial support for his PhD study (File No.201908610182).

Data Availability Statement: Not Applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. United Nations Summary Progress Update 2021: SDG 6—Water and Sanitation for All. Available online: https://www.unwater.org/publications/summary-progress-update-2021-sdg-6-water-and-sanitation-all (accessed on 1 July 2023).
2. Idris-Nda, A.; Aliyu, H.K.; Dalil, M. The Challenges of Domestic Wastewater Management in Nigeria: A Case Study of Minna, Central Nigeria. *Int. J. Dev. Sustain.* **2013**, *2*, 1169–1182.
3. Saxena, G.; Bharagava, R. Organic and Inorganic Pollutants in Industrial Wastes. In *Environmental Pollutants and Their Bioremediation Approaches*; CRC Press: Boca Raton, FL, USA, 2017; pp. 23–56.
4. United Nations Environment Programme 2017 UN World Water Development Report, Wastewater: The Untapped Resource. Available online: https://www.unep.org/resources/publication/2017-un-world-water-development-report-wastewater-untapped-resource (accessed on 1 July 2023).
5. Wani, A.L.; Ara, A.; Usmani, J.A. Lead Toxicity: A Review. *Interdiscip. Toxicol.* **2015**, *8*, 55–64. [CrossRef]
6. Choong, T.S.Y.; Chuah, T.G.; Robiah, Y.; Gregory Koay, F.L.; Azni, I. Arsenic Toxicity, Health Hazards and Removal Techniques from Water: An Overview. *Desalination* **2007**, *217*, 139–166. [CrossRef]
7. Costa, M.; Klein, C.B. Toxicity and Carcinogenicity of Chromium Compounds in Humans. *Crit. Rev. Toxicol.* **2006**, *36*, 155–163. [CrossRef] [PubMed]
8. Rafati Rahimzadeh, M.; Rafati Rahimzadeh, M.; Kazemi, S.; Moghadamnia, A.-A. Cadmium Toxicity and Treatment: An Update. *Casp. J. Intern. Med.* **2017**, *8*, 135–145. [CrossRef]
9. Poongothai, S.; Ravikrishnan, R.; Balikrishna Murthy, P. Endocrine Disruption and Perspective Human Health Implications: A Review. *Internet J. Toxicol.* **2007**, *4*, 10–1210.
10. Raghav, M.; Eden, S.; Mitchell, K.; Witte, B. *Contaminants of Emerging Concern in Water*; The University of Arizona: Tucson, AZ, USA, 2013.

11. Crini, G.; Lichtfouse, E. Advantages and Disadvantages of Techniques Used for Wastewater Treatment. *Environ. Chem. Lett.* **2019**, *17*, 145–155. [CrossRef]
12. Ahmed, M.B.; Zhou, J.L.; Ngo, H.H.; Guo, W. Adsorptive Removal of Antibiotics from Water and Wastewater: Progress and Challenges. *Sci. Total Environ.* **2015**, *532*, 112–126. [CrossRef]
13. Xu, B.; Liu, S.; Zhou, J.L.; Zheng, C.; Weifeng, J.; Chen, B.; Zhang, T.; Qiu, W. PFAS and Their Substitutes in Groundwater: Occurrence, Transformation and Remediation. *J. Hazard. Mater.* **2021**, *412*, 125159. [CrossRef]
14. Palansooriya, K.N.; Yang, Y.; Tsang, Y.F.; Sarkar, B.; Hou, D.; Cao, X.; Meers, E.; Rinklebe, J.; Kim, K.-H.; Ok, Y.S. Occurrence of Contaminants in Drinking Water Sources and the Potential of Biochar for Water Quality Improvement: A Review. *Crit. Rev. Environ. Sci. Technol.* **2020**, *50*, 549–611. [CrossRef]
15. Qiu, B.; Tao, X.; Wang, H.; Li, W.; Ding, X.; Chu, H. Biochar as a Low-Cost Adsorbent for Aqueous Heavy Metal Removal: A Review. *J. Anal. Appl. Pyrolysis* **2021**, *155*, 105081. [CrossRef]
16. Chen, W.-H.; Hoang, A.T.; Nižetić, S.; Pandey, A.; Cheng, C.K.; Luque, R.; Ong, H.C.; Thomas, S.; Nguyen, X.P. Biomass-Derived Biochar: From Production to Application in Removing Heavy Metal-Contaminated Water. *Process Saf. Environ. Prot.* **2022**, *160*, 704–733. [CrossRef]
17. Carra, I.; Sánchez Pérez, J.A.; Malato, S.; Autin, O.; Jefferson, B.; Jarvis, P. Performance of Different Advanced Oxidation Processes for Tertiary Wastewater Treatment to Remove the Pesticide Acetamiprid. *J. Chem. Technol. Biotechnol.* **2016**, *91*, 72–81. [CrossRef]
18. Sun, Y.; Xue, S.; Li, L.; Ding, W.; Liu, J.; Han, Y. Sulfur Dioxide and o -Xylene Co-Treatment in Biofilter: Performance, Bacterial Populations and Bioaerosols Emissions. *J. Environ. Sci.* **2018**, *69*, 41–51. [CrossRef] [PubMed]
19. Antony, A.; Low, J.H.; Gray, S.; Childress, A.E.; Le-Clech, P.; Leslie, G. Scale Formation and Control in High Pressure Membrane Water Treatment Systems: A Review. *J. Memb. Sci.* **2011**, *383*, 1–16. [CrossRef]
20. Sardare, M.D.; Admane, S.V. A Review on Plant without Soil-Hydroponics. *Int. J. Res. Eng. Technol.* **2013**, *02*, 299–304. [CrossRef]
21. Fussy, A.; Papenbrock, J. An Overview of Soil and Soilless Cultivation Techniques—Chances, Challenges and the Neglected Question of Sustainability. *Plants* **2022**, *11*, 1153. [CrossRef]
22. Magwaza, S.T.; Magwaza, L.S.; Odindo, A.O.; Mditshwa, A. Hydroponic Technology as Decentralised System for Domestic Wastewater Treatment and Vegetable Production in Urban Agriculture: A Review. *Sci. Total Environ.* **2020**, *698*, 134154. [CrossRef]
23. Taiz, L.; Zeiger, E. *Fisiologia Vegetal*, 5th ed.; Artmed: Joane, Portugal, 2013.
24. Boyden, B.H.; Rababah, A.A. Recycling Nutrients from Municipal Wastewater. *Desalination* **1996**, *106*, 241–246. [CrossRef]
25. Krishnasamy, K.; Nair, J.; Bäuml, B. Hydroponic System for the Treatment of Anaerobic Liquid. *Water Sci. Technol.* **2012**, *65*, 1164–1171. [CrossRef] [PubMed]
26. Adrover, M.; Moyà, G.; Vadell, J. Use of Hydroponics Culture to Assess Nutrient Supply by Treated Wastewater. *J. Environ. Manag.* **2013**, *127*, 162–165. [CrossRef] [PubMed]
27. da Silva Cuba Carvalho, R.; Bastos, R.G.; Souza, C.F. Influence of the Use of Wastewater on Nutrient Absorption and Production of Lettuce Grown in a Hydroponic System. *Agric. Water Manag.* **2018**, *203*, 311–321. [CrossRef]
28. KHAN, F.A. A Review on Hydroponic Greenhouse Cultivation for Sustainable Agriculture. *Int. J. Agric. Environ. Food Sci.* **2018**, *2*, 59–66. [CrossRef]
29. Norström, A. *Treatment of Domestic Wastewater Using Microbiological Processes and Hydroponics in Sweden*; Royal Institute of Technology: Stockholm, Sweden, 2005.
30. Majid, M.; Khan, J.N.; Ahmad Shah, Q.M.; Masoodi, K.Z.; Afroza, B.; Parvaze, S. Evaluation of Hydroponic Systems for the Cultivation of Lettuce (*Lactuca sativa* L., Var. *Longifolia*) and Comparison with Protected Soil-Based Cultivation. *Agric. Water Manag.* **2021**, *245*, 106572. [CrossRef]
31. Grewal, H.S.; Maheshwari, B.; Parks, S.E. Water and Nutrient Use Efficiency of a Low-Cost Hydroponic Greenhouse for a Cucumber Crop: An Australian Case Study. *Agric. Water Manag.* **2011**, *98*, 841–846. [CrossRef]
32. Neocleous, D.; Vasilakakis, M. Effects of NaCl Stress on Red Raspberry (*Rubus Idaeus* L. 'Autumn Bliss'). *Sci. Hortic.* **2007**, *112*, 282–289. [CrossRef]
33. Munns, R. Comparative Physiology of Salt and Water Stress. *Plant Cell Environ.* **2002**, *25*, 239–250. [CrossRef]
34. Trajkova, F.; Papadantonakis, N.; Savvas, D. Comparative Effects of NaCl and $CaCl_2$ Salinity on Cucumber Grown in a Closed Hydroponic System. *HortScience* **2006**, *41*, 437–441. [CrossRef]
35. Germano, R.P.; Melito, S.; Cacini, S.; Carmassi, G.; Leoni, F.; Maggini, R.; Montesano, F.F.; Pardossi, A.; Massa, D. Sweet Basil Can Be Grown Hydroponically at Low Phosphorus and High Sodium Chloride Concentration: Effect on Plant and Nutrient Solution Management. *Sci. Hortic.* **2022**, *304*, 111324. [CrossRef]
36. Velazquez-Gonzalez, R.S.; Garcia-Garcia, A.L.; Ventura-Zapata, E.; Barceinas-Sanchez, J.D.O.; Sosa-Savedra, J.C. A Review on Hydroponics and the Technologies Associated for Medium- and Small-Scale Operations. *Agriculture* **2022**, *12*, 646. [CrossRef]
37. Damasceno, L.M.O.; de Andrade Júnior, A.S.; Gheyi, H.R. Cultivation of Gerbera Irrigated with Treated Domestic Effluents. *Rev. Bras. Eng. Agrícola E Ambient.* **2010**, *14*, 582–588. [CrossRef]
38. Greipsson, S. Phytoremediation. *Nat. Educ. Knowl.* **2011**, *30*, 7.
39. Chaney, R.L. Phytoextraction and Phytomining of Soil Nickel. In *Nickel in Soils and Plants*; CRC Press: Boca Raton, FL, USA, 2018; pp. 341–374.
40. Dinh, T.; Dobo, Z.; Kovacs, H. Phytomining of Noble Metals—A Review. *Chemosphere* **2022**, *286*, 131805. [CrossRef] [PubMed]
41. Dang, P.; Li, C. A Mini-Review of Phytomining. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 12825–12838. [CrossRef]

42. Nagata, T.; Morita, H.; Akizawa, T.; Pan-Hou, H. Development of a Transgenic Tobacco Plant for Phytoremediation of Methylmercury Pollution. *Appl. Microbiol. Biotechnol.* **2010**, *87*, 781–786. [CrossRef]
43. Zayed, A.; Pilon-Smits, E.; deSouza, M.; Lin, Z.-Q.; Terry, N. Remediation of Selenium-Polluted Soils and Waters by Phytovolatilization. In *Phytoremediation of Contaminated Soil and Water*; CRC Press: Boca Raton, FL, USA, 2020; pp. 61–83.
44. Wang, L.; Hou, D.; Shen, Z.; Zhu, J.; Jia, X.; Ok, Y.S.; Tack, F.M.G.; Rinklebe, J. Field Trials of Phytomining and Phytoremediation: A Critical Review of Influencing Factors and Effects of Additives. *Crit. Rev. Environ. Sci. Technol.* **2020**, *50*, 2724–2774. [CrossRef]
45. Etim, E.E. Phytoremediation and Its Mechanisms: A Review. *Int. J. Environ. Bioenergy* **2012**, *2*, 120–136.
46. Kristanti, R.A.; Ngu, W.J.; Yuniarto, A.; Hadibarata, T. Rhizofiltration for Removal of Inorganic and Organic Pollutants in Groundwater: A Review. *Biointerface Res. Appl. Chem.* **2021**, *11*, 12326–12347. [CrossRef]
47. Wang, H.; Sheng, L.; Xu, J. Clogging Mechanisms of Constructed Wetlands: A Critical Review. *J. Clean. Prod.* **2021**, *295*, 126455. [CrossRef]
48. Wang, M.; Chen, S.; Jia, X.; Chen, L. Concept and Types of Bioremediation. In *Handbook of Bioremediation*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 3–8.
49. Tonelli, F.C.P.; Tonelli, F.M.P.; Lemos, M.S.; Nunes, N.A.d.M. Mechanisms of Phytoremediation. In *Phytoremediation*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 37–64.
50. Bedabati Chanu, L.; Gupta, A. Phytoremediation of Lead Using Ipomoea Aquatica Forsk. in Hydroponic Solution. *Chemosphere* **2016**, *156*, 407–411. [CrossRef]
51. Khumanleima Chanu, H.; Gupta, A. Necrosis as an Adaptive Response to Copper Toxicity in Ipomoea Aquatica Forsk. and Its Possible Application in Phytoremediation. *Acta Physiol. Plant* **2014**, *36*, 3275–3281. [CrossRef]
52. Garousi, F.; Kovács, B.; Andrási, D.; Veres, S. Selenium Phytoaccumulation by Sunflower Plants under Hydroponic Conditions. *Water Air Soil. Pollut.* **2016**, *227*, 382. [CrossRef]
53. January, M.C.; Cutright, T.J.; Van Keulen, H.; Wei, R. Hydroponic Phytoremediation of Cd, Cr, Ni, As, and Fe: Can Helianthus Annuus Hyperaccumulate Multiple Heavy Metals? *Chemosphere* **2008**, *70*, 531–537. [CrossRef] [PubMed]
54. Wan, S.; Pang, J.; Li, Y.; Li, Y.; Zhu, J.; Wang, J.; Chang, M.; Wang, L. Hydroponic Phytoremediation of Ni, Co and Pb by *Iris sibirica* L. *Sustainability* **2021**, *13*, 9400. [CrossRef]
55. Lee, J.H.; Hossner, L.R.; Attrep, M., Jr.; Kung, K.S. Uptake and Translocation of Plutonium in Two Plant Species Using Hydroponics. *Environ. Pollut.* **2002**, *117*, 61–68. [CrossRef]
56. Dushenkov, S.; Vasudev, D.; Kapulnik, Y.; Gleba, D.; Fleisher, D.; Ting, K.C.; Ensley, B. Removal of Uranium from Water Using Terrestrial Plants. *Environ. Sci. Technol.* **1997**, *31*, 3468–3474. [CrossRef]
57. Lewis, B.G.; MacDonell, M.M. Release of Radon-222 by Vascular Plants: Effect of Transpiration and Leaf Area. *J. Environ. Qual.* **1990**, *19*, 93–97. [CrossRef]
58. Wang, J.; Wang, W.; Xiong, J.; Li, L.; Zhao, B.; Sohail, I.; He, Z. A Constructed Wetland System with Aquatic Macrophytes for Cleaning Contaminated Runoff/Storm Water from Urban Area in Florida. *J. Environ. Manag.* **2021**, *280*, 111794. [CrossRef]
59. Vymazal, J. Removal of Enteric Bacteria in Constructed Treatment Wetlands with Emergent Macrophytes: A Review. *J. Environ. Sci. Health Part. A* **2005**, *40*, 1355–1367. [CrossRef]
60. Dhir, B. Effective Control of Waterborne Pathogens by Aquatic Plants. In *Waterborne Pathogens*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 339–361.
61. Shingare, R.P.; Thawale, P.R.; Raghunathan, K.; Mishra, A.; Kumar, S. Constructed Wetland for Wastewater Reuse: Role and Efficiency in Removing Enteric Pathogens. *J. Environ. Manag.* **2019**, *246*, 444–461. [CrossRef]
62. Alufasi, R.; Gere, J.; Chakauya, E.; Lebea, P.; Parawira, W.; Chingwaru, W. Mechanisms of Pathogen Removal by Macrophytes in Constructed Wetlands. *Environ. Technol. Rev.* **2017**, *6*, 135–144. [CrossRef]
63. Wang, Q.; Hu, Y.; Xie, H.; Yang, Z. Constructed Wetlands: A Review on the Role of Radial Oxygen Loss in the Rhizosphere by Macrophytes. *Water* **2018**, *10*, 678. [CrossRef]
64. von Martels, J.Z.H.; Sadaghian Sadabad, M.; Bourgonje, A.R.; Blokzijl, T.; Dijkstra, G.; Faber, K.N.; Harmsen, H.J.M. The Role of Gut Microbiota in Health and Disease: In Vitro Modeling of Host-Microbe Interactions at the Aerobe-Anaerobe Interphase of the Human Gut. *Anaerobe* **2017**, *44*, 3–12. [CrossRef]
65. Wu, S.; Carvalho, P.N.; Müller, J.A.; Manoj, V.R.; Dong, R. Sanitation in Constructed Wetlands: A Review on the Removal of Human Pathogens and Fecal Indicators. *Sci. Total Environ.* **2016**, *541*, 8–22. [CrossRef] [PubMed]
66. Curtis, T.P.; Mara, D.D.; Silva, S.A. Influence of PH, Oxygen, and Humic Substances on Ability of Sunlight to Damage Fecal Coliforms in Waste Stabilization Pond Water. *Appl. Environ. Microbiol.* **1992**, *58*, 1335–1343. [CrossRef]
67. Fernández, A.; Tejedor, C.; Chordi, A. Effect of Different Factors on the Die-off of Fecal Bacteria in a Stabilization Pond Purification Plant. *Water Res.* **1992**, *26*, 1093–1098. [CrossRef]
68. Headley, T.; Nivala, J.; Kassa, K.; Olsson, L.; Wallace, S.; Brix, H.; van Afferden, M.; Müller, R. *Escherichia coli* Removal and Internal Dynamics in Subsurface Flow Ecotechnologies: Effects of Design and Plants. *Ecol. Eng.* **2013**, *61*, 564–574. [CrossRef]
69. Stefanakis, A.I.; Bardiau, M.; Trajano, D.; Couceiro, F.; Williams, J.B.; Taylor, H. Presence of Bacteria and Bacteriophages in Full-Scale Trickling Filters and an Aerated Constructed Wetland. *Sci. Total Environ.* **2019**, *659*, 1135–1145. [CrossRef]
70. Haichar, F.e.Z.; Santaella, C.; Heulin, T.; Achouak, W. Root Exudates Mediated Interactions Belowground. *Soil. Biol. Biochem.* **2014**, *77*, 69–80. [CrossRef]

71. Seidel, K. Macrophytes and Water Purification. In *Biological Control of Water Pollution*; University of Pennsylvania Press: Philadelphia, PA, USA, 1970; pp. 109–121.
72. RodrÃguez-Navarro, D.N.; Dardanelli, M.S.; RuÃz-SaÃnz, J.E. Attachment of Bacteria to the Roots of Higher Plants. *FEMS Microbiol. Lett.* **2007**, *272*, 127–136. [CrossRef]
73. Bais, H.P.; Weir, T.L.; Perry, L.G.; Gilroy, S.; Vivanco, J.M. The Role of Root Exudates in Rhizosphere Interactions with Plants and other Organisms. *Annu. Rev. Plant Biol.* **2006**, *57*, 233–266. [CrossRef]
74. Huang, X.-F.; Chaparro, J.M.; Reardon, K.F.; Zhang, R.; Shen, Q.; Vivanco, J.M. Rhizosphere Interactions: Root Exudates, Microbes, and Microbial Communities. *Botany* **2014**, *92*, 267–275. [CrossRef]
75. Mustafa, H.M.; Hayder, G. Evaluation of Water Lettuce, Giant Salvinia and Water Hyacinth Systems in Phytoremediation of Domestic Wastewater. *H2Open J.* **2021**, *4*, 167–181. [CrossRef]
76. Lu, S.; Zhang, X.; Wang, J.; Pei, L. Impacts of Different Media on Constructed Wetlands for Rural Household Sewage Treatment. *J. Clean. Prod.* **2016**, *127*, 325–330. [CrossRef]
77. Steer, D.; Fraser, L.; Boddy, J.; Seibert, B. Efficiency of Small Constructed Wetlands for Subsurface Treatment of Single-Family Domestic Effluent. *Ecol. Eng.* **2002**, *18*, 429–440. [CrossRef]
78. Romeo, D.; Vea, E.B.; Thomsen, M. Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon. *Procedia CIRP* **2018**, *69*, 540–545. [CrossRef]
79. Gong, L.; Chen, G.; Li, J.; Zhu, G. Utilization of Rural Domestic Sewage Tailwaters by Ipomoea Aquatica in Different Hydroponic Vegetable and Constructed Wetland Systems. *Water Sci. Technol.* **2020**, 386–400. [CrossRef]
80. Yadav, S.K.; Rajagopal, K. Hydroponic Treatment System Plant for Canteen Wastewater Treatment in Park College of Technology. In *Zero Waste*; CRC Press: Boca Raton, FL, USA, 2019; pp. 187–202.
81. Sangare, D.; Coulibaly, L.S.; Andrianisa, H.A.; Coulibaly, J.Z.; Coulibaly, L. Investigating the Capacity of Hydroponic System Using Lettuce (*Lactuca sativa* L.) in the Removal of Pollutants from Greywater while Ensuring Food Security. *Int. J. Environ. Agric. Biotechnol.* **2021**, *6*, 123–131. [CrossRef]
82. Kaushal, J.; Mahajan, P. Design and Evaluation of Hydroponic System for Tertiary Treatment of STP Wastewater: An Eco Friendly Approach. *Mater. Today Proc.* **2021**, *45*, 4914–4918. [CrossRef]
83. Nguyen, T.V.D.; Huynh, H.N.T.; Nguyen, M.N.H.; Ngo, T.V.; Vu, N.; Thinh, D. The Use of Water Spinach (Ipomoea Aquatica) in Domestic Wastewater Treatment. *J. Agric. Dev.* **2018**, *17*, 49–54. [CrossRef]
84. Cui, H.; Schröder, P. Uptake, Translocation and Possible Biodegradation of the Antidiabetic Agent Metformin by Hydroponically Grown Typha Latifolia. *J. Hazard. Mater.* **2016**, *308*, 355–361. [CrossRef] [PubMed]
85. Panja, S.; Sarkar, D.; Zhang, Z.; Datta, R. Removal of Antibiotics and Nutrients by Vetiver Grass (Chrysopogon Zizanioides) from a Plug Flow Reactor Based Constructed Wetland Model. *Toxics* **2021**, *9*, 84. [CrossRef] [PubMed]
86. Ndulini, S.F.; Sithole, G.M.; Mthembu, M.S. Investigation of Nutrients and Faecal Coliforms Removal in Wastewater Using a Hydroponic System. *Phys. Chem. Earth Parts A/B/C* **2018**, *106*, 68–72. [CrossRef]
87. Goren, A.Y.; Yucel, A.; Sofuoglu, S.C.; Sofuoglu, A. Phytoremediation of Olive Mill Wastewater with *Vetiveria zizanioides* (L.) Nash and *Cyperus alternifolius* L. *Environ. Technol. Innov.* **2021**, *24*, 102071. [CrossRef]
88. Eregno, F.; Moges, M.; Heistad, A. Treated Greywater Reuse for Hydroponic Lettuce Production in a Green Wall System: Quantitative Health Risk Assessment. *Water* **2017**, *9*, 454. [CrossRef]
89. Jesse, S.D.; Zhang, Y.; Margenot, A.J.; Davidson, P.C. Hydroponic Lettuce Production Using Treated Post-Hydrothermal Liquefaction Wastewater (PHW). *Sustainability* **2019**, *11*, 3605. [CrossRef]
90. Keller, R.; Perim, K.; Semionato, S.; Zandonade, E.; Cassini, S.; Gonçalves, R.F. Hydroponic Cultivation of Lettuce (Lactuca Sativa) Using Effluents from Primary, Secondary and Tertiary +UV Treatments. *Water Supply* **2005**, *5*, 95–100. [CrossRef]
91. Davamani, V.; Indhu Parameshwari, C.; Arulmani, S.; Ezra John, J.; Poornima, R. Hydroponic Phytoremediation of Paperboard Mill Wastewater by Using Vetiver (*Chrysopogon zizanioides*). *J. Environ. Chem. Eng.* **2021**, *9*, 105528. [CrossRef]
92. Jin, E.; Cao, L.; Xiang, S.; Zhou, W.; Ruan, R.; Liu, Y. Feasibility of Using Pretreated Swine Wastewater for Production of Water Spinach (*Ipomoea Aquatic Forsk.*) in a Hydroponic System. *Agric. Water Manag.* **2020**, *228*, 105856. [CrossRef]
93. Cui, L.-H.; Luo, S.-M.; Zhu, X.-Z.; Liu, Y.-H. Treatment and Utilization of Septic Tank Effluent Using Vertical-Flow Constructed Wetlands and Vegetable Hydroponics. *J. Environ. Sci* **2003**, *15*, 75–82.
94. Worku, A.; Tefera, N.; Kloos, H.; Benor, S. Bioremediation of Brewery Wastewater Using Hydroponics Planted with Vetiver Grass in Addis Ababa, Ethiopia. *Bioresour. Bioprocess.* **2018**, *5*, 39. [CrossRef]
95. Gong, Y.; Chen, J.; Pu, R. The Enhanced Removal and Phytodegradation of Sodium Dodecyl Sulfate (SDS) in Wastewater Using Controllable Water Hyacinth. *Int. J. Phytoremediation* **2019**, *21*, 1080–1089. [CrossRef]
96. Ispolnov, K.; Aires, L.M.I.; Lourenço, N.D.; Vieira, J.S. A Combined Vermifiltration-Hydroponic System for Swine Wastewater Treatment. *Appl. Sci.* **2021**, *11*, 5064. [CrossRef]
97. Gebeyehu, A.; Shebeshe, N.; Kloos, H.; Belay, S. Suitability of Nutrients Removal from Brewery Wastewater Using a Hydroponic Technology with Typha Latifolia. *BMC Biotechnol.* **2018**, *18*, 74. [CrossRef] [PubMed]
98. Gao, G.; Xiong, H.; Chen, J.; Chen, K.; Chen, P.; Yu, C.; Zhu, A. Hydroponic Method for Ramie and Removal of Nitrogen and Phosphorus from Livestock Wastewater. *Int. J. Phytoremediation* **2018**, *20*, 545–551. [CrossRef] [PubMed]

99. Mokuolu, O.A.; Olokoba, S.O.; Aremu, S.A.; Olanlokun, O.K. Fish Pond Wastewater Hydroponic Treatment Potential of Citrullus Colocynthis. *J. Res. Wildl. Environ.* **2019**, *11*, 118–126.
100. Zhang, D.Q.; Gersberg, R.M.; Hua, T.; Zhu, J.; Goyal, M.K.; Ng, W.J.; Tan, S.K. Fate of Pharmaceutical Compounds in Hydroponic Mesocosms Planted with Scirpus Validus. *Environ. Pollut.* **2013**, *181*, 98–106. [CrossRef]
101. Mackuľak, T.; Mosný, M.; Škubák, J.; Grabic, R.; Birošová, L. Fate of Psychoactive Compounds in Wastewater Treatment Plant and the Possibility of Their Degradation Using Aquatic Plants. *Environ. Toxicol. Pharmacol.* **2015**, *39*, 969–973. [CrossRef]
102. Cui, H.; de Angelis, M.H.; Schröder, P. Iopromide Exposure in *Typha latifolia* L.: Evaluation of Uptake, Translocation and Different Transformation Mechanisms in Planta. *Water Res.* **2017**, *122*, 290–298. [CrossRef]
103. Gahlawat, S.; Gauba, P. Phytoremediation of Aspirin and Tetracycline by *Brassica Juncea*. *Int. J. Phytoremediation* **2016**, *18*, 929–935. [CrossRef]
104. Dordio, A.V.; Belo, M.; Martins Teixeira, D.; Palace Carvalho, A.J.; Dias, C.M.B.; Picó, Y.; Pinto, A.P. Evaluation of Carbamazepine Uptake and Metabolization by *Typha* Spp., a Plant with Potential Use in Phytotreatment. *Bioresour. Technol.* **2011**, *102*, 7827–7834. [CrossRef]
105. Yan, Q.; Feng, G.; Gao, X.; Sun, C.; Guo, J.; Zhu, Z. Removal of Pharmaceutically Active Compounds (PhACs) and Toxicological Response of Cyperus Alternifolius Exposed to PhACs in Microcosm Constructed Wetlands. *J. Hazard. Mater.* **2016**, *301*, 566–575. [CrossRef]
106. Enyoh, C.E.; Isiuku, B.O. 2,4,6-Trichlorophenol (TCP) Removal from Aqueous Solution Using *Canna Indica* L.: Kinetic, Isotherm and Thermodynamic Studies. *Chem. Ecol.* **2021**, *37*, 64–82. [CrossRef]
107. González García, M.; Fernández-López, C.; Pedrero-Salcedo, F.; Alarcón, J.J. Absorption of Carbamazepine and Diclofenac in Hydroponically Cultivated Lettuces and Human Health Risk Assessment. *Agric. Water Manag.* **2018**, *206*, 42–47. [CrossRef]
108. Madikizela, L.M.; Ncube, S.; Chimuka, L. Uptake of Pharmaceuticals by Plants Grown under Hydroponic Conditions and Natural Occurring Plant Species: A Review. *Sci. Total Environ.* **2018**, *636*, 477–486. [CrossRef] [PubMed]
109. Shenker, M.; Harush, D.; Ben-Ari, J.; Chefetz, B. Uptake of Carbamazepine by Cucumber Plants—A Case Study Related to Irrigation with Reclaimed Wastewater. *Chemosphere* **2011**, *82*, 905–910. [CrossRef]
110. Ravichandran, M.K.; Philip, L. Fate of Carbamazepine and Its Effect on Physiological Characteristics of Wetland Plant Species in the Hydroponic System. *Sci. Total Environ.* **2022**, *846*, 157337. [CrossRef]
111. Topal, M. Uptake of Tetracycline and Degradation Products by Phragmites Australis Grown in Stream Carrying Secondary Effluent. *Ecol. Eng.* **2015**, *79*, 80–85. [CrossRef]
112. Gul, H.; Raza, W.; Lee, J.; Azam, M.; Ashraf, M.; Kim, K.-H. Progress in Microbial Fuel Cell Technology for Wastewater Treatment and Energy Harvesting. *Chemosphere* **2021**, *281*, 130828. [CrossRef] [PubMed]
113. Yadav, R.K.; Chiranjeevi, P.; Sukrampal; Patil, S.A. Integrated Drip Hydroponics-Microbial Fuel Cell System for Wastewater Treatment and Resource Recovery. *Bioresour. Technol. Rep.* **2020**, *9*, 100392. [CrossRef]
114. Wang, S.; Adekunle, A.; Raghavan, V. Exploring the Integration of Bioelectrochemical Systems and Hydroponics: Possibilities, Challenges, and Innovations. *J. Clean. Prod.* **2022**, *366*, 132855. [CrossRef]
115. Kantanoleon, N.; Zampetakis, L.; Manios, T. Public Perspective towards Wastewater Reuse in a Medium Size, Seaside, Mediterranean City: A Pilot Survey. *Resour. Conserv. Recycl.* **2007**, *50*, 282–292. [CrossRef]
116. Drechsel, P.; Mahjoub, O.; Keraita, B. Social and Cultural Dimensions in Wastewater Use. In *Wastewater*; Springer: Dordrecht, The Netherlands, 2015; pp. 75–92.
117. Verhoest, P.; Gaume, B.; Bauwens, J.; te Braak, P.; Huysmans, M. Public Acceptance of Recycled Water: A Survey of Social Attitudes toward the Consumption of Crops Grown with Treated Wastewater. *Sustain. Prod. Consum.* **2022**, *34*, 467–475. [CrossRef]
118. Lahlou, F.Z.; Mackey, H.R.; McKay, G.; Al-Ansari, T. Reuse of Treated Industrial Wastewater and Bio-Solids from Oil and Gas Industries: Exploring New Factors of Public Acceptance. *Water Resour. Ind.* **2021**, *26*, 100159. [CrossRef]
119. Schikora, A.; Virlogeux-Payant, I.; Bueso, E.; Garcia, A.V.; Nilau, T.; Charrier, A.; Pelletier, S.; Menanteau, P.; Baccarini, M.; Velge, P.; et al. Conservation of Salmonella Infection Mechanisms in Plants and Animals. *PLoS ONE* **2011**, *6*, e24112. [CrossRef] [PubMed]
120. Hirneisen, K.A.; Kniel, K.E. Comparative Uptake of Enteric Viruses into Spinach and Green Onions. *Food Environ. Virol.* **2013**, *5*, 24–34. [CrossRef]
121. DiCaprio, E.; Ma, Y.; Purgianto, A.; Hughes, J.; Li, J. Internalization and Dissemination of Human Norovirus and Animal Caliciviruses in Hydroponically Grown Romaine Lettuce. *Appl. Environ. Microbiol.* **2012**, *78*, 6143–6152. [CrossRef]
122. Li, Y.; Chen, Y.-F.; Chen, P.; Min, M.; Zhou, W.; Martinez, B.; Zhu, J.; Ruan, R. Characterization of a Microalga *Chlorella* Sp. Well Adapted to Highly Concentrated Municipal Wastewater for Nutrient Removal and Biodiesel Production. *Bioresour. Technol.* **2011**, *102*, 5138–5144. [CrossRef] [PubMed]
123. Ji, M.-K.; Kabra, A.N.; Salama, E.-S.; Roh, H.-S.; Kim, J.R.; Lee, D.S.; Jeon, B.-H. Effect of Mine Wastewater on Nutrient Removal and Lipid Production by a Green Microalga Micratinium Reisseri from Concentrated Municipal Wastewater. *Bioresour. Technol.* **2014**, *157*, 84–90. [CrossRef]
124. Zhao, X.; Zhou, Y.; Huang, S.; Qiu, D.; Schideman, L.; Chai, X.; Zhao, Y. Characterization of Microalgae-Bacteria Consortium Cultured in Landfill Leachate for Carbon Fixation and Lipid Production. *Bioresour. Technol.* **2014**, *156*, 322–328. [CrossRef]
125. Sun, Z.; Guo, W.; Yang, J.; Zhao, X.; Chen, Y.; Yao, L.; Hou, H. Enhanced Biomass Production and Pollutant Removal by Duckweed in Mixotrophic Conditions. *Bioresour. Technol.* **2020**, *317*, 124029. [CrossRef] [PubMed]

126. Elshafai, S.; Elgohary, F.; Nasr, F.; Petervandersteen, N.; Gijzen, H. Nutrient Recovery from Domestic Wastewater Using a UASB-Duckweed Ponds System. *Bioresour. Technol.* **2007**, *98*, 798–807. [CrossRef] [PubMed]
127. Xu, J.; Shen, G. Growing Duckweed in Swine Wastewater for Nutrient Recovery and Biomass Production. *Bioresour. Technol.* **2011**, *102*, 848–853. [CrossRef] [PubMed]