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Chapter- 19

Duckweed: A Natural Solution for Wastewater Treatment

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Abstract:
Duckweeds (members of Lemnaceae) are a highly effective solution for wastewater treatment, known for their fast growth, efficient nutrient uptake, and adaptability to diverse environments. This review presented duckweed's role in purifying polluted wastewater by removing contaminants such as nitrogen, phosphorus, heavy metals and other pollutants. Through bioaccumulation and phytoremediation, duckweed significantly lowers Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and total dissolved solids (TDS). Its rapid biomass production also presents biofuel, feed, or biofertilizer opportunities. Duckweed further improves water clarity by reducing turbidity and suspended solids, offering a sustainable, cost-effective wastewater treatment option that supports environmental and resource conservation goals.

Introduction:

Duckweed, a small and rapidly growing aquatic plant, has garnered interest in recent years due to its capacity for wastewater treatment. Despite their diminutive size, duckweeds are among the most prevalent organisms in freshwater ecosystems, often forming dense mats on the water's surface (Godfrey and Wooten, 1979; Ziegler et al., 2023).

Lemna's capacity to absorb toxic compounds found in water makes it a great indicator plant for evaluating water quality. It gathers phosphate, nitrogen, heavy metals, and antibiotics (Krupka et al., 2021).

Duckweed, a member of the Lemnaceae family, is frequently considered an annoyance in ponds and lakes because it grows well in nutrient-rich settings. In light of this, they may extract heavy metals like copper (Zhao et al., 2015), chromium (Uysal, 2013), cadmium (Wang et al., 2022) and many more, as well as contaminants (particularly nitrogen and phosphorus) (Iqbal et al., 2019; Liu et al., 2016) from wastewater at a high rate. Due to this capacity, Duckweed has already been utilized to purify wastewater from swine, industry, and homes.

Therefore, its unique physiological characteristics make it an effective bioagent for cleansing wastewater and accumulating heavy metals, which has drawn considerable attention to environmental remediation.

Biological Features of Duckweed:

There are 37 duckweed species, a type of floating aquatic plant, in 5 genera (*Spirodela*) (Tippery and Les, 2020). Duckweed is abundantly spread around the world. Despite being

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flowering plants, most of the duckweed propagates asexually, dedicating nearly all of its energies to vegetative growth. It may therefore quadruple its biomass in two days and develop faster than the majority of other plants (Chen et al., 2018).

With an exceptionally rapid growth rate and foliar pigment properties resembling those of terrestrial perennials, duckweed displayed characteristics of both slow-growing evergreens and fast-growing annuals. Because it can grow in various light conditions, duckweed can succeed in environments with dynamic light cycles and quick expansion cycles (Stewart et al., 2021).

The high rate of *Lemna* multiplication has resulted in numerous prospective biotechnological implements, including biofuel (Yang, 2022), animal feed (Pagliuso et al., 2022; Sembada et al., 2024) and even human food production (Appenroth et al., 2018). This is why, in ecotoxicological studies, the duckweed is recommended (OECD, 2006) as a test organism.

Duckweed as a Natural Cleanser for surpassed nutrients:

Agricultural fertilizers are fundamental for preserving soil fertility and boosting crop yields. From 2011/2012 to 2023/2024, global demand for primary nutrient fertilizers—nitrogen (N), phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O)—has grown significantly. Nitrogen remains the most in-demand, with 109.7 million metric tons used in 2022/2023 and 111.6 million metric tons forecasted for 2023/2024 as per the report presented by Statistica, 2024 (Statistica Research Department, 2024). These nutrients are essential for plant growth: nitrogen aids protein production (Anas et al., 2020; Frink et al., 1999), phosphorus supports root growth and participates in the generation of nucleic acids and different biomolecules and mediates signalling processes and resistance in abiotic stresses (Bechtaoui et al., 2021; Khan et al.,2023). The most prevalent inorganic cation is potassium (K), essential for overall plant growth (White and Karley, 2010). Numerous vital enzymes, including those involved in protein synthesis, sugar transport, N and C metabolism, and photosynthesis, are activated by K. It is crucial to developing improved yield and quality (Marschner, 2012; Oosterhuis et al., 2014).

Fertilizer demand has risen from 177.2 million metric tons in 2011/2012 to a projected 195.4 million metric tons in 2023/2024, reflecting its importance in global agriculture (Statistica, 2024). However, overuse can lead to environmental issues like nutrient runoff, pollution, and eutrophication (Chandini et al., 2019; Buda et al., 2015), underscoring the need for sustainable practices.

Crops probably absorb at most 40% of this total (Zhou and Borisjuk, 2019; Sylvester-Bradley and Kindred, 2009), with the remainder reaching freshwater reservoirs before entering the ocean. Ammonium, organic N and P are the primary pollutants found in aquaculture wastewater effluent (Cao and Wang, 2010).

Duckweed's ability to remove excess nutrients, particularly nitrogen and phosphorus, is one of its most well-documented features. High concentrations of these nutrients are common in agricultural runoff and domestic wastewater, where they contribute to eutrophication, leading to harmful algal blooms and oxygen depletion in aquatic systems (Zhou et al., 2023).

A recent study analyzed water quality in aquaculture waters at 64 random locations in the western delta region of Andhra Pradesh. Around 78% of the water samples collected from that area were classified as poor and unsafe for drinking or domestic use. The mean ammonia concentration was 0.15 mg/L, with 78% of samples exceeding the World Health Organization's (WHO) acceptable 0.5 mg/L limit. Ammonia levels ranged from 0.05 to 2.8 mg/L, highlighting significant concerns about toxicity in aquaculture waters (Nagaraju et al., 2023).

Duckweed's key advantage is that it withstands elevated levels of ammonium ions (NH_4^+), which are toxic to many plants, animals, and humans at elevated concentrations. Common duckweed (*Lemna minor*) has been shown to thrive at NH_4^+ levels as high as 84 mg/L. This ability to absorb and tolerate high NH_4^+ concentrations make duckweed ideal for treating wastewater from domestic, agricultural, and aquaculture sources, which often have high NH_4^+ due to urea breakdown and fertilizer runoff. Unlike most plants, duckweeds prefer NH_4^+ over nitrate (NO_3^-) as their nitrogen source, a trait first observed in *Landoltia punctata* (Tian et al., 2021) and later confirmed in several other duckweed species.

In China, a study shows that the initial concentrations of pollutants in the wastewater were 6.00 ± 0.09 mg/L TN (Total Nitrogen) and 0.56 ± 0.02 mg/L TP (Total Protein), worse than Grade V under the Chinese Surface Water Environment Quality Standard (CSWEQS). Pollutants were assessed every two days, and after 16 days, TN and TP levels in all four duckweed treatment systems dropped below 0.5 and 0.1 mg/L, respectively, improving the water to Grade II, suitable for protected drinking water sources. Duckweed removed over 70% of pollutants through uptake, alongside microbial conversion, sedimentation, and volatilization (Chen et al., 2018).

In India, this study evaluated the nutrient removal efficiency of *Lemna minor* (duckweed) in municipal, sewage, and seafood processing plant wastewaters at four dilutions: raw, 25%, 50%, and 75%. Duckweed was added at 0.6 kg/m², and water grade factors were measured weekly. The highest removal efficiency—96% NH_3-N—was observed in 25% dilution across all wastewater types. In municipal wastewater, *Lemna minor* removed NH_3, NO_2, NO_3, PO_4, BOD, and COD at rates of 96%, 98%, 98%, 96%, 79%, and 79%, respectively. This demonstrates duckweed's potential as a cost-effective natural tool for wastewater treatment, with reuse potential in agriculture and aquaculture (Selvarani et al., 2015). Before *Lemna minor* (duckweed) was introduced to cover at least 50% of the maturation ponds, baseline wastewater quality was measured weekly for three months in a study conducted in Zimbabwe. According to Zimbabwe's 2000 Waste and Effluent Disposal rules, the influent and effluent were evaluated monthly for bacteriological, physical, and chemical criteria. After five months, the emphasis switched to parameters over limits, such as turbidity, TDS, TSS, conductivity, BOD, iron, phosphates, nitrates, pH and turbidity. Most metrics showed significant reductions within allowable limits, although phosphates, BOD, COD, and turbidity still showed reductions of more than 60% (Dalu and Ndamba, 2003)

The ability of *Lemna minor* L. to lower sulfate and chloride in Biological Oxygen Treatment (BOT) effluent from a coke oven factory was the focus of this study, which investigated phytoremediation as an economical and environmentally beneficial way to remove toxins from wastewater. Physico-biochemical indices like pH, Total Dissolved Solids (TDS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and elemental concentrations were accounted for to assess the quality of the water. The findings showed that raising the pH enhanced the water quality. Duckweed demonstrated its phytoremediation capacity by removing 30% chloride, 16% sulfate, and 14% TDS from BOT wastewater. Furthermore, after 21 days, a maximum growth rate increase of 30% was noted, indicating that duckweed is a practical choice for treating coke oven plant wastewater (Saha et al., 2014).

Total dissolved inorganic nitrogen (T-DIN) levels of 20–50 mg/L in effluents were effectively reduced using 0.3–1.0 g/L of duckweed. *Spirodela polyrhiza* achieved the highest nitrogen removal rates (2.0–10.8 mg T-DIN/L/day) and biomass production (52.6–70.3 mg d.w./L/day) across municipal, swine, and anaerobic digestion effluents. Duckweed biomass from all effluents was used to produce ethanol and methane. *S. polyrhiza* and *Lemna punctata* exhibited greater ethanol (0.166–0.191 g/g-biomass) and methane (340–413 NL CH4/kg VS) production due to their higher carbon, starch content, and calorific values. So, it is a two-way benefit coming from the study (Toyama et al., 2017).

In a study (Zhao et al., 2014) adding a carrier had no notable impact on duckweed growth, composition, or the recovery of total nitrogen (TN), total phosphorus (TP), and CO2, nor on TP removal. However, it significantly increased the effectiveness of the elimination of TN and NH_4^+-N by 19.97% and 15.02%, respectively.

Considering morphological observations and 16S rRNA gene analysis, strain RWX31 was preliminarily identified as *Pseudomonas sp*. This strain is the first aerobic denitrifying bacteria, isolated from the rhizosphere of *Lemna minor* (duckweed) with the capability to reduce nitrate leaching. Bacterium RWX31 exhibited stable growth and efficient nitrogen removal, with a nitrate removal efficiency of 81.3% at an initial concentration of 140 mg/L NO_3-N. Under aerobic conditions, the maximum nitrate-N removal rates were 30.9 mg/L/h for nitrate, 24.3 mg/L/h for nitrite, and 11.5 mg/L/h for ammonium as sole nitrogen sources (Ying-Ru et al., 2013).

A thorough investigation of denitrifying bacteria linked to the duckweeds *Lemna minor* and *Spirodela polyrhiza* showed that particular fatty acid derivatives and stigmasterol—two essential constituents of duckweed cuticles—have an impact on the interactions between plants and microorganisms (Borisjuk et al., 2018). These substances activate the enzymes nitrate and nitrite reductases, which promote bacterial nitrogen metabolism. Furthermore, the chemical composition of duckweed root exudates was discovered to be influenced by the denitrifying rhizospheric bacterium *Pseudomonas sp.* RWX31, which specifically caused the release of stigmasterol. Consequently, stigmasterol changed the makeup of the rhizosphere's microbial community, which in turn encouraged the development of denitrifying bacteria (Lu et al., 2021; Lu et al., 2014).

Effective on herbicides, fungicides and weedicides:

As the demand for food rises and agriculture and aquaculture expands, large quantities of toxic agrochemicals like pesticides (Pathak et al., 2022; Tudi et al., 2021), herbicides (Ghazi et al., 2023; Barroso et al., 2023) and fungicides are produced and applied each year. Many of these chemicals enter aquatic environments untreated, putting immense strain on ecosystems. Herbicides frequently come into contact with aquatic organisms through multiple short-term pulses rather than prolonged exposure, making their ability to recover between exposures crucial in determining overall toxicity. The chosen organism must tolerate and metabolize the compounds at relevant concentrations for bioremediation. Most studies on duckweed's ability to absorb and tolerate agrochemicals have focused on *Lemna minor*.

Lemna minor (common duckweed) is widely used in environmental risk assessments. Studies have revealed that glyphosate accumulation in duckweed reduces growth, yield, chlorophyll and carotenoid synthesis, and PSII activity while increasing shikimic acid levels. Exposure to 20 µM of glyphosate also elevated ornithine decarboxylase activity fourfold and increased biogenic amines like tyramine and spermidine. Peroxidase and catalase activities peaked at 20 µM and 7 µM, respectively (Sikorski et al., 2019).

Prasertsup and Ariyakanon (Prasertsup and Ariyakanon, 2010) demonstrated that duckweed effectively removes chlorpyrifos (CPF) from water in laboratory greenhouse conditions, advocating its capacity for mitigating ecological risks coupled with the release of 14C-CPF-BR in aquatic environments. Additionally, another study (Li et al., 2018) identified 2–OH-TCP as the 14C-radioactivity absorbed by duckweed from water. The bio-concentration factor (BCF) for 14C-TCP in duckweed enhanced with prolonged exposures, indicating duckweed's ability to absorb and accumulate 2-OH-TCP, likely aided by its fine, long roots.

A study assessed the toxicity of the herbicides MCPA (an auxin-like growth inhibitor) and chloridazon (CHD, a PSII inhibitor), as well as their mixtures, on floating plants and planktonic algae. Using two-way ANOVA and Abbott's formula, the researchers found that MCPA and chloridazon showed an antagonistic interaction with *Lemna minor*, while their joint impact was additive for *Desmodesmus subspicatus* (Bisewska et al., 2012). Other agrochemicals also impact aquatic plants. For instance, a research team (Yilmaz et al., 2021) investigated the effects of the insecticide zeta-cypermethrin on duckweed growth and bioremediation. Low concentrations (150 µg/L) of zeta-cypermethrin boosted development, while greater concentrations (300–600 µg/L) were toxic. According to the initial concentration, *L. minor* removed between 35.4% and 95.9% of the insecticide. Another study demonstrated that *L. minor* effectively cleans water contaminated with terbuthylazine, with its efficiency enhanced by biostimulants like Megafol or safeners like benoxacor (Panfili et al., 2018).

L. minor has proven to be a highly effective macrophyte for phytoremediation organic pollutants (Walsh et al., 2024; Mohedano et al., 2012). In some cases, it outperformed traditional wastewater treatment facilities, achieving a 94.45% reduction in BOD and a 79.39% reduction in phosphate, compared to the 50% reduction achieved by primary and secondary treatments (Priya et al., 2011) Besides, *L. minor*'s ability to remove and metabolize 4-chloro-2-fluorophenol (4-Cl-2-FP) (Tront & Saunders, 2007) finding that over 95% of the compound was metabolized within 77 hours, with less than 10% remaining in the plant has been confirmed (Reinhold, 2007).

Research has also explored duckweed's remediation potential against various agrochemicals. When there held a comparative study regarding the remediation efficiency of three macrophytes (*L. minor*, *Elodea canadensis*, and *Cabomba aquatica*) exposed to two fungicides (dimethomorph and copper sulfate) and a herbicide (flazasulfuron). *L. minor* proved the most successful at removing pesticides, with copper sulfate and dimethomorph being more bioavailable to macrophytes than flazasulfuron (Dosnon-Olette et al., 2009). Further studies on two duckweeds including *L. minor* and *S. polyrhiza*, noticed that both species were 10 times more effective at removing dimethomorph and pyrimethanil than the other macrophytes tested, with dimethomorph showing a higher removal rate (Dosnon-Olette et al., 2010).

Additionally, much research has looked into how duckweed reacts to various insecticides, individually or in combination. These include metolachlor, atrazine, metribuzin, lactofen, linuron, monolinuron, diuron, 2,4-D, alachlor, paraquat, propanil, and others, focusing on their removal rates and the plant's sensitivity to these chemicals (Rice et al., 1997; Mitsou et al., 2005; Gatidou et al., 2014; Wang et al., 2016; Tagun & Boxall, 2018; Kostopoulou et al., 2019).

In some instances, *L. minor* is less effective than other species, such as *S. polyrhiza*, when exposed to the metazachlor herbicide (Muller et al., 2010). However, *L. minor* demonstrated better atrazine adaptation than *M. aquaticum* (Teodorovic et al., 2011). While *L. minor* often outperforms *S. polyrhiza*, the roots of its selected accumulation of agrochemicals remain unclear. The distribution of duckweed species may confer advantages, but further research is needed on its behavior with various agrochemicals. For example, the limited uptake of compounds like lactofen, isoproturon, and glyphosate calls for more detailed investigation.

Heavy metals:

Water polluted by contaminants like heavy metals has become a significant global environmental issue, posing severe risks to human health and aquatic ecosystems. The growth of urban areas, changes in the climate, and industry are the primary contributors to an upsurge in heavy metal pollution. Key sources encompass municipal and industrial wastewater, city runoff, landfill leachates, mining waste and natural events like volcanic eruptions, weathering, and rock erosion (Thakur et al., 2021; Das et al., 2022). Heavy metal ions are toxic, potentially carcinogenic, and capable of bioaccumulating in living organisms. Even at low exposure levels, damages occur in the lungs, nervous system, liver, stomach, skin, reproductive systems, and kidneys. In response, more research is being done on effective ways to remove heavy metals from wastewater. Nevertheless, while some approaches are practical, their high preparation and operational costs may limit widespread use (Aziz et al., 2023).

Among the many technologies developed to tackle this issue, phytoremediation is an eco-friendly and low-cost biotechnology solution.

One of the most hazardous heavy metals is copper (Cu), which is categorized as a trace element (Bha et al., 2022; Tchounwou et al., 2012). Cu typically originates in wastewater from sources such as instruments, electroplating, glass, metal, ceramics, and plumbing (Van Schaik and Reuter, 2014).

The release of hazardous heavy metal-containing industrial effluents has a harmful effect on aquatic ecosystems. It threatens the survival of organisms, which disrupts the food chain and poses risks to human health (Singh et al., 2022). Therefore, efficient methods for treating wastewater containing heavy metals are essential.

A study conducted showed the removal of copper (Cu) from contaminated water by two floating plant species, *Azolla filiculoides* and *L. minor*, was studied under varying Cu (II) concentrations (0.25–1.00 mg/L) and sampling times (Days 0, 1, 2, 5, and 7). Both species demonstrated the ability to remove Cu at a concentration of 1.00 mg Cu/L, with *A. filiculoides* achieving a 100% removal rate and *L. minor at* 74% by the fifth day. *L. minor* experienced both growth inhibition and morphological damage, including shrinkage of its internal structure, due to higher Cu accumulation in *L. minor* (2.86 mg/g) compared to *A. filiculoides* (1.49 mg/g) (Al-Baldawi et al., 2012).

Plant diversity is vital for ecosystem productivity and stability, but mechanisms behind resilience in harsh conditions are not fully understood. In another study examined how *Lemna aequinoctialis* and *Spirodela polyrhiza* respond to copper stress (1.0 mg/L) and low temperatures (5°C) when grown alone or together. At 25°C, both species grew similarly, but *L. aequinoctialis* grew 55.5% faster in co-culture with *S. polyrhiza* under high copper. *S. polyrhiza* accumulated more copper in cell walls, reducing copper toxicity for *L. aequinoctialis*. Low temperatures heightened copper toxicity, reducing growth and photosynthesis, but co-culture improved *L. aequinoctialis*'s growth and photosynthetic activity through metal compartmentalization and increased biomass (Shi et al., 2020).

Aquatic macrophytes can bioaccumulate toxic metals from wastewater, making them valuable for use in phytoremediation.

The bioaccumulation of four heavy metals—Cr, Cu, Pb, and Zn—in *Lemna gibba* (duckweed) was analyzed to assess its potential as an environmental indicator of contaminated industrial wastewater. A previous study (Hegazy et al.,2009) found that *L. gibba* bioaccumulated Zn most, followed by Cr, Pb, and Cu, with respective bioaccumulation factors of 13.9, 6.3, 5.5, and 2.5. Heavy metal buildup led to frond color changes from green to pale green and eventually degreened. As metal accumulation rose, chlorophyll a levels fell, chlorophyll b increased, and carotenoid content surpassed combined chlorophyll levels, especially in pale green fronds. Zinc had the most substantial negative impact on chlorophyll, while Cr and Cu correlated positively with carotenoids. This visible color change and high metal accumulation highlight *L. gibba*'s potential for phytoremediation and bioindication.

Lead (Pb) is one of the most hazardous environmental contaminants. A recent study evaluated *Lemna gibba* as a bioaccumulator and bioindicator of Pb pollution, studying its Pb re-release and pigmentation recovery over 12 days. Duckweed was exposed to PbCO3 (10–100 mg/L), with bioaccumulation, removal efficiency, and pigment recovery assessed every two days. At 10 mg/L, Pb removal efficiency reached ~50% after 12 days but decreased at higher Pb concentrations. The highest bioconcentration factor (BCF) was 943 mg/L at 10 mg/L Pb exposure. Pigment recovery was ~50% in plants exposed to 10–40 mg/L, indicating *L. gibba*'s potential as a Pb biosensor due to active Pb uptake (Hegazy et al.,2017).

The ability of *Lemna minor* to absorb Cr (VI) under ideal nutritional circumstances was investigated in this work. Over seven days, the plant's uptake of chromium was estimated at different amounts. *Lemna minor*, which was harvested every 24 hours for five days, shown no toxicity in a time-course experiment with 3 mg/L chromium. Atomic absorption spectroscopy was employed to assess the buildup of chromium. As chromium concentration rose, plant growth and chlorophyll content fell. The bio-concentration factor (BCF) declined with increasing doses, while the maximum absorption (5.8×10^3 µg/g) was attained at 8 mg/L. At 3 mg/L, the BCF was 1000. By the third day, growth and chromium accumulation had peaked (3119 µg/g), suggesting that *Lemna minor* is a potent chromium accumulator that can be exploited to remove Cr (VI) from waterways (Thayaparan et al., 2015).

Exposure to metal concentrations beyond physiological tolerance limits triggers antioxidant enzyme activity, as well as proline and organic acid synthesis in duckweeds, helping them mitigate metal toxicity. Metal tolerance among different duckweed species varies depending on environmental water conditions, including pH, temperature, electrical conductivity, and the types and concentrations of metals present. The concentration and duration of exposure primarily influence duckweed's metal uptake and bioaccumulation potential (Ali et al., 2015).

Recent research (Rezania et al., 2016; Mustafa and Hayder, 2020) found that among four species of free-floating macrophytes—*Pistia stratiotes*, *Eicchornia spp*., *Lemna spp*., and *Salvinia spp*.—*Pistia stratiotes* demonstrated the highest potential for phytoaccumulation. Similarly, another study (Badr El-Din and Abdel-Aziz, 2018) established that aquatic plants such as duckweed, water hyacinth, and green algae effectively reduced water quality indicators in wastewater to levels suitable for irrigation. In this study, duckweed outperformed water hyacinth and green algae in nutrient uptake. Additionally, it has been concluded effluent treatment plants (ETP) that use biological methods over chemical methods are preferred due to lower inorganic sludge production, reduced operating costs, and the complete mineralization/stabilization of dyes through biological processes

In a study using a 3:1:18 mix of textile, distillery, and domestic wastewater, *Lemna minor* and *Azolla filiculoides* treated the water over 28 days (Holkar et al., 2016). Both macrophytes met reuse and discharge limits for electric conduction, total dissolved solids, heavy metals, pH and sulfate. *A. filiculoides* removed 96% of chemical oxygen demand, slightly higher than *L. minor* (92%), while *L. minor* achieved greater biochemical oxygen demand removal (92% vs. 90%). Phosphorus, nitrogen, and fecal coliforms exceeded limits, with counts of 400 for *L. minor* and 267 for *A. filiculoides*. Both plants significantly improved wastewater quality compared to the control (Amare et al., 2018).

In another study, it assessed the toxic and genotoxic effects of surface water samples on duckweed using growth parameters and biomarkers like pigment content, peroxidase activity, lipid peroxidation, and alkaline comet assay. Water samples were brought monthly for three months from three sites along the Sava River and its confluent (Croatia), with physicochemical tests measuring conductivity, oxygen demand, suspended solids, nitrates, and other nutrients. Surface water samples reduced duckweed growth, chlorophyll, carotenoids, and peroxidase activity, increasing lipid and DNA damage, especially from industrial wastewater. The results highlight duckweed's sensitivity and value as a water quality indicator (Radić et al., 2011).

Although microplastics (1–1000 μm) are ubiquitous in many settings, their impact on freshwater plants is not well understood. According to this study, on the surface of *Lemna minor*, 10–45 μm polyethylene microplastics adsorb at concentrations of up to 7 particles/mm2, yet they had no influence on growth or photosynthesis after seven days. However, because the freshwater amphipod *Gammarus duebeni* consumed microplastics by feeding on contaminated *L. minor*, with no immediate consequences on mortality or mobility, *L. minor* may spread microplastics along the food chain. This emphasizes the role of trophic transmission and plant adsorption in the environmental fate of microplastics (Mateos-Cárdenas et al., 2019; Das et al., 2023).

The impacts and adherence of two natural particles (cellulose and wood dust) and three types of microplastics (polyethene microbeads, tyre wear particles, and polyethene terephthalate fibres) on *L. minor* were investigated in this study. The findings indicated that microbeads and tyre wear particles considerably shortened the root length of duckweed and fibres, and natural particles and did not affect the plant's growth rate, chlorophyll content, or root length. Specific adhesion was demonstrated by the ten-fold higher rate of attachment of polyethylene microbeads to duckweed compared to other particles. Duckweed may be useful for biomonitoring microplastic pollution because polyethylene microplastics are common in freshwater (Rozman and Kalčíková, 2022).

Technological innovations and metal extraction:

This study lays the groundwork for using ionic liquids (ILs) to pretreat duckweed biomass, leveraging its properties for efficient metal removal (Sekomo et al., 2012), starch accumulation (Cui et al., 2011) and protein recovery. Two ILs, dimethyl ethanol ammonium formate ([DMEtA][HCOO]) and N, N-dimethyl butyl ammonium hydrogen sulfate ([DMBA][HSO_4]), were tested on *Spirodela polyrhiza* and *Lemna minor* for starch recovery (Xu et al., 2011), sugar release, protein recovery, and metal extraction. [DMEtA][HCOO] achieved near-complete starch recovery at 120°C, while [DMBA][HSO4] performed similarly at 90°C, both within 2 hours. Saccharification yields surpassed 90% after 8 hours, outperforming traditional biomasses. Protein solubilization was 50% in [DMEtA][HCOO] and 80% in [DMBA][HSO_4], though the low molecular weight of solubilized protein prevented recovery. [DMEtA][HCOO] was more effective for metal extraction, removing 81% of nickel from *Lemna minor*, compared to 28% with [DMBA][HSO_4]. Further optimization is needed for simultaneous metal extraction using ILs (Firth et al., 2024).

The latest study (Rai et al., 2024) gave an account of the eco-sustainable use of duckweed (*Landoltia* and *Lemna*) for phytoremediation of metallic contaminants in wastewater. Duckweed bioreactors primarily rely on phytoextraction and rhizofiltration, influenced by physico-chemical factors and plant-microbe interactions. Gene manipulation could enhance this process. The high starch and protein content of metal-contaminated duckweed makes it a valuable feedstock for biorefineries, supporting bioenergy (Xu et al., 2012; Chen et al., 2012), value-added products, and biofertilizers. Integrating duckweed-based phytoremediation with biorefineries can promote a circular economy and contribute to Sustainable Development Goals (SDGs).

Future outlook of duckweeds as a wastewater-manager:

Owing to their high nutrient intake, resilience in a variety of environments, and quick development, duckweeds—especially *Lemna* species—hold great potential for the treatment of wastewater in the future.

Duckweed absorbs phosphorus as phosphate ions and nitrogen as nitrate and ammonium ions during wastewater treatment. It works just as well as traditional therapy techniques, and in certain situations, better.

In addition to efficiently removing heavy metals, organic contaminants, and even certain microplastics from wastewater, these aquatic floras are likewise capable of absorbing nutrients like phosphate and nitrogen. Duckweed lowers these contaminants to levels that can considerably lessen their detrimental effects on aquatic habitats through nutrient uptake and accumulation.

Future studies aim to improve duckweed species and growing conditions for increased biomass output, pollutant uptake, and wastewater type adaptation. Furthermore, duckweed can flourish in various environments and be used in various water systems, including municipal wastewater and industrial effluents.

The environmental and financial advantages of collected duckweed biomass can also be increased by using it to make biofuel, animal feed, or biofertilizer. Incorporating duckweed systems into wastewater treatment plants is a sustainable and affordable way to enhance water quality and promote circular economy goals.

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