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Small Aquatic Duckweed Plants with Big Potential for the Production of Valuable Biomass and Wastewater Remediation

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Mini Review

Pollution and shortages in clean water supplies are some of the most serious problems that humanity is facing. In many Asian countries and elsewhere, the demand for potable water doubles every 10-15 years due to rising domestic consumption and the increasing needs of industry [1,2]. Eutrophication of municipal and industrial water reservoirs is a global concern and has been identified as a major environmental problem for water resource management. Furthermore, about 80 million tons of nitrogen fertilizers are applied globally per year to maximize yield [3], and no more than 40% of this amount is taken up by crops [4]. The rest of the chemicals eventually end up in the fresh water reservoirs on their way to the ocean. The excess of agrochemical fertilizers-primarily nitrogen (N) and phosphorus (P)- are considered as the major causes of eutrophication. Another source of water pollutant is the nutrients used in the fast-growing aquaculture systems. The main contaminants from aquaculture wastewater effluent are ammonium, organic N, and P [5]. Only about 15% of N and 25% of P from aquaculture feed are assimilated by fish and shrimps, and the unutilized part accumulates in the water or in the sediment [6]. The eutrophication of water bodies due to aquaculture wastewater has been sharply rising during the last 20 years at a rate of 2-4% per year in the Yangtze River Basin and Zhujiang Delta Basin [6].

The need to reduce anthropogenic nutrients in aquatic ecosystems to prevent water eutrophication has been widely recognized [7]. A number of physical, chemical, and biological methods used in wastewater treatment have been tested. As the eco-friendliest method, the cultivation of aquatic plants is attractive for the restoration of eutrophic water bodies by nutrient removal, accumulating toxic nutrients and heavy metals, and regulating oxygen balance [8]. Duckweed is a group of small aquatic plants with high growth rates that often completely cover the surface of a water body (Figure 1). Its productivity can reach 80-100 tons of dry mass per hectare per year, which is over 5 times as high as maize [9]. In the process of biomass accumulation, duckweed can very efficiently remediate different types of wastewater [10]. These complementary features of water remediation and fast biomass accumulation have made duckweed a subject of intense global research interest in recent years [9,11]. This mini-review highlights the numerous benefits that these tiny plants can provide.

Duckweed, an efficient global wastewater remediator

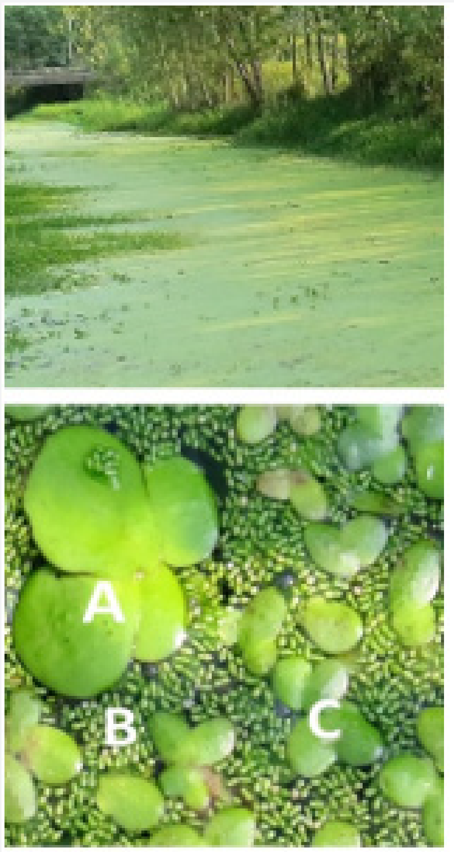

Figure 1: Duckweed covering the water surface of a pond near Huaian city in China (top), with a community of representative species (bottom): A- *Spirodela polyrhiza*, B - *Wolffia globosa*, C - *Lemna aequinoctialis*.

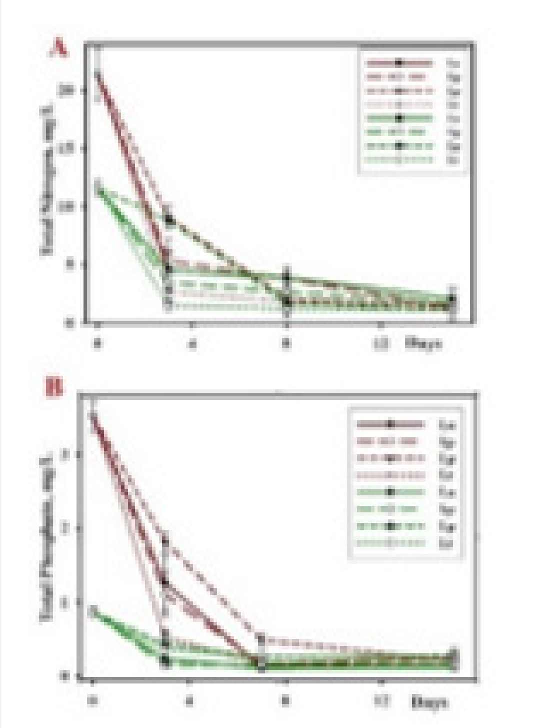

Figure 2: Removal of total nitrogen (A) and total phosphate (B) from municipal wastewater by four duckweed species. Red lines refer to duckweeds cultivated in influent wastewater, and the green lines refer to duckweeds cultivated in effluent wastewater. La: *L. aequinoctialis*; Sp: *S. polyrhiza*; Lp: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

Various aquatic plants have been tested for the bioremediation of wastewater based on their specific physiological features, high growth rates, and simple maintenance. Special attention has been paid to plants in the *Lemnaceae* family, which are commonly known as duckweeds. This family of monocotyledonous aquatic plants contains five genera: *Lemna, Spirodela, Wolffia, Wolffiela*, and *Landoltia* [12]. There are 37 species distributed around the globe [13]. Floating aquatic duckweeds are the most morphologically reduced form of all flowering plants. The largest of these species, *Spirodela polyrhiza*, has fronds of about 5 mm, and the smallest species, *Wolffia*, does not exceed 1 mm (Figure 1). Duckweeds are widely distributed geographically, and most species are primarily tropical or subtropical, but others occur in temperate regions. Due to their aquatic lifestyle, duckweed species can rapidly remove nitrogen and phosphorous from anthropogenic waste streams. Duckweed can accumulate up to 9.1 t/ha/year of total nitrogen and 0.8 t/ha/year of total phosphorus in their biomass. Our experiments have demonstrated that after just 3 days of incubation of the duckweed *Lemna turionefera* in local municipal wastewater, the main nutrient concentrations (total nitrogen and total phosphate) were lower than those in the effluent from a local wastewater treatment plant (Figure 2) [14]. With 15 days of growth, four duckweed species were able to remove more than 93% of both total nitrogen and total phosphate in local municipal wastewater (Figure 2) [14]. The final total nitrogen concentration was of 1 mg/L, which is much lower than the national standard for treated wastewater (1.5mg/L, China Standard GB 18918-2002) and is close to the total nitrogen level accepted for drinking water(1.5 mg/L, China Standard GB3838-2002).

Similarly, high rates of removal were also demonstrated with duckweed growing on sewage water [15] and wastewater from a hog farm [16]. Moreover, 98% removal of N and P from pig-farm effluent has been achieved [17]. This was accompanied by a significant increase in the level of dissolved oxygen and the production of duckweed biomass with 35% crude protein [17]. Another advantage of duckweed is its tolerance of relatively high concentrations of ammonia (NH_4^+), which is toxic to plants, animals, and humans. The common duckweed (*L. minor*) has been reported to grow well at NH_4^+ concentrations of up to 84 mg/L [18]. The ability of duckweeds to take up and tolerate such high levels of NH_4^+ makes the plants particularly suited to the remediation of wastewater from domestic and agricultural sources, which often contain considerable amounts of this ion.

Due to these specific features, duckweed is considered as a low-cost wastewater-treatment platform that efficiently accumulates water contaminants such as remaining N and P fertilizers [19]. In addition, it also has potential for monitoring and remediating heavy metals [10]. Heavy metals are released into the environment from both natural and anthropogenic sources, predominantly from mining and industrial activities. Duckweed is relatively tolerant and able to take up many heavy metal ions, including Cu, Fe, Zn, Cr, Cd, Pd, Pb, Ni, and As. Thus, it is being used for the heavy-metal phytoremediation of aquatic ecosystems [20].

Duckweed as a renewable source of valuable biomass

In addition to its abilities to clean wastewater, the current renewed interest in duckweeds [11] 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 [10]. 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 [16]. 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 [22]. 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

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animal and human nutrition [24-25]. 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 [26]. 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 [16,27].

Fish feed is the most widespread use of this plant since it can be used in a green state and is very suitable for both herbivorous and omnivorous animals [28]. Generally, protein feed with high biological value is very expensive and cannot be supported by fish farming. Duckweed is locally available and a low-cost solution for intensive fish aquaculture [29]. Moreover, duckweed can be grown directly in the fish farm ponds or in nearby ponds that are integrated for wastewater remediation and the production of duckweed-based feed. Therefore, in addition to providing a cheap, renewable source of protein, such a multi-trophic aquaculture system could serve to bio-recuperate waste nutrients produced during fish cultivation from aquaculture wastewater, which would increase economic efficiency and minimize the negative effects on the environment.

As an alternative to inorganic fertilizers, green manure is an attractive option to increase soil fertility and can provide substantial benefits for farmers. General studies of green manure are mainly focused on leguminous plants, and very limited information is available regarding duckweed as green manure, despite its easy availability and substantial biomass accumulation in certain areas. Yao showed that urea combined with duckweed cover reduced NH_3 loss by 36-52% and increased nitrogen accumulation in ground plants by 14-25% compared to the control over a 3-year test period [30]. This resulted in 9-10% higher rice yield and 10-11% higher net economic benefit compared to the control. Thus, duckweed as green manure combined with chemical fertilizer application provides an approach for increasing the rice yield without increasing the inputs of nitrogen fertilizer. This could provide a financially attractive option for farmers to achieve environmental integrity and ensure food security in rice production.

Conclusion

Duckweed features environmental remediation capabilities and potential as an efficient feedstock for fuel and bioproducts. Thus, we believe the continual acceptance and optimization of duckweed farming will make the system a valuable integrative part of the modern cycling economy. Its success will benefit many important areas of human activities, including water resources, renewable energy, agriculture practices, and food production.

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