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Review

Vetiver Grass (*Chrysopogon zizanoides* L.): A Hyper-Accumulator Crop for Bioremediation of Unconventional Water

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Abstract: The increase of the global population and the requirement of food production and agricultural development, combined with a lack of water resources, have led to human attention being drawn to unconventional water sources, including saline water and wastewater. Most unconventional water treatment methods are not cost-effective; however, researchers have become interested in the phytoremediation method due to its cost-efficient and eco-friendly removal of many pollutants in recent years. Research showed that due to its unique characteristics, vetiver grass can be useful in phytoremediation. In the current review, research on vetiver-based phytoremediation of unconventional water, especially wastewater, was reviewed. The vetiver-reduced contaminants in wastewater can be related to the interactions between (1) the root-released oxygen into the rhizosphere; (2) the root-based uptake of nutrients from the wastewater; (3) the existence of an appropriate surface area for the attached microbial growth; as well as (4) the root-exuded organic carbon.

Keywords: phytoremediation; vetiver grass; root exude; saline water; contaminants

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1. Introduction

Global warming and decreased precipitation have led to climate change and the consequent water shortage, specifically in arid areas [1]. The increased human population as well as expanded agricultural and industrial activities have also decreased the freshwater resources and increased pollution [2]. Consequently, the application of unconventional water seems necessary because water pollution makes economic development increasingly vulnerable and fragile [3]. Unconventional water sources cannot be used normally; therefore, their usage management and protection policies are needed [4]. In many countries, the urban and industrial-resulted unconventional water is applied for agricultural purposes as a solution to droughts [5,6]. However, its prolonged agricultural applications face challenges due to health problems and significant organic and mineral substances [7]. Among these cases, we can mention soil salinization, groundwater pollution, and health risks for the producers and customers [8]. For instance, high levels of carbonate and bicarbonate within wastewater could negatively impact plant roots by inhibiting the uptake of manganese, iron, magnesium, zinc, potassium, as well as phosphorus [9].

One of the technologies that applies resistant plants with the purpose of the removal or decrease of organic/inorganic contaminants, as well as eco-unfriendly heavy metals, petroleum substances, and herbicides, is phytoremediation, which is also referred to as a plant-based biological treatment. Today, the use of green plants is prevalent based on their extraordinary ability to accumulate elements and remove harmful compounds from the environment [10,11].

Compared to other technologies, the following advantages are recognized for phytoremediation: (1) phytoremediation can be used in large areas for a wide range of pollutants due to its economic feasibility, low energy consumption [12], and environmental compatibility [10,11,13,14]; (2) being publicly acceptable and practical [15]; (3) the decreasing effects on wind and water erosion on a site; and (4) feedstock generation for a variety of different applications [12]. However, this method has several limitations, including: (1) the limited range of the affected contaminants, relatively prolonged time scale, and inappropriate achievable levels of the residual contaminant [16]; (2) although the method is not technically complex, considerable experience and expertise may be required to design and implement a successful phytoremediation program due to the need of a complete evaluation of a site for suitability and to optimize the conditions to achieve a satisfactory result [17]; (3) limitations of the depth of root-occupied phytoremediation; as well as (4) contamination of the food chain which resulted from the toxic-compound-absorbed plants [18].

Phytoremediation-involved plants are highly tolerant against the desired pollutants. Applied research conducted on vetiver grass showed that the unique characteristics of vetiver grass can be useful in phytoremediation. This plant has a high range of tolerance against toxic elements, salinity, alkalinity, sodium, and various heavy metals [19–22]. Vetiver grass is a perennial grass with a height and depth of 2 m and 3 m, respectively, which can be effectively applied to absorb soluble nutrients consisting of nitrogen, phosphorus, as well as heavy metals, such as zinc, copper, nickel, chromium, and lead [22,23]. As a consequence, the vetiver-grass-based phytoremediation is a reliable method to purify polluted water. Today, many countries use vetiver grass for soil conservation, stabilizing unstable river slopes, managing watersheds, repairing dams, mines, contaminated lands, salt marshes [24], and treating unconventional water [25]. The current study reviews recent studies on vetiver-grass-resulted effects on the removal of pollutants from unconventional water.

2. Phytoremediation

Various physical and chemical approaches are applied to the process of unconventional water treatment [26,27]; however, most of them are associated with both disadvantages and limitations, such as the production of toxic sludge [28], high costs [29], and incomplete target removal [30]. Therefore, researchers have turned their interest toward the biological technique due to its low cost, nature-mimicking, and practical [31] bioremediation. This technique is based on the biogeochemical cycles, which is applicable to soil, surface water, groundwater, sediments, as well as ecosystem restoration and cleanup [32,33]. Phytoremediation, bioleaching land farming, bioventing, bioreaction, composting bio augmentation rhizofiltration, and biostimulation are known as bioremediation technologies [12].

The developed application of green plants with the purpose of purification of polluted environments, including soil, water, and wastewater, is known as phytoremediation [13]. "Phytoremediation" comes from the Greek word "phyto" (meaning plant) and the Latin word "remedium", which, respectively, mean "plant" and "removal/correction". The process can be applied to the green restoring of polluted sites [12]. Moreover, it cannot have any environmental adverse effects due to its biological traits [34]. Phytoremediation can also be defined as a process whereby soil or water pollutants are degraded, extracted, or immobilized through the use of plants [28,32]. The process is associated with nonintrusiveness, aesthetical smoothing, as well as biodegradant effects on polluted sites [35]. The mentioned technique can be used in places with different weather conditions through an appropriate plant selection [12]. It is recommended that the plant selection procedure be carried out considering the adequate growth ability in polluted water and soil. Studies showed that even within one genus, the pollutant uptake varies between species [11]. It has been demonstrated that phytoremediation, in combination with the simultaneous application of minerals, can have a significant impact on its capacity [10].

Plants are capable of remediating contamination through a number of different mechanisms and paths, including those of the roots and those of the foliar surface. The active surface area of a plant in the phytoremediation process refers to the pollutants' directly connected plant parts, which contribute to the remediation. For the remediation of aquatic media, plant shoots [36] or roots [37] can be considered as the active parts of the plant. Highly active surface areas of plants can develop the efficiency of remediation through providing more sites of micro-organism absorption [38].

According to several investigations, unconventional water phytoremediation using various plants, including common reeds (*Phragmites australis*) [39], water hyacinth (*Eichhornia crasspies*) [24], water lettuce (*Pistia stratiotes*) [40], bulrush (Typha) [41], duckweed (Lemna) [42], pampas grass (*Cortaderia selloana*) [43], vetiver grass (Chrysopogon zizanoioides) [21–24], and Quinoa plant (*Chenopodium quinoa* willd) [44], could be a supplementary approach.

3. Mechanisms of Phytoremediation

In phytoremediation, a variety of phytotechniques may be used to ameliorate a wide variety of pollutants using a variety of mechanisms depending on the application (Figure 1). There are various phytoremediation methods, including phytoextraction, phytostabilization, phytovolatilization, rhizodegradation, phytodegradation, as well as rhizofiltration, investigated comprehensively in several studies [12,18]. These techniques are characterized in Table 1 [12,13,45]:

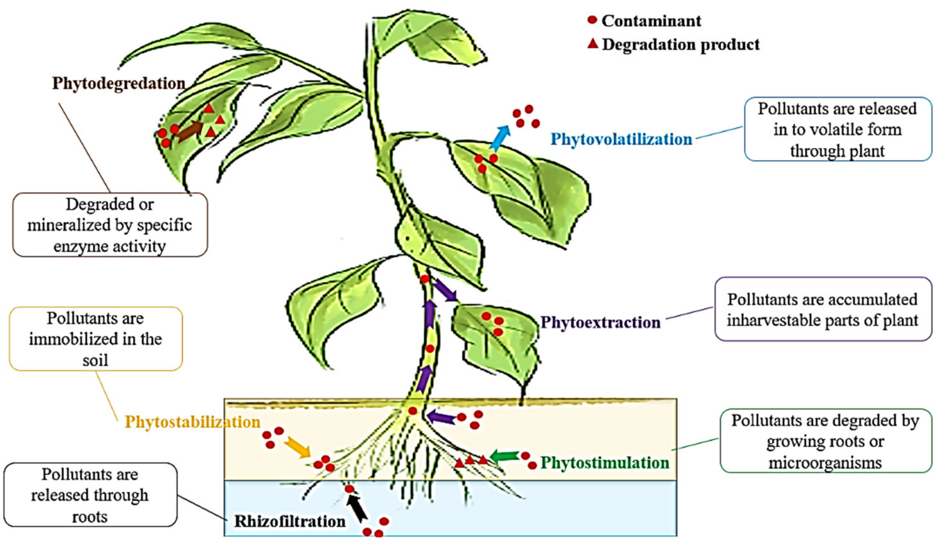

Figure 1. Schematic diagram of different approaches of phytoremediation.

According to the previous literature, the mechanism of decontaminating unconventional water by vetiver grass is usually phytoextraction. The vetiver root system is dense and can be grown up to 7 m. The pollutants can be adsorbed by the channels, and then transferred in the plasma membrane of the root [22]. To understand the mechanism of vetiver grass for the decontaminating of industrial wastewaters, two factors consisting of the bioaccumulation factor (*BAF*), and translocation factor (*TF*) were evaluated. The *BAF* and TF can be expressed by Equations (1) and (2), respectively.

$$BAF = \frac{C_{planttissue}}{C_{wastewater}} \tag{1}$$

$$TF = \frac{C_{shoot}}{C_{root}} \tag{2}$$

where $C_{planttissue}$, C_{shoot}, and C_{root} are the concentration of the pollutant in the harvested plant tissue, shoots, and roots, respectively, and also $C_{wastewater}$ is the initial concentration of pollutant in the wastewater. Previous research indicated that both *BAF* and *TF* are greater than 1, indicating that phytoextraction is the main mechanism for the phytoremediation of pollutants in wastewater using vetiver grass [22].

Table 1. Characteristics of phytotechniques.

Processes	Other Names	Mechanism	Pollutants	Applicability	Benefits	References
Phytoextraction [1]	Phytoaccumulation, phytoabsorption, phytosequestration	Hyper-accumulation.	Pb, Cd, Zn, Ni, Cu, radionuclides, pentachlorophenol, and aliphatic compounds.	Polluted soil/sites, water, and wastewaters.	Instant abundant biomass, decreased soil erosion, cost-effectiveness, wide range of applications.	[46–48]
Rhizofiltration [2]	Phytofiltration	Rhizosphere accumulation.	Pb, Cd, Zn, Ni, Cu, radionuclides (Cs, Sr, U), hydrophobic organics, and radionuclides.	Polluted water and wastewaters.	Purification of polluted surface water, industrial wastewaters, as well as agricultural runoff.	[49–51]
Phytostabilization [3]	Phytoimmobilization	Precipitation, complexation, and metal valence decrease.	Pb, Cd, Zn, As, Cu, Cr, Se, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCBs), dioxins, furans, pentachlorophenol, Dichlorodiphenyltrichloroethane (DDT), and dieldrin.	Polluted soil/sediments and sludge.	Ecologic efficiency, polluted medium stabilization without polluted biomass disposal, decreased soil erosion, and applicability in field and mine contaminated area.	[52–54]
Phytovolatilization [4]	Phytoevaporation	Leaves-based volatilization/evaporative.	Chlorinated solvents, such as carbon tetrachloride, trichloroethylene, methylene chloride, and tetrachloroethylene.	Polluted wastewaters, soil, sediments, and sludges.	Environment cleaner without leading to plant harvesting and biomass disposal.	[55–57]
Phytodegradation [5]	Phytotransformation	Plant-tissue degradation.	DDT, PAHs, bisphenol A, and organo-phosphorus compounds.	Polluted soil, sediments, sludge, groundwater, surface water, and wastewaters.	Rhizosphere biodegraded recalcitrant contaminants.	[58–60]
Phytostimulation [6]	Rhizodegradation	Rhizosphere degradation.	Atrazine, ammunition wastes, petroleum hydrocarbon, Polychlorinated biphenyl (PCBs), PAHs, Trichloroethylene (TCE), and diesel fuel.	Polluted soil, sediments, sludge, groundwater, and wastewaters.	Organic acid release; rhizosphere-resulted increase of biodegradation; more consumption of metabolic compounds by micro-organisms in rhizosphere.	[54,61,62]

[1] Roots are responsible for pollutant absorption and then transferred to the aerial part of the plant; consequently, the pollution accumulated in harvestable biomass, such as shoots. Fast absorption of contaminants, high accumulation, high aerial biomass, fast growth, high resistance to diseases, being unsuitable for feeding animals, and having the lowest risk for the food chain are considered as the particular traits of plants applied to the mentioned method. [2] The internal or surface absorption of pollutants was performed by the roots and then transferred to aerial organs. High resistance to heavy metals, low maintenance cost, high biomass in the roots, and high accumulation power are the main characteristics of the plants used in this method. [3] In this method, plants do not remove pollutants and metals from the soil and make them immobile by fixing them on their roots; therefore, they are not transferred to the atmosphere and underground water sources. Resistance to high concentrations of heavy metals, root biomass high output, as well as inability to transfer pollutants from roots to aerial organs, such as branches and leaves, are the main characteristics of the plants used in this method. [4] In the proposed method, soil-extracted metals are achieved using plants and then the gas is released into the atmosphere. The gene-manipulated plants are usually used for this purpose. This method is mostly used to absorb mercury and selenium pollutants. The use of this method has the disadvantage that in areas close to densely populated centers or with special weather conditions, volatile pollutants settle on the surface of the earth and cause risks. Therefore, conducting investigations on the site conditions and consequences before the proposed method selection is required. [5] The above-mentioned method is regarding the plant-absorbed organic materials from soil, mud, and water. After absorption, the process of converting these substances into other substances takes place in the plant tissue. The mechanism of transformation and change of materials inside the plant tissue is dependent upon a number of factors, including the traits of the region, concentration, composition of pollutants, and plant species. This mechanism is used for some organic materials that have the ability to pass through the protective barriers of the rhizosphere zone. [6] Increasing the activity of micro-organisms in order to remove contamination, which is often done by root-linked micro-organisms, is called rhizodegradation.

4. Vetiver System

The vetiver system is based on the use of the Nash vetiver plant. First, it was developed in 1985 by the World Bank to protect India's soil and water [21]. The system contributes to the procedures of agricultural land management [33], environmental protection [63], soil and water conservation [64], infrastructure balancing [65], contamination management [23], as well as water and wastewater treatment [66–68]. The origin of the *Chryspogon zizanioides* species is in South India [69]. This plant is sterile, non-invasive, and propagated by dividing the plant [70]. The plants are grown according to various factors, including soil moisture, soil texture, temperature, and chemical traits of heavy metal concentration, salinity, as well as pH value. This plant is able to grow and survive in harsh environmental conditions. Even though vetiver grass is tropical grass, it can survive extremely cold temperatures. Under frost conditions, the plant's top growth dies back or becomes dormant; however, the underground growing points remain active. According to a comparison, it was found that severe frost at –14 °C could not affect vetiver growth in Australia, while it respectively survived briefly at –22 °C (−8 °F) and −10 °C in northern China and Georgia (USA) [70]. This plant is a 4-carbon (C4) plant with different anatomical features, such as the type of stomata and epidermal nature. Moreover, its cellular arrangement is different from other C4 plants. It could be the reason for the plant's survival under different severe conditions [70]. Furthermore, its by-products could be applied to make handicrafts, thatches, animal feed, manure, and organic compost if the plant does not accumulate heavy metals.

4.1. Genetic and Taxonomic Properties

The vetiver grass (*Chrysopogon zizanioides* L.) family is similar to that of maize, sorghum, sugarcane, and lemon grass. It is extensively found in South and Southeast Asia. Specifically, it is native to tropical and subtropical Indian areas (Figure 2 and Table 2). In addition to *Chrysopogon zizanioides* L., there are various accessions of *Vetiveria zizanioides* (*L. Nash*) and Vetiver species, including *Chrysopogon fulvus* (Spreng.), *C. gryllus*, *Sorghum bicolor* (L.), and *S. halepense* (L.). Due to the fact that Chrysopogon and Vetiveria could not be separated through Random Amplified Polymorphic DNAs (RAPDs), their genera are merged. *Vetiveria zizanioides* (*L. Nash*) is recently referred to as *Chrysopogon zizanioides* (*L. Roberty*), which contains chromosomes x = 5 and 10, as well as 2n = 20 and 40 [71].

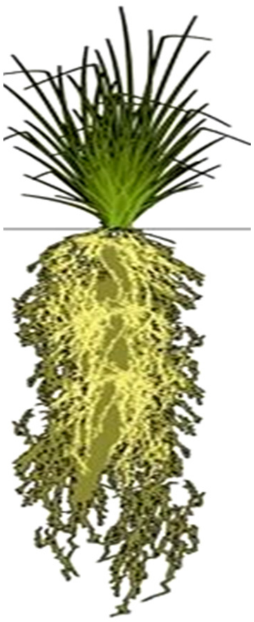

Figure 2. Vetiver grass plant.

Table 2. Scientific classification of vetiver grass.

Index	Scientific Classification
Kingdom	Plantae
Order	Poales
Family	Graminae
Subfamily	Panicoideae; Tribe-Andropogoneae; Subtribe-Sorghinae
Genus	Chrysopogon
Species	Zizanioides
General name	Vetiver grass

4.2. Morphological Characteristics

This plant belongs to Poaceae family and is free of stolons or rhizomes. It contains voluminous roots with fine structures that lead to its fast growth, which can even be increased to a depth of 3 to 4 m during the first year [20]. The deep roots of the plant can cause its extreme resistant against drought and makes it hard to uproot in strong water currents and wind. The stems are stiff and erect, highly resistant to pests, diseases, and fires, which form dense hedges that act as sediment filters and water spreaders when planted closely together. After being buried in sediment, new roots grow from nodes and vetiver develops new shoots from its underground crown. Therefore, it will be resistant to fire, frost, traffic, as well as high grazing pressure [20].

4.3. Physiological Characteristics

Vetiver grass has the ability to handle extreme weather conditions, such as extended drought, flood, submersion, as well as severe temperatures ranging from −14 °C to +55 °C. After the above-mentioned extreme conditions, the process of plant recovery will occur immediately. It can simply tolerate extensive soil pH values without soil amendment ranging from 3.3 to 12.5. It is highly resistant to pesticides and herbicides and efficient in absorbing heavy metals and dissolved nutrient solutions within polluted water. It is also extremely tolerant against high acidity, alkalinity, salinity, sodicity, magnesium growing mediums, as well as Al, Mn, and heavy metals such as As, Cd, Cr, Ni, Pb, Hg, Se, and Zn [72,73].

4.4. Ecologic Properties

Vetiver is highly resistant against the above-mentioned extreme conditions; however, it is not tolerant against shade as it could be observed for most of tropical grasses. The shading effect decreases vetiver growth over time and, in extreme cases, it can even eradicate the plant. Due to the fact that the best growth condition for the plant is an open weed-free environment, it is required that we control the weeds at the establishment stage. Vetiver initially decreases erosion and stabilizes slopes, especially steep slopes. Consequently, micro-environment development occurs due to its nutrient and moisture conservation, which leads to the establishment of volunteered plants or sown seeds [70].

5. Vetiver System to Reduce/Eliminate Contaminants from Unconventional Water

The plant selection is crucial for a successful phytoremediation [15]. There are different types of aquatic plants that can absorb and eliminate pollutants [28], such as free-floating plants (*Pistia stratiotes*, *Salvinia molesta*, Lemna spp., *Azolla pinnata*, *Landoltia punctata*, *Spirodela polyrhiza*, *Marsilea mutica*, *Eichhornia crassipes*, and *Riccia fluitans*), submerged plants (*Hygrophilla corymbosa*, *Najas marina*, *Ruppia maritima*, *Hydrilla verticillata*, *Egeria densa*, *Vallisneria americana*, and *Myriophyllum aquaticum*), and emergent plants (*Distichlis spicata*, Cyperus spp., *Imperata cylindrical*, *Iris virginica*, *Nuphar lutea*, *Justicia americana*, *Diodia virginiana*, Nymphaea spp., Typha spp., *Phragmites autralis*, and *Hydrochloa caroliniensis*) [74]. In that regard, available records of aquatic plant species applied to the unconventional water phytoremediation, especially wastewater, are provided in Table 3.

Table 3. Phytoremediation capacities of aquatic plant for unconventional water.

NO.	Plants	Type of Unconventional Water	Residence Time	Initial Concentration	Removal Efficiency	References
1	*Egeria densa* (Brazilian waterweed)	Industrial wastewater	17 days/laboratory scale reactor within batch systems	BOD (104.5 mg/L), COD (426.4 mg/L)	BOD (93%), COD (95%)	[75]
2	*Salvinia. cucullata*	Industrial wastewater (textile industries)	45 days/batch cultures	COD (71.6–122.7 mg/L), NH_3-N (5.32–8.4 mg/L), DO (1.55–1.99 mg/L), BOD (160–188 mg/L), Nitrate (1.4–1.96 mg/L), TP (160–240 mg/L)	COD (31.04%), NH_3-N (5.26%), DO (100%), BOD (43.02%), Nitrate (20%), TP (81.25%)	[76]
3	*Typha angustifolia* L.	Textile wastewater	7 days/constructed wetlands	COD (1328 mg/L), BOD (1140 mg/L), Colour (1035 Unit), TDS (9562 mg/L), Cd (0.07 mg/L), Cr (2.91 mg/L), As (2.12 mg/L), Pb (0.42 mg/L), TSS (7280 mg/L)	COD (65%), BOD (68%), Colour (62%), TDS (45%), Cd (28%), Cr (59%), As (60%), Pb (45%), TSS (35%)	[77]
4	*Ipomeo aquatica* (Water spinach)	Palm oil mill effluent	25 days/bucket treatment system	COD (1500 mg/L), NH_3–N (4–80 mg/L), TSS (5000 mg/L)	COD (80%), NH_3–N (82.7%), TSS (90%)	[78]
5	*Lemna minor* (Lesser duckweed)	Mixture of textile, distillery, and institutional wastewater	28 days	COD (34133.3 mg/L), EC (5.58 dS/m), BOD (15493.3 mg/L), pH (7.16); TDS (2641 mg/L)	COD (92%), EC (68%), BOD (92%), pH (8–9), TDS (68%)	[79]
6	*Lemna minor* (Lesser duckweed)	Treated industrial wastewater	7 days (summer and winter)	N (12.2 mg/L in summer), P (2.9 mg/L in summer; 4.1 mg/L in winter)	N (56% in summer), P (76% summer; 66% winter)	[80]
7	*Pistia stratiotes*	Polluted rural river water	6 months/PVC water tanks	TN (14.18–19.9 mg/L), COD (61–72 mg/L), TP (1.07–1.79 mg/L), NH_4^+-N (9.94–15.17 mg/L)	TN (77%), COD (61.70%), TP (88%), NH_4^+-N (93%)	[81]
8	Common reed (*Phragmites australis*), Manna Grass (*Glyceria grandis*), and Virginia Mallow (*Sida hermaphrodita*)	Secondary domestic wastewater	5 years)/hybrid constructed wetland systems	BOD (284 mg/L), TSS (143 mg/L), TN (84.9 mg/L), COD (588 mg/L), TP (13.6 mg/L)	BOD (95%), TSS (95%), TN (94%), COD (95%), TP (95%)	[82]
9	*Alternanthera* (Joyweed)	Domestic wastewater	10 days/level of sheet flow root (Shefrol bioreactor)	BOD (1400–1950 mg/L), COD (2900–3400 mg/L), TKN (63–91 mg/L), TP (37–59 mg/L), suspended solids (221–263 mg/L) (93%), Cu (3.9 mg/L)	BOD (87%), COD (78.9–83.9%), TKN (45%), TP (36%), suspended solids (SS) (93%), Cu (43%)	[83]
10	*Nelumbo nucifera*	Contaminated surface water	30 days/batch type	turbidity (80.7 NTU), BOD (95 mg/L), COD (78.4 mg/L)	turbidity (88.3%), BOD (97.1%), COD (55%)	[84]
11	*Limnobium laevigatum*	Swine wastewater (10% effluent)	3 months/batch system	TN (151.67 mg/L), TP (82.77 mg/L)	TN (48.80%), TP (28.20%)	[85]
12	*Salvinia natans*	Raw domestic wastewater	8 months/tanks	TKN (102.4 mg/L), NH_4-N (64.4 mg/L), BOD_5 (311.1 mg/L), COD (981.7 mg/L), NO_2-N (0.128 mg/L), PO_4 (10.95 mg/L)	TKN (85.2%), NH_4-N (79%), BOD_5 (96.9%), COD (95%), NO_2-N (40%), PO_4 (37%)	[86]
13	*Eichhornia crassipes* (Water hyacinth)	*Eichhornia crassipes* (Water hyacinth)	15 days	pH = 6.7–7.2; initial concentration: not found	Cr (66%), Zn (79%), Ni (67%), Fe (83%), Cu (63%), Cd (76%)	[87]

Table 3. *Cont.*

NO.	Plants	Type of Unconventional Water	Residence Time	Initial Concentration	Removal Efficiency	References
14	*Myriophyllum spicatum* (Eurasian watermilfoil)	Wastewater contaminated with constant/ radioactive Cobalt (Co) and Cesium (Cs)	20 days	Cs and Co (20, 50, 100 and 150 mg/L)	Cs (60%), Co (90%)	[88]
15	*Vertiveria zizaniodes*	Fish pond wastewater	Six weeks/ aquaculture system	NH_3 (0.0034 mg/L), NO_2 (0.05 mg/L), NO_3 (0.13 mg/L), NH_4 (0.49 mg/L), PO_4 (0.04 mg/L)	NH_3 (65.16%), NO_2 (27.51%), NO_3 (25.5%), NH_4 (30.17%), PO_4 (42.75%)	[72]
16	*Atriplex Lentiformis*	Well drainage	28 days	EC (14.7 dS/m), Ca (252 mg/L), Mg (157.9 mg/L), Na (3355 mg/L), Cl (4041 mg/L)	EC (11.80%), Ca (8.75%), Mg (5.9%), Na (13.7%), Cl (12.7%)	[89]
17	*Chenopodium quinoa Willd.*	Well drainage	30 days	EC (2 dS/m), Ca (200 mg/L), Mg (72 mg/L), Na (285 mg/L), Cl (532 mg/L)	EC (9.35%), Ca (10%), Mg (7.62%), Na (5.6%), Cl (7.01%)	[90]

Vetiver's specific properties include the growth capability under undesirable conditions, deep long roots, fleshy leaves, root aroma, soil agglomeration that resulted from extreme root-based absorption, metal adsorption capability, as well as tolerance against inadequate climatic conditions. Therefore, it is considered as an appropriate candidate for bioremediation [91]. In fact, this plant can remove many pollutants from soil and water or even detoxify them in its own tissue. It is reported that vetiver grass can effectively treat contaminants, such as organic matter, nutrients, heavy metals, as well as aromatic mixtures that are highly tolerant against extreme weather conditions (cold, hot, flood, and water shortage). According to the reports, vetiver has the capability of remediating toxic heavy-metal-polluted soil and water [92], herbicides [93], petroleum hydrocarbons (PHCs) [94], nuclear waste [95], acid mine drainage [96], textile dyes [97], ciprofloxacin (CIP), and tetracycline (TTC) [98], as well as 3-nitro-1,2,4-triazol-5-one (NTO) [99]. According to the unique characteristics reported for vetiver grass in the previous sections, several recent studies used this plant species to remove or decrease pollutants in unconventional water. Table 4 provides a number of the mentioned investigations.

Table 4. Phytoremediation potentials of vetiver grass for unconventional water.

NO.	Type of Unconventional Water	Residence Time	Initial Concentration	Removal Efficiency	References
1	Domestic effluent	4 days	TH (60%), P (10 mg/L), N (100 mg/L), EC (928 µS/cm), pH (7.26)	TH (60%), P (90%), N (94%), EC (50%), pH (17.63%)	[100]
2	Pig farm wastewater	4 days	COD (825.63 mg/L), BOD (509.89 mg/L), NH_3-N (134.43 mg/L), TP(24.31 mg/L)	COD (64%), BOD (68%), NH_3-N (20%), TP (18%), TN (75%), TP (58%)	[101]
3	Textile wastewater	60 days	N (8.76 mg/L), P(4.8 mg/L), K (3.4 mg/L), pH (8.6), EC (1.45 dS/m)	N (85.61%), P(79%), K (94.7%), pH (9.3%), EC (73%)	[102]
4	Groundwater	5 min	TDS (1400 ppm)	TDS (55.93%)	[103]
5	Saline groundwater/ Mine wastewater	30 days	TDS (11.2 mg/L), EC (27.27 mmhos/cm), TH (6243 mg/L), SO_4 (98.5 meq/L), Cl (326 meq/L), Na (247 meq/L), K (0.514 meq/L), Mg (42 meq/L), Ca (66 meq/L) / TDS (20.6 mg/L), EC (46.30 mmhos/cm), TH (9884 mg/L), SO_4 (94.9 meq/L), Cl (586 meq/L), Na (397 meq/L), K (1.12 meq/L), Mg (36.7 meq/L), Ca (247 meq/L)	TDS (33%), EC (28%), TH (45.1%), SO_4 (70.86%), Cl (48.77%), Na (59.10%), K (58.36%), Mg (23.80%), Ca (51.47%) / /TDS (31.5%), EC (28.3%), TH (46.1%), SO_4 (63.9%), Cl (47.6%), Na (52.4%), K (19.6%), Mg (43.6%), Ca (46.6%)	[104]

Table 4. *Cont.*

NO.	Type of Unconventional Water	Residence Time	Initial Concentration	Removal Efficiency	References
6	Piggery effluent	5 days	BOD (854.77 mg/L), COD (1690.44 mg/L), TN (104.38 mg/L), TP (67.19), EC (3591.94 dS/m)	BOD (%74), COD (%70), TN (%87), TP (%83), EC (78.41%)	[105]
7	Synthetic wastewater	7 days	Pb (9.94 ppm), Mn (10.01 ppm), Cu (9.96 ppm), Fe (10.5 ppm), Zn (10.2 ppm)	Pb (50%), Mn (33%), Cu (25%), Fe (96%), Zn (75%)	[106]
8	Bagmati river	30 days	BOD5 (7.11 mg/L), Cl (123.54 mg/L), NO_3 (3.3 mg/L), PO_4 $^{-3}$ (4.3 mg/L), TH (139.33 mg/L), alkalinity (153.34 mg/L)	BOD_5 (71.03%), Cl (42.9%), NO^3 (93.93%), PO_4 $^{-3}$ (88.04%), TH (46.04%), alkalinity (22.2%).	[107]
9	Tofu wastewater	15 days	TSS (552 mg/L), pH (3.9), BOD (580 mg/L), COD (5759 mg/L)	TSS (75.28%), pH (7.8%), BOD (76%), COD (71.78%)	[15]
10	Carwash wastewater	70 days	BOD (398 mg/L), COD (812 mg/L), P (12.10 mg/L), N (16.11 mg/L), Pb (0.13 mg/L), Zn (0.29 mg/L), NO_3 (1.27 mg/L), NO_2 (3.76 mg/L), NH_3 (11.08 mg/L)	BOD (64.8%), COD (65.3%), P (69%), N (57.9%), Pb (61.5%), Zn (82.8%), NO_3 (69.3%), NO_2 (59.3%), NH_3 (56.1%)	[108]
11	Sewage effluent	6 days	BOD (233.8 mg/L), TSS (346.8 mg/L), TP (12.2 mg/L)	BOD (92%), TSS (92%), TP (87%)	[109]
12	Polluted river water	42 days	COD (41 mg/L), NO_3 (2.6 mg/L), PO_4 (1.86 mg/L), TSS (5.20 mg/L)	COD (77%), NO_3 (73%), PO_4 (35%), TSS (26%)	[110]
13	Domestic wastewater	60 days	pH (8.36), EC (0.015 dS/m), TDS (1754 mg/L), TH (2010.33 mg/L), NO_3 (10.44 mg/L), Cl (65.82 mg/L), PO_4 $^{-3}$ (8.65 mg/L), K (39.4 mg/L)	pH (8.73%), EC (40.88%), TDS (30.84%), TH (33.46%), NO_3 (44.25%), Cl (25.84%), PO_4 $^{-3}$ (50.63%), K (12.16%).	[111]
14	Abattoir wastewater	6 days	N (131 mg/L), P (56.3 mg/L), Mg (1.06 mg/L), Fe (1.30 mg/L), BOD (206 mg/L), COD (204 mg/L)	N (52%), P (70%), Mg (88%), Fe (99.2%), BOD (84%), COD (86%)	[112]
15	Synthetic wastewater	3 days	TDS (1463.20 mg/L), Zn (0.97 mg/L), Pb (0.63 mg/L), Cu (1.59 mg/L), DO (7.53 mg/L), BOD (2.26 mg/L),	TDS (74.91%), Zn (13.40%), Pb (34.92%), Cu (23.89%), DO (79.46%), BOD (78.10%)	[113]
16	Synthetic wastewater	52 days	Cr (5 ppm), Cr (10 ppm), Cr (30 ppm), Cr (70 ppm)	Cr (5 ppm) (87%), Cr (10 ppm) (51%), Cr (30 ppm) (28%), Cr (70 ppm) (5.11%)	[22]
17	Fish pond wastewater	6 weeks	NH_3 (0.0034 mg/L), NO_2 (0.05 mg/L), NO_3 (0.13 mg/L), NH_4 (0.48 mg/L), PO_4 (0.04 mg/L)	NH_3 (65.16%), NO_2 (27.51%), NO_3 (25.5%), NH_4 (30.17%), PO_4 (42.75%).	[72]
18	Effluent sewage	18 days	Na (55.4 mg/L), K (21.9 mg/L), Mg (49 mg/L), HCO_3 (260 mg/L), Ca (378.8 mg/L), Cl (167.1 mg/L), SO_4 (137.5 mg/L)	Na (9%), K (29%), Mg (10%), HCO_3 (4%), Ca (25%), Cl (25%), SO_4 (9%)	[32]
19	Landfill leachate	21 days	BOD (1153 mg/L), COD (2895 mg/L), PO_4 (3.2 mg/L), NO_3 (121 mg/L)	BOD (60%), COD (68%), PO_4 (82%), NO_3 (83%)	[114]
20	Wastewater effluent	30 days	NO_3 (29 mg/L), PO_4 $^{-3}$ (10.5 mg/L), COD (62 mg/L)	NO_3 (40%), PO_4 $^{-3}$ (60%), COD (40%)	[67]
21	Paper board mill effluent (treated)	10 days	TDS (1000 mg/L), TSS (200 mg/L), BOD (44 mg/L), COD (256 mg/L), TN (25 mg/L), TP (8.50 mg/L), Cd (0.42 mg/L), pH (8.18), EC (1.98 dS/m)	TDS (59.94%), TSS (74.58%), BOD (72.3%), COD (56.25%), TN (70%), TP (42.94%), Cd (80.95), pH (4.3%), EC (37.37%)	[115]
22	Municipal wastewater	14 days	NH_4 (55 mg/L), NO_3 (18 mg/L), K (20.5 mg/L), PO_4 (5.70 mg/L), BOD (103 mg/L), COD (262 mg/L)	NH_4 (91%), NO_3 (66%), K (97%), PO_4 (89%), BOD (42%), COD (55%)	[116]
23	Olive mill wastewater (15%)	67 days	TN (26.6 mg/L), Phenolic compounds (219 mg/L)	TN (23.7%), Phenolic compounds (92.1%)	[117]

Table 4. *Cont.*

NO.	Type of Unconventional Water	Residence Time	Initial Concentration	Removal Efficiency	References
24	Automobile service station effluent (50%)	15 days	TDS (6240 mg/L), Cl (184.9 mg/L), Ca (121.6 mg/L), Mg (75.50 mg/L), Na (437.50 mg/L), K (79.8 mg/L), Fe (10.60 mg/L), SO_4 (172.60 mg/L), BOD (11.62 mg/L), COD (740 mg/L)	TDS (91.73%), Cl (49.67%), Ca (60.48%), Mg (61.48%), Na (60.78%), K (58.41%), Fe (67.08%), SO_4 (63.38%), BOD (69.02%), COD (72.16%)	[118]
25	Industrial wastewater	9 days	BOD_5 (1641 mg/L), COD (6953.33 mg/L), SO_4 (1072.82 mg/L), Cl (1919 mg/L), TDS (5877.30 mg/L), EC (8550 µS/cm), Salinity (0.69%)	BOD_5 (96.24%), COD (97.9%), SO_4 (91.81%), Cl (80.16%), TDS (90.89%), EC (88.27%), Salinity (79.71%)	[119]
26	Well drainage	14 days	EC (10.01 dS/m), Na (61.65 mg/L), Ca (32 mg/L), Mg (1.40 mg/L), NO_3 (146.11 mg/L), PO_4 (43.17 mg/L)	EC (15.88%), Na (14.36%), Ca (41.67%), Mg (57.14%), NO_3 (44%), PO_4 (44.51%)	[120]
27	Electroplating wastewater	28 days	Cr (50.77 mg/L), Ni (24.73 mg/L)	Cr (61.10%), Ni (95.65%)	[121]
28	Synthetic water	10 days	Cu (1.94 mg/L), Fe (0.84 mg/L), Mn (2.77 mg/L), Pb (0.67 mg/L), Zn (1.02 mg/L)	Cu (48.96%), Fe (90.47%), Mn (29.24%), Pb (53.74%), Zn (25.49%)	[122]
29	Synthetic wastewater	72 days	Phenanthrene (194.24 mg/L), Pyrene (123.82 mg/L), Benzo (101.11 mg/L)	Phenanthrene (67%), Pyrene (66%), Benzo (73%)	[123]
30	Treated wastewater	3 days	TH (502.75 mg/L), TDS (966.40 mg/L), SAR (0.41)	TH (20.19%), TDS (12.58%), SAR (34.14%)	[124]
31	Municipal wastewater	15 days	EC (1.51 dS/m), Ca (67.33 mg/L), Mg (81.09 mg/L), Na (8.49 mg/L), K (14.61 mg/L), Cl (130.16 mg/L)	EC (15.67%), Ca (71.82%), Mg (10%), Na (38.32%), K (84.60%), Cl (72.60%)	[125]

6. Traditional and Medicinal Uses of Vetiver Grass

In addition to the use of vetiver grass in the above-mentioned parts, this plant has also had many traditional and medicinal uses. For example, vetiver grass is used to improve nausea and vomiting, relieve genital disorders, improve sperm quality, promote lactation, relieve pain, and reduce fatigue. More precisely, the root of this plant is used for the improvement of burns, as a blood purifier/for the enhancement of blood circulation, as a gastrointestinal system strengthener, for the improvement of cataract/convulsions [126], for the improvement of malarial fever [127,128], as a respiratory system strengthener, as an immunity enhancer [129], and its stem is used to improve urinary tract infections [130].

The leaves of this plant have also been used to remove parasitic infections in feed animals [131], and the mixture of its roots and leaves has been used as a pain reliever for rheumatoid arthritis, lumbago, and sprain [126]. Recently, the utility of vetiver grass as a green infrastructure tool for transportation planning to reduce the risks of erosion, landslides, and flooding was reported [132].

7. Economic Analysis

An economic analysis based on the cost–benefit method indicated that phytoremediation of polluted soils with vetiver grass could be used as an eco-friendly, low-cost, and high-efficiency alternative to other treatment methods for ecological and environmental applications [133]. The approximate cost of the decontamination of polluted soil is found to be about 25 US$ ton^{-1}, which is lower than other methods.

8. Outlook

The vetiver system is in the primary phase and its usage in a full-scale setting is still highly limited. The use of new technology should be approached with caution, as with all new technologies. Public opposition to genetic modification may be the most significant barrier to the advancement of the mentioned technology. This public opposition includes concerns about a decrease in biodiversity, the introduction of potentially harmful genes into foods, and the slippery slope created when a novel foreign DNA is introduced and transferred between unrelated species. As all-natural hyper-accumulators have a small size, genetic modification can apply the technology to other species or lead to an increased natural hyper-accumulator biomass and, consequently, make them more efficient phytoremediators. Nevertheless, the advantages of using vetiver grass for stressed environments are more than its costs. According to the related studies, the following concepts and results could be derived: (1) Phytoremediation of soils has been of interest for the past decades; however, the phytoremediation of solutions, such as water and wastewater, has recently received attention due to the environmental effects of their reuse. (2) The success of phytoremediation (removal of contaminants) is dependent upon the exposure time, contaminant concentration, environmental elements (pH and temperature), as well as plant potential (species, root system, etc.). (3) The ideal plants for phytoremediation are expected to be able to grow in contaminated areas. Moreover, other properties are observed for the mentioned plants such as fast growth, high-quality biomass, easy harvesting, as well as the accumulation of large amounts of pollutants and heavy metals. Currently, there is not any plant that meets all of the mentioned criteria. (4) Vetiver's high effectiveness in the treatment of pollutants indicates its applicability in creating a cost-efficient and eco-friendly treatment for non-conventional water (especially wastewater). Vetiver is tolerant against 3.5–11.5 pH values, as well as extended salinity (calcium, magnesium, sodium, etc.) and heavy metals (arsenic, cadmium, copper, chromium, etc.). Due to the high root depth, it can decrease or remove the leaching of deep nitrate into groundwater. Compared to other herbs, vetiver grass is more efficient because of its roots' high adsorption capacity.

However, further research is recommended in the following areas since vetiver phytoremediation requires more accurate scientific evidence, including investigations on (1) a larger scale with continuous flow; (2) the characteristics of root morphology, type and amount of secretions, and the mechanism of root-surrounded contaminant removal; (3) the possibility of using vetiver by-products as the biomass for biofuel production; (4) and the effects of vetiver grass on removing methane from anaerobic treatment processing.

9. Conclusions

Phytoremediation with vetiver grass, which is a green and environmentally friendly method, could enable the creation of green space in polluted areas. This system is also useful as a part of the filtration systems of treatment plants and irrigation systems because it can grow in almost any climate. In the vetiver system, the contaminants' mobility is eliminated as a result of the plant's roots in their rhizosphere. Therefore, vetiver grass is much more suitable for phytostabilization. The production of fodder for livestock, oil and essential oil for the perfumery industry, branches and leaves for the textile industry, and roots for the medical industry, in addition to the purification of pollutants, are considered for the system selection. In other words, the mentioned plant can be considered as an effective solution in sustainable agriculture even if the phytoremediation of pollutants fails. According to the previous studies, vetiver grass is much more appropriate for phytoextraction.

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