

REVIEW ARTICLE

Enhanced Phytoremediation and Resource Recovery: The Efficacy of Duckweed in Mitigating Wastewater Pollution

Sneha Desai^{*}, Prerana Belekar, Sakib Pathan, Aakash Pawar

Department of Biological Sciences, School of Science, Sandip University, Nashik, Maharashtra (India)

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ABSTRACT

Duckweeds, including species like *Lemna minor* and *Spirodela polyrhiza*, are small, fast-growing, surface-floating plants with a high potential for phytoremediation and resource recovery. This study investigates duckweed's capacity to reduce wastewater pollution while producing protein-rich biomass. Duckweeds effectively remove nutrients such as nitrogen and phosphorus from contaminated water, significantly lowering total suspended solids (TSS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Their rapid growth, high dry matter accumulation, adaptability to varying environmental conditions, and bioaccumulation of heavy metals make them ideal for eco-friendly wastewater treatment, particularly in industrial settings. Harvested biomass from duckweed systems holds potential applications as animal feed, biofertilizer, and biofuel, supporting sustainable resource recovery. The wastewater-duckweed-carp polyculture model offers an integrated solution for pollution control and nutrient recovery, contributing to enhanced water quality for aquaculture. However, responsible disposal of contaminated duckweed biomass is essential to prevent environmental harm. Duckweed culture thus emerges as a low-cost, environmentally sustainable method to mitigate water pollution, protect aquatic and terrestrial ecosystems, and reduce the burden on groundwater reserves. However, proper disposal of contaminated biomass is essential to avoid environmental harm. This study highlights the need for further research to optimize large-scale applications, particularly for aquaculture and bioenergy, demonstrating duckweed's potential as an effective solution for water remediation and resource recovery.

Keywords: Duckweed, Wastewater treatment, Phytoremediation, Resource recovery.

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INTRODUCTION

Duckweed: small aquatic plant

Pollution and the scarcity of potable water represent two of the most significant challenges confronting humanity because of growing industrial and domestic usage (Srivastava et al, 2008). Furthermore, a major environmental issue for water resource management is eutrophication, which is the nutrient enrichment of municipal, agricultural, and industrial water reservoirs brought on by human activity and resulting in the stimulation of plant, algae, and bacterial growth as well as oxygen limitation (Priya et al, 2012). Duckweed is a frequent term that has collections of various floating aquatic plants, and they are among the fastest-growing floral plants because of their fastest growth and used as an eco-friendly treatment (Sree et al, 2020). A range of aquatic plants with distinct physiological characteristics, rapid growth, and

reduced maintenance requirements have been researched for the bioremediation of wastewater. Focus has been placed on plants belonging to the family *Lemnaceae*, which are popularly referred to as duckweeds (Appenroth KJ et al, 2013) (Fig.1). The five genera of monocotyledonous aquatic plants in this family include *Landoltia*, *Spirodela*, *Wolffia*, and *Wolffiella* (Les DH 2002). Compared to most other plant species, duckweeds have roots, and a sleek structure called a frond that combines the leaves and stalks (Fu et al, 2020). Surprisingly, duckweeds are widely dispersed. Most species are tropical or subtropical, while some are also found in temperate areas (Zhou Y et al, 2018). Duckweed species can quickly extract phosphorus and nitrogen from anthropogenic waste streams because of their watery existence (Ziegler et al, 2015). In its biomass, duckweed can store up to 9.1 t/ha/year of total nitrogen and 0.8 the year of total phosphorus. The primary nutrient contents (total nitrogen and total phosphate) in the duckweed *Lemna turionifera* were

*Author for Correspondence: prerana2362002@gmail.com

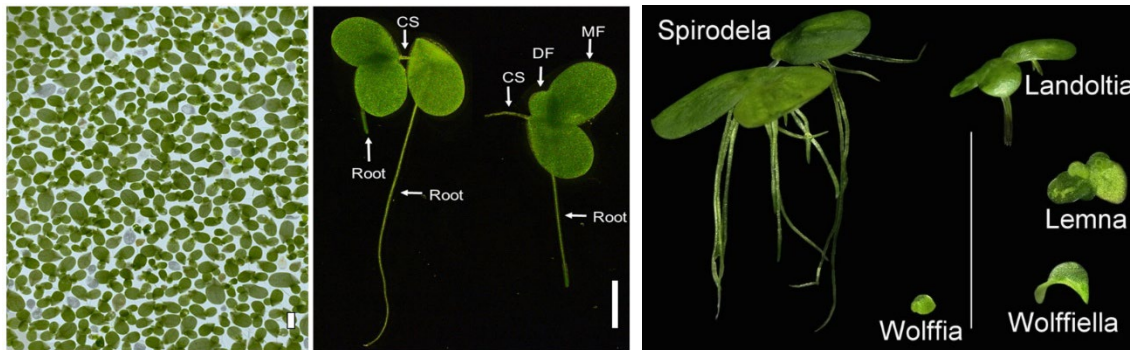


Figure 1: Duckweed, the *Linaceae* plant family (Zhou et al, 2023).

lower in the wastewater-treated plant effluent after just three days of incubation in local municipal wastewater (Sylvester-Bradley et al, 2009). Sundried as well as pelleted varieties of duckweed can be stored for 13 years without any trace of fungal development and nutritional loss (Mbagwu et al, 2001) (Table 1). The reason for this is that plants have a wax layer on their upper surface that prevents fungus growth (Effiong et al, 2009).

Duckweeds as nutrient pump

Duckweeds serve as an excellent “Nutrient Pump” for harvesting nutrients over a short time in wastewater treatment like nitrate, phosphate, calcium, sodium, potassium, magnesium, carbon, and chloride (Van der Spiegel et al, 2013). This is because they may spread quickly by consuming dissolved nutrients from water. Duckweed is a highly protein-rich plant and variety of amino acids (Fasakin et al, 1999). Duckweed compost is therefore high in nitrogen and phosphorous (Kostecka et al, 2008) and as feed or fodder for fish and other livestock (Leng et al, 1995). Duckweed is a plant-based ingredient that could be used in food preparation items in the future (Appenroth et al, 2018). As an aquatic plant, duckweed develops without occupying land and may collect vast amounts of starch, which is a raw material for making biofuel, through phototrophic autotrophy (Cheng et al, 2009). The nutrient content of the water that the duckweed grows in determines its nutritional worth. They have a low protein

and high fiber content when growing slowly in nutrient-poor waters and vice-versa (Mbagwu et al, 1998). Duckweeds with shorter roots (10 mm or less) have a higher protein content and the opposite is true for fiber content (Rodriguez et al, 1996). In addition, duckweed is a good source of beta-carotene and xanthophylls, as well as carbs (30–35%), vitamin A, and colors. The collected biomass can be sun-dried in 4–6 days in the winter and 24–48 hours in the dry summer (Chau et al, 1998).

Phytoremediation recovery

Aquatic plant application for the removal of contaminants from water resources or aquatic ecosystems is known as phytoremediation (Ekperusi et al, 2019). Because they can withstand harsh environments, duckweed is well-known for being an efficient resource for wastewater pollution cleanup buildup by adsorption or absorption (Ceschin et al, 2020). It has been observed that duckweed can purify medicinal, organic, and inorganic compounds. Since ammonium causes pond eutrophication and generates nitrates in groundwater, it must be removed to purify wastewater (Oron et al, 1998). Ammonium is absorbed from water by *Landoltia punctata*, which then stores the ammonium ions as a helpful supply of nitrogen (Nafea et al, 2016). Recovering and reusing the nitrogen and phosphorus emissions from manure in livestock systems is crucial since these emissions cause ecosystems to become eutrophic (Stadtlander et al, 2019). For instance, by eliminating nitrogen

Table 1: List of duckweeds used as different resources

Sr.No.	Resources	Species	References
1.	Amino acid supplement	<i>W. globosa</i>	(Kaplan et al, 2019)
2.	Vitamin B ₁₂ supplement	<i>W. globosa</i>	(Kaplan et al, 2019)
3.	Cattle	<i>Lemna</i> spp., <i>Spirodela</i> spp. <i>Wolffia</i> spp.	(Huque et al, 1996)
4.	Fish	<i>L. gibba</i> , <i>L. minor</i> , <i>L. perpusilla</i> , and <i>S. polyrrhiza</i>	(Aslam et al, 2017)
5.	Antibacterial activity	<i>L. minor</i> and <i>S. polyrrhiza</i>	(González-Renteria et al, 2020)
6.	Antifungal activity	<i>L. aequinoctialis</i> and <i>S. polyrrhiza</i>	(Das et al, 2012)
7.	Ammonium	<i>Landoltia punctata</i>	(Fang et al, 2007)
8.	Nitrogen	<i>Landoltia punctata</i> , <i>L. gibba</i> , <i>L. minuta</i> , and <i>S. polyrrhiza</i>	(Verma et al, 2014)
9.	Bioethanol	<i>L. aequinoctialis</i> , <i>L. minor</i> , and <i>S. polyrrhiza</i>	(Zhao et al, 2012)
10.	Biogas	<i>L. minor</i>	(Muradov et al, 2012)

and phosphorus, *Landoltia punctata*, *L. gibba*, *L. minuta*, *L. turionifera*, *S. polyrrhiza*, and *W. borealis* purify wastewater or swine lagoons. Since nitrogen and phosphorus may be released back into the soil by using duckweed as a fertilizer, their adsorption capacity is very beneficial (Sharma et al, 2017). Because duckweeds may accumulate heavy metals like arsenic, cadmium, chromium, cobalt, copper, lead, nickel, selenium, and zinc, they can be used for bioremediation of municipal and industrial wastewater (Li et al, 2020). To minimize damage and regulate oxidative stress brought on by heavy metals, they have an enzymatic antioxidant system (da-Silva et al, 2017). Many plants and animals are negatively impacted by the release of different medicines into the environment; therefore, phytoremediation is a crucial method of getting rid of them. Drugs such as acetaminophen, fluoxetine, progesterone, and sulfamethoxazole could be eliminated by *L. turionifera* and *W. borealis* (Farrell JB, 2012) (Fig. 2).

Duckweed-based wastewater treatment: processes

Duckweed wastewater treatment is potentially suitable for small-scale application at the rural level and for medium-sized facilities at the community and industrial level (Edwards et al. 1992). Duckweed-based wastewater treatment technologies have been extensively investigated and applied to various types of wastewaters (Wolverton 1979), including dairy effluent lagoons, raw and diluted municipal sewage, secondary effluents from wastewater treatment plants, aquaculture systems (Culley et al. 1981, Whitehead et al. 1987).

By creating a dense covering of duckweed that floats on the surface and overshadows the planktonic algae, duckweeds inhibit the formation of planktonic algae (Bonomo et al, 1997). Duckweed is easily gathered, which removes nutrients directly from the waste stream, whereas phytoplankton is harder to harvest and typically releases its nutrients back into the ecosystem (Dan Willett, 2005). Working with both aerobic and

anaerobic bacteria, duckweed purifies wastewater. Therefore, the duckweed plants themselves should be considered as just one component of a comprehensive DWT system (Skillicorn et al, 1993) (Fig. 3).

Effectiveness of DWT

A system design that enables the ideal mix of organic loading rate, water depth, and hydraulic retention period is essential to the efficacy of DWT. These will change based on the source and level of effluent of pre-treatment (Alaerts et al, 1996). The main goal of treatment in the case of raw sewage (human or animal waste) processing is to get rid of the solids. Conventional deep anaerobic ponds that promote the fermentation and decomposition of settling materials can accomplish these materials by bacterial activities into basic organic and inorganic compounds (Mkandawire et al, 2005). Duckweed maintains anaerobic conditions in these ponds, which improves initial treatment. Additionally minimizes odor interference. Ammonification reaches high levels in initial treatment systems (Phan et al, 2002). It was shown, nevertheless, that duckweed can require some time to acclimatize to the extremely high N concentrations in untreated agricultural wastewaters (Skillicorn et al, 1993). Nonetheless, the majority of studies indicate that DWT yields higher efficiency increases in secondary and tertiary effluent treatments, where organic sludge has already been eliminated or transformed into simple organic and inorganic compounds that duckweed can directly utilize (Alaerts et al, 1996).

Duckweed Harvesting schedule

When the plants are harvested, these nutrients are eliminated from the system forever (Korner et al, 1998). Duckweeds remove nutrients from wastewater and substantially reduce its total suspended solids (TSS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD) (Sylvester-Bradley et al, 2009). The effectiveness of treatment and the nutritional value of the plants is significantly influenced by the quantity and frequency of duckweed harvesting (Caicedo et al, 2000). Regular harvesting maintains crop vitality by

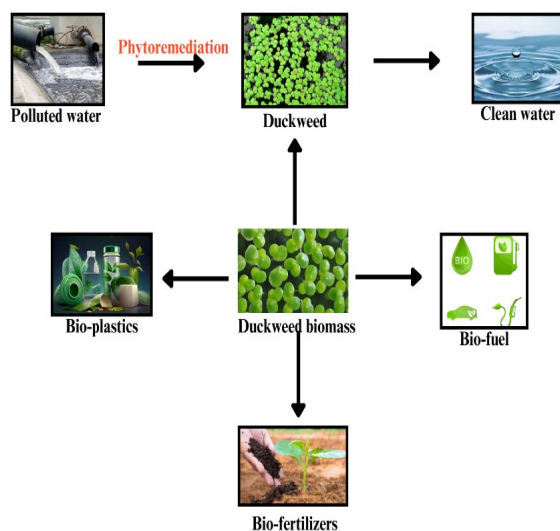


Figure 2: Phytoremediation with other industrial applications (Rai et al, 2024).

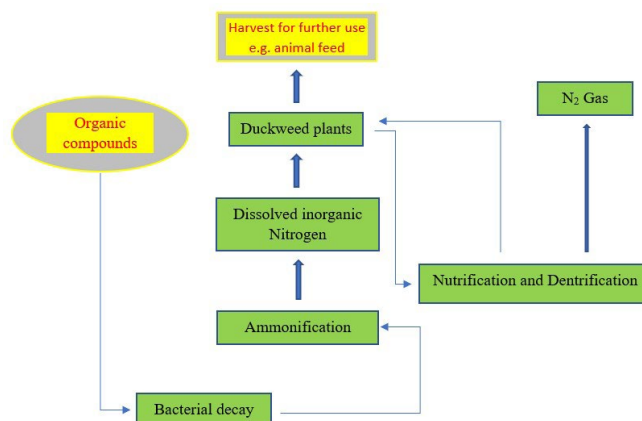


Figure 3: Nitrogenous nutrients within a DWT system utilizing bacterial processing and uptake by duckweed plants (Dan Willett, 2005).

removing excess nutrients and toxins, fostering optimal growth rates and nutrient profiles, and promoting overall health and productivity (Cheng et al, 2002). younger plants exhibit a better nutritional profile and higher growth rate than older plants. Harvesting your crop regularly is essential to keeping it healthy and beneficial (Dalu et al, 2003). The optimal standing crop density that maximizes duckweed productivity will dictate the frequency and magnitude of harvests, thereby influencing the biomass yield and sustainability of the duckweed cultivation system (Skillicorn et al, 1993).

Issues of Duckweed

A growing body of research indicates that duckweeds emit substances with insecticidal qualities specific to mosquito larvae (Eid et al, 1992). In rural regions where malaria is a major concern, the development of duckweed aquaculture in the wet tropics may also have ramifications for mosquito control (Marten et al, 1996). Allelo compounds produced by *Lemna trisulca* seem to have anti-algal properties which indicates that *Lemna minor* extracts were effective in preventing *Staphylococcus aureus* from growing (Bellini et al, 1994). Duckweeds can inhibit algal growth in two ways: first, by producing algaecides; second, by reducing the availability of nutrients, especially concentrations in sewage plant effluent waters and water bodies (Crombie et al, 1994).

CONCLUSION

Duckweed may be the most effective plant for purifying water. Duckweed is characterized by its high rate of growth, high dry matter accumulation, and excellent environmental adaptability. Duckweed is a cheap and eco-friendly way to stop pollution in the environment and protect terrestrial and aquatic ecosystems through phytoremediation. Nonetheless, care should be taken when disposing of tainted duckweed and evaluating the purifying potential of duckweeds. Duckweed culture is an environmentally friendly method of phytoremediation that can assist make ponds, lakes, and other bodies of water more suitable for aquaculture by bioremediating them and providing free nutrient extraction in the form of biomass high in protein. Duckweed species, such as *Lemna minor* and *Spirodela polyrrhiza*, offer promising, eco-friendly solutions for water purification and nutrient recovery through phytoremediation. Their rapid growth, adaptability, and high biomass yield enable efficient removal of nitrogen, phosphorus, TSS, COD, and BOD from wastewater, with additional benefits in heavy metal accumulation, making them suitable for industrial and municipal water treatment. Integrating duckweed into a wastewater-duckweed-carp polyculture system supports sustainable aquaculture, with harvested biomass repurposed as animal feed, biofertilizers, or biofuel, contributing to a circular economy. Duckweed cultivation alleviates the strain on land resources, offering a viable alternative for food and fodder production in response to urbanization and population growth. The ideal integrated package for pollution management and nutrient recovery is wastewater-duckweed-carp polyculture. Furthermore,

using an alternative resource for this purpose makes sense given the rising strain that has been placed on land over time for the production of food and fodder (due to factors like urbanization, industrialization, and population growth). This path offers many opportunities for duckweed culture, including the production of high-quality food through aquaculture and the reduction of pressure on groundwater reservoirs. Proper disposal of harvested duckweed is essential to avoid environmental contamination. Future research should focus on optimizing large-scale applications and enhancing duckweed's resilience across diverse water conditions. Duckweed-based systems present scalable, nature-based solutions that advance global sustainability goals, supporting ecosystem health, resource recovery, and sustainable aquaculture.

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DISCLOSURE STATEMENT

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