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Significant Potential of Aquatic Duckweed Plants for Biomass Production and Wastewater Remediation

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Abstract
Duckweed (Lemnaceae) has emerged as a pivotal model system in plant biology due to its unique physiological characteristics and broad-spectrum applications. Its significance spans across nutrient uptake, ion transport dynamics, detoxification processes, stress tolerance, and intricate signaling mechanisms. These attributes underline its utility in advancing physiological research and addressing environmental challenges through phytoremediation. Duckweed demonstrates exceptional potential for bioremediation and wastewater treatment, playing a vital role in mitigating environmental pollutants and promoting sustainability. Moreover, recent advancements in genomic studies and transgenic development of Lemnaceae species open new avenues for genetic manipulation and biotechnological innovations. Strategies for germplasm conservation further ensure the preservation of genetic diversity, essential for future research and breeding initiatives. This review highlights the transformative prospects of duckweed research, fostering interdisciplinary collaborations and technological breakthroughs to harness its full potential as a model organism.

Keywords: *Duckweed; Lemnaceae; Phytoremediation; Sustainability; Bioremediation*

1. Introduction

Water contaminations, along with limited availability of water, have put a severe burden on the environment. Around 40% population of the world is facing the problem of water scarcity due to climate change, rapid urbanization, food requirement and unchecked consumption of natural resources. During the past few decades' rapid urbanization, industrialization, agricultural activities, discharge of geothermal waters and olive wastewater especially in olive-cultivating areas enhanced the discharge of polluted wastewater into the environment. Wastewater carrying soaring concentrations of pollutants is immensely noxious for aquatic ecosystem and human health. Reclamation of wastewater has been the only option left to meet the increasing demand of water in growing industrial and agricultural sectors. Industrial and domestic untreated wastewater contains pesticides, oils, dyes, phenol, cyanides, toxic organics, phosphorous, suspended solids, and heavy metals (HMs). Heavy metals among these toxic substances can easily be accumulated in the surrounding environment [2-3].

Removal of toxic pollutants is extremely important to minimize the threat to human health and the surrounding environment. Removal of heavy metals achieved through various techniques such as reverse osmosis, ion exchange, chemical precipitation, adsorption and solvent extraction include enormous operational and maintenance costs and are usually not environmentally friendly. These conventional techniques for the remediation of heavy metals are generally costly and time-consuming. These treatment technologies require high capital investment and, in the end, generate the problem of sludge disposal. For the remediation of wastewater polluted with heavy metals contaminants, an environmentally friendly and economical treatment technology is needed [2-3] Phytoremediation is an aspect of bioremediation that deals with the application of plants for the remediation of polluted environment. It is the potentials of plant species to remove pollutants from polluted media. Phytoremediation deals with the application of certain plants species to accumulate pollutants in terrestrial and aquatic environment. Plant species selected for phytoremediation have the potentials to accumulate specific or wide range of pollutants. In some case plants known as hyper accumulators have the potentials to bioaccumulate pollutants several times above the plant biomass. Several species of plants have the potentials to take up, bioaccumulates, immobilize and degrade pollutants in their tissues. Phytoremediation has been applied in the three matrices of the environment such as air, land and water pollution [3-4]. Pollution and shortages in clean water supplies represent some of the most critical challenges faced by humanity. In many Asian countries and other regions, the demand for potable water doubles every 10 to 15 years, driven by increased domestic consumption and the rising needs of industrial activities. The eutrophication of municipal and industrial reservoirs is a global concern and has been identified as a significant environmental issue in water resource management.

Globally, approximately 80 million tons of nitrogen fertilizers are applied annually to maximize crop yields, yet only about 40% of this amount is assimilated by crops. The remainder is eventually discharged into freshwater reservoirs en route to the oceans. Excessive application of agrochemical fertilizers, particularly nitrogen (N) and phosphorus (P), is widely regarded as a primary driver of eutrophication [6-7] Another notable source of water pollution stems from the nutrients utilized in rapidly expanding aquaculture systems. The primary contaminants in aquaculture wastewater include ammonium, organic nitrogen, and phosphorus. Only about 15% of nitrogen and 25% of phosphorus from aquaculture feed are absorbed by fish and shrimp, with the unutilized fractions accumulating in water bodies or sediments. Over the past two decades, eutrophication caused by aquaculture wastewater has been increasing sharply, at an annual rate of 2–4% in the Yangtze River Basin and the Zhejiang Delta Basin [7]. The necessity of reducing anthropogenic nutrients in aquatic ecosystems to mitigate water eutrophication has been widely acknowledged. Various physical, chemical, and biological methods for wastewater treatment have been tested. Among these, the cultivation of aquatic plants is recognized as an eco-friendly approach, offering benefits for the restoration of eutrophic water bodies through nutrient removal, accumulation of toxic substances and heavy metals, and oxygen balance regulation. Duckweed represents a group of small, fast-growing aquatic plants that often form a complete cover over the surface of water bodies. Its productivity can reach 80–100 tons of dry biomass per hectare per year, exceeding the yield of maize by more than fivefold. During biomass accumulation, duckweed efficiently remediates various types of wastewater. These complementary attributes—water remediation and rapid biomass production—have made duckweed a focus of intensive global scientific research in recent years. This mini-review highlights the numerous advantages that these diminutive plants can provide [9-11]

1.1. Duckweed, An Efficient Global Wastewater Remediator

Various aquatic plants have been tested for wastewater bioremediation, considering their specific physiological characteristics, high growth rates, and ease of maintenance. Special attention has been given to plants of the Lemnaceae family, commonly known as duckweeds. This family of monocotyledonous aquatic plants comprises five genera: Lemna, Spirodela, Wolffia, Wolffiella, and Landoltia, with a total of 37 species distributed globally [13]. Floating aquatic duckweeds represent the most morphologically reduced form of all flowering plants. The largest species, Spirodela polyrhiza, has fronds approximately 5 mm in size, while the smallest species, Wolffia, does not exceed 1 mm. Duckweeds are widely distributed geographically, with most species inhabiting tropical and subtropical regions, though some occur in temperate zones[14]. Due to their aquatic lifestyle, duckweed species are capable of rapidly removing nitrogen and phosphorus from anthropogenic effluents. Duckweed can accumulate up to 9.1 t/ha/year of total nitrogen and 0.8 t/ha/year of total phosphorus in its biomass [12]. Our experiments demonstrated that after just three days of incubating Lemna turionefera in local municipal wastewater, the concentrations of key nutrients (total nitrogen and total phosphorus) were lower than those in the effluent from a local wastewater treatment plant. Over 15 days of growth, four duckweed species removed more than 93% of both total nitrogen and total phosphorus from municipal wastewater. The final total nitrogen

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concentration was 1 mg/L, significantly below the national standard for treated wastewater (1.5 mg/L, China Standard GB 18918-2002) and close to the total nitrogen level acceptable for drinking water (1.5 mg/L, China Standard GB 3838-2002).

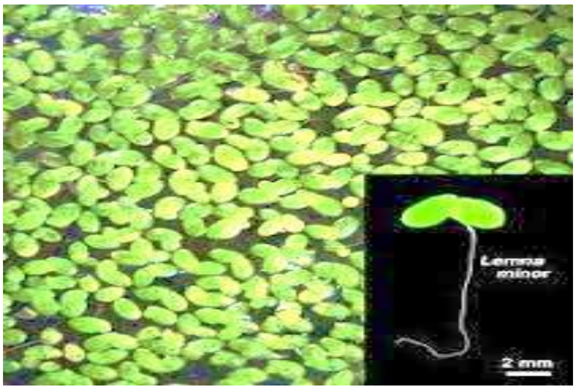

Figure 1 Lemna Minor

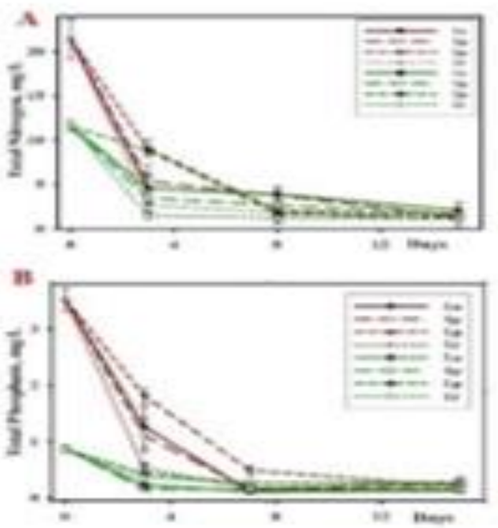

Figure 2 Removal of total nitrogen (A) and total phosphate (B) from municipal wastewater by four duckweed species. Red lines refer to duckweeds cultivated in influent wastewater, and the green lines refer to duckweeds cultivated in effluent wastewater. La: *L. aequinoctialis*; Sp: *S. polyrhiza*; Lp: *L. punctata*; Lt: *L. turionefera*.

Similarly, high removal rates of nitrogen and phosphorus were observed when duckweed was grown in sewage and hog farm wastewater, shown in Figure 1 & Figure 2. Up to 98% removal of nitrogen and phosphorus was achieved from pig farm effluents, accompanied by a substantial increase in dissolved oxygen levels and the production of duckweed biomass containing 35% crude protein. Another advantage of duckweed is its tolerance of relatively high concentrations of ammonium (NH4+), which is toxic to plants, animals, and humans. Common duckweed (Lemna minor) has been reported to thrive at NH4+ concentrations of up to 84 mg/L. This ability to absorb and tolerate high levels of NH4+ makes duckweed particularly suitable for remediating wastewater from domestic and agricultural sources, which often contain significant amounts of this ion [10]. Due to its specific properties, duckweed is considered a cost-effective platform for wastewater treatment, capable of efficiently accumulating water contaminants, such as residual nitrogen (N) and phosphorus (P) fertilizers. Additionally, it shows potential for monitoring and remediating heavy metals. Heavy metals are introduced into the environment through both natural and anthropogenic sources, primarily from mining and industrial activities. Duckweed demonstrates relative tolerance and the ability to absorb various heavy metal ions, including Cu, Fe, Zn, Cr, Cd, Pd, Pb, Ni, and As. Consequently, it is widely used for the phytoremediation of heavy metals in aquatic ecosystems [19]. Duckweed can be an excellent model organism for biological studies, including genetics, genomics, ecology, and renewable energy research. Considering the several advantages associated with Duckweed, it can be used for different research studies [20].

1.2. Duckweed as a Renewable Source of Valuable Biomass

In addition to its abilities to clean wastewater, the current renewed interest in duckweeds is driven by its potential as a promising platform for the production of valuable biomass [21]. Because of its high growth rate, low lignin content, and high starch content, duckweed is regarded as a promising renewable feedstock for biofuel [22]. With a doubling time of about 24 hours for some species, duckweed is the fastest-growing flowering plant and has an annual biomass productivity of 39-105 tons of dry weight per hectare per year. For comparison, the productivity of

Miscanthus, a major bioenergy grass, is 5-44 t DW/ha/year. A high percentage of starch (up to 50% dry weight) can be obtained in some strains under some growth conditions. Along with the low amount of lignin (< 5%), this makes duckweed a quite competitive system compared to other plants being considered for the biomass production of fuel alcohols. Duckweed can also yield about 50% more ethanol per hectare than maize, a standard ethanol crop in the US [26]. Additionally, because of its aquatic lifestyle, duckweed does not compete with crops for arable land, and its floating biomass allows for rapid, low-energy input collection for further processing. To obtain biofuel, the biomass of duckweed could be directly fermented into ethanol/butanol or converted into bio-oils by pyrolysis [23]. A number of recent studies have demonstrated that some duckweed species have excellent nutrition qualities both for animal and human nutrition [25]. It can easily be observed that various animals, such as ducks, geese, and fish, naturally feed on duckweeds. Furthermore, duckweed is instinctively used for feeding domesticated animals, either by providing them with access to natural vegetation or by supplementing the diet with harvested duckweed in both fresh and dry forms. In some Asian countries, duckweed is also used as food for humans. For example, fresh Wolffia plants are used to prepare salads, omelets, or vegetable curries in some countries [24]. Recognizing the nutrition value combined with the extremely fast grow of Wolffia, the Israeli company GreenOnyx advertises a small machine for growing Wolffia, which can be used to prepare fresh juice or salad at home (www.greenonyx.biz). Soybean is currently the most important and preferred source of vegetable protein for animal and fish feed. However, duckweed species have an average of 30.0% crude protein, which is close to the protein contents yielded by soybean (between 33 and 49%). With high contents of protein and starch, duckweed can be used as viable source to produce feed and as feed supplement for animals. Many studies have been carried on animals such as fishes, dairy cows, pigs, sheep, goats, and poultry, which have shown that protein intake, can be partially or completely substituted by duckweed without impeding growth [28]. The most common application of this plant is as fish feed, as it can be used in its fresh state and is highly suitable for both herbivorous and omnivorous species [27]. Generally, protein-rich feed with high biological value is expensive and not economically sustainable for aquaculture operations. Duckweed represents a locally available, low-cost alternative for intensive aquaculture. Furthermore, it can be cultivated directly in fish farm ponds or in nearby ponds integrated for wastewater treatment and the production of duckweed-based feed. Thus, in addition to providing an economical and renewable protein source, such a multitrophic aquaculture system can recover waste nutrients generated during fish farming from aquaculture effluent, enhancing economic efficiency while mitigating environmental impacts [31]. As an alternative to inorganic fertilizers, green manure is an attractive option for enhancing soil fertility and can provide significant benefits to farmers. Research on green manure has primarily focused on leguminous plants, while information regarding the use of duckweed as green manure remains limited, despite its easy availability and substantial biomass production in certain regions. Yao demonstrated that urea combined with duckweed cover reduced NH3 volatilization by 36-52% and increased nitrogen accumulation in surface plants by 14-25% compared to the control over a three-year study period. This resulted in a 9-10% increase in rice yield and a 10-11% improvement in net economic benefit compared to the control. Therefore, the use of duckweed as green manure in combination with chemical fertilizer applications offers a strategy to increase rice yield without additional nitrogen fertilizer inputs. This approach could provide farmers with a financially viable solution to enhance environmental sustainability and ensure food security in rice production [30].

Conclusion

Duckweed presents a promising, sustainable solution for wastewater treatment, addressing both environmental and economic challenges. While its potential is significant, further research is needed to overcome existing limitations and optimize its application on a larger scale. uckweed possesses notable environmental remediation capabilities and demonstrates significant potential as an efficient feedstock for fuel and bioproducts. Therefore, we anticipate that the ongoing adoption and optimization of duckweed farming will establish it as a valuable component of the modern circular economy. Its successful integration could positively impact numerous critical aspects of human activity, including water resource management, renewable energy development, sustainable agricultural practices, and food production.

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