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Duckweed as a Circular Economy Solution for Treating Agro-Industrial Wastewaters

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ABSTRACT

Water pollution resulting from nutrient-rich wastewater (WW) discharged by industries such as distilleries, sugar mills, and dairy farms poses significant ecological and public health challenges. Conventional treatment methods often fail to effectively reduce nutrient loads, contributing to environmental degradation. This review critically examines the use of duckweed (Lemna spp.), a fast-growing aquatic plant, as a sustainable solution for wastewater remediation. Duckweed demonstrates a high capacity for nutrient uptake, particularly nitrogen (N) and phosphorus (P), while simultaneously producing protein-rich biomass suitable for animal feed. The review synthesizes findings on the effectiveness of duckweed-based systems in reducing chemical oxygen demand (COD) and biological oxygen demand (BOD), and explores their integration into circular economy models that couple wastewater treatment with resource recovery. Additionally, it addresses current limitations in system design, scalability, and long-term implementation, highlighting areas requiring further research. Overall, duckweed-based wastewater treatment offers a cost-effective, eco-friendly strategy to enhance environmental sustainability and food-feed security.

INTRODUCTION

Water is vital for all life-sustaining activities, and the adage "no life without water" emphasizes its universal importance. Water can be sourced from natural reservoirs such as rivers, lakes, ponds, and wells. The anthropogenic activities and external factors often compromise its quality, necessitating treatment before use for drinking or other purposes (Katko 2017). The increasing demand for water in domestic, agricultural, industrial, and commercial sectors highlights the importance of maintaining its quality. Industrial activities, while consuming relatively small quantities of water, significantly impact its quality, often discharging untreated effluents into surface and groundwater systems (Wang & Yang 2016). Domestic sewage and industrial effluents, which constitute over three-quarters of the freshwater drawn, profoundly influence the degradation of water quality (Mukherjee et al. 2006). Wastewater is adversely affected by human use, making it unfit for direct consumption or discharge into the environment without treatment. It typically originates from domestic, industrial, agricultural, or commercial activities and contains a broad spectrum of pollutants, such as nutrients, organic matter, pathogens, heavy metals, chemicals, and suspended solids (Musa Yahaya et al. 2023). This poorly treated WW poses numerous health, environmental, and ecological risks. It can lead to eutrophication, ecological damage, and severe health consequences, particularly in areas with inadequate wastewater management (González-Mariño et al. 2016, Wang & Yang 2016).

This issue is exacerbated by population growth, rapid urbanization, and the increasing demand for water in food production, which relies on water for nearly

40% of the global food supply (Department of Environmental Engineering 2015). As global water quality management struggles to keep pace with these challenges, innovative and cost-effective solutions are critical to resolve the limitations of conventional WW treatment systems (Saha et al. 2017, Sharifinia et al. 2016). Duckweed (Lemna spp.) (Fig.1) has been found to be a promising, eco-friendly alternative for WW treatment. Its ability to thrive on various wastewater sources—including municipal, industrial, and agricultural effluents such as dairy, sugar, and distillery wastewater—makes it a cheap and justifiable resolution for nutrient recovery and pollution mitigation (Cheng et al. 2002, Landesman et al. 2005). It effectively removes N and P and lessens BOD and COD in wastewater (Jadhav et al. 2024).

Furthermore, its nutrient-rich biomass, with a protein content of 15–45% dependent on progress conditions, can be repurposed as animal feed or bioenergy, creating a circular economy (Chantiratikul et al. 2010, Culley Jr, & Epps 1973). This article emphasizes the application of duckweed in WW treatment and its potential to address environmental and economic challenges associated with traditional methods. It explores duckweed's nutrient removal efficiency, protein content variability based on wastewater characteristics, and its scalability for diverse wastewater sources. The review also highlights the need for further research to optimize duckweed-based systems, emphasizing their cost-effectiveness and sustainability for community-level implementation.

MATERIALS AND METHODS

This review followed a systematic screening approach. A total of 137 articles were identified from databases such as PubMed, Web of Science, and Scopus. After removing duplicates and applying inclusion criteria (industrial wastewater characterization, duckweed application), 58 studies were included.

Fig. 1: Top-view photograph of *Lemna minor* cultured in nutrient medium under controlled laboratory conditions.

The inclusion criteria: i) Articles based on the characteristics, challenges, and case studies of industrial wastewater. It also included Duckweed applications, nutritional compositions, and the mechanism of pollutant removal. ii) This paper also explored operational challenges, research gaps, and future investigation.

The exclusion criteria: Articles lacking specifics on the other natural plant strategy for pollutant removal, and domestic sewage were excluded.

Characterization of Industrial Wastewaters

Dairy, sugar, and distillery industries generate wastewater rich in organic matter, nutrients, and sometimes toxic compounds. Dairy wastewater typically contains lactose, fats, proteins, and detergents, contributing to high BOD and COD. Duckweed has shown up to 90% efficiency in nutrient removal from such effluents. Sugar industry wastewater includes organic acids and high salinity, often treated with duckweed species like Lemna gibba, achieving 75–80% BOD and COD reduction. Distillery wastewater is highly polluting due to melanoidins and phenolics. Duckweed treatment systems have achieved up to 85% BOD removal and significant reductions in color and toxicity. Duckweed's role in these sectors combines simplicity, cost-effectiveness, and biomass generation potential, making it a scalable phytoremediation option (Fenandes et al. 2023a).

Dairy Wastewater (DWW)

DWW typically comprises maximum levels of organic matter, nutrients as mentioned earlier, and suspended solids. It arises from processes such as milk processing, cleaning, and sanitizing operations (Botondi et al. 2023). The main components of DWW include lactose, proteins, fats, and minerals, which contribute to its high BOD and COD values. The high BOD and COD can significantly impact aquatic ecosystems if discharged untreated (Kolev Slavov 2017). The presence of these organic compounds poses significant challenges for treatment, as they require efficient removal to prevent environmental contamination (Ting & Praveena 2017). Biological treatment methods, including aerobic and anaerobic digestion, have been extensively researched for their efficacy in degrading organic matter in dairy wastewater (Dereli et al. 2012). However, these methods frequently face restrictions related to operational stability as well as efficiency under varying load conditions (Gao et al. 2011). To overcome these limitations, the duckweed plant plays an important part in the treatment of dairy wastewater (Zhou et al. 2023a).

Multiple recent studies have highlighted the potential of duckweed in managing DWW due to its ability to assimilate higher concentrations of nutrients and organic matter. Duckweed systems offer advantages such as low operational costs, ease of maintenance, and the production of valuable biomass (Chen et al. 2020, Xu et al. 2023). Several studies have demonstrated the effectiveness of duckweed in treating DWW. For example, Muradov et al. (2014) examined the usage of *Lemna minor* in a pilot-scale treatment for dairy wastewater. The results displayed that duckweed could achieve over 90% effluent of N & P, significantly reducing the nutrient load of the treated effluent.

Additionally, the duckweed biomass produced during the treatment process was found to have high protein content, making it appropriate for animal feed (Muradov et al. 2014). Sreehari et al. highlighted this plant's potential in eliminating organic matter and nutrients from DWW. Researchers reported that duckweed-based systems achieved significant reductions in BOD and COD values, with removal efficiencies exceeding 80%. The treated effluent met the discharge standards set by regulatory authorities, demonstrating the feasibility of duckweed for dairy wastewater treatment (Sreehari et al. 2017). *El-Sheekh et al*. further confirmed the effectiveness of duckweed in DWW treatment. The study showed that duckweed could effectively remove nutrients and organic matter from dairy effluents, with removal efficiencies comparable to conventional treatment methods. The harvested biomass was analyzed for its nutritional composition and found to be rich in proteins and other essential nutrients, making it a valuable feedstock for animal feed production (El-Sheekh et al. 2019). These studies have demonstrated its effectiveness in removing various pollutants (Hemalatha & Venkata Mohan 2022). The phytoremediation performance of duckweed is particularly effective in diluted wastewater, with removal efficiencies reaching up to 87% for phosphorus and 65% for nitrogen (Sahi & Megateli 2023) and effectively removing 74% of organic carbon from dairy wastewater.

- The duckweed biomass grew significantly over time, with an amplifying time of 0.87 days and a final dry weight of 3.73 g.
- The pretreated duckweed biomass was used as a substrate for microbial protein production using *Bacillus subtilis*, resulting in a high protein content (60%) and carbohydrate content (21%) in the final microbial protein product.

Sugar Industry Wastewater (SWW)

It poses significant environmental threats if discharged untreated (Malik et al. 2019). The wastewater generation rate is approximately 1,000 L per ton of sugarcane crushed in India. Various treatment methods have been explored, including aerobic, anaerobic, and physico-chemical processes (Kushwaha 2015). The wastewater contains significant amounts of organic and inorganic materials. These complexes contribute to the high organic load and make it challenging to treat using conventional methods (Sahu et al. 2008). Anaerobic digestion and aerobic treatment processes are commonly employed for treating sugar industry wastewater, but they often require extensive infrastructure, high operational costs, and limitations in degrading oil and grease (Dahiya et al. 2001, Pant & Adholeya 2007).

Additionally, the presence of refractory compounds and high salinity levels can inhibit microbial activity, reducing treatment efficiency (Mohana et al. 2009). Advanced treatment includes filtration, flocculation, UV disinfection, etc (Yadav et al. 2021). Batch reactor studies have shown that the wastewater is amenable to aerobic biodegradation. The quality and features of SWW depend on the region and water consumption practices (Ahmad & Mahmoud 1982). The water pinch methodology has been proposed to minimize fresh water consumption in sugar industries (Poddar & Sahu 2017).

Duckweed-based treatment systems have shown promise in effectively removing organic matter and nutrients from sugar industry wastewater (Patel et al. 2017, Verma & Suthar 2015). Duckweed's rapid growth rate and nutrient uptake ability make it an ideal candidate for bioremediation, offering an alternative option to traditional treatment methods (Leng 1999). The application of duckweed in treating sugar industry wastewater has also been explored. Patel et al. (2017) discovered research on the treatment of sugar mill effluent using duckweed species such as *Lemna gibba* and *Spirodela polyrhiza* (Cheng et al. 2002). The study reported significant reductions in COD and BOD, with removal efficacies of up to 80%. The treated effluent met the discharge standards set by regulatory authorities, highlighting the prospect of duckweed-based systems for industrial wastewater treatment (Patel et al. 2017). Ali et al. (2016) investigated the usage of duckweed for the management of SWW from a sugar refinery. The results showed that duckweed could achieve substantial reductions in organic matter and nutrient concentrations, with removal efficiencies exceeding 75%. The researchers also highlighted the economic benefits of using duckweed, as it provided a low-cost and sustainable treatment option (Ali et al. 2016). Further research by Kumar et al. (2020) demonstrated the potential of duckweed in treating wastewater from sugarcane processing. The study reported that duckweed-based systems could effectively reduce BOD, COD, and nutrient levels, with removal efficiencies comparable to conventional treatment methods. The harvested biomass was analyzed for its nutritional composition and found to be suitable for use as animal feed (Kumar et al. 2020).

Distillery Wastewater

Distillery wastewater is the effluent generated during the production of alcoholic beverages such as ethanol, whisky, beer, and spirits from the fermentation of sugars. It is one of the most polluting wastewaters, which offers characteristics such as:

Distillery wastewater poses significant environmental hazards, leading to issues such as eutrophication. This process adversely affects human health and disrupts the flora and fauna in water bodies. Molasses-based wastewater contains toxic substances such as melanoidins, phenolics, and heavy metals, which cause hazards to human health, animals, and ecosystems. (Kumar et al. 2020). The presence of phenolic compounds and other toxic substances further complicates the treatment process. Hence, there is a need for effective treatment methods that are critical due to these environmental concerns (Raj et al. 2020). Traditional treatment methods, such as anaerobic digestion, aerobic treatment, and physicochemical processes, are used to manage distillery wastewater (Pant & Adholeya 2007, Satyawali & Balakrishnan 2008). Though these methods often face challenges related to high operational costs, sludge generation, and the inability to completely remove color and refractory compounds (Kumar et al. 2019).

Duckweed's ability to treat distillery wastewater has been highlighted in several studies. Kumar et al. (2017) evaluated the performance of *Spirodela polyrhiza* in treating distillery effluent in a laboratory-scale experiment. The results indicated a lessening of COD and BOD, along with the removal of phenolic compounds. The duckweed biomass harvested from the treatment system was analyzed for its nutritional composition and found to be rich in proteins and other essential nutrients, suggesting its potential use as animal feed (Kumar et al. 2019). Joshi et al. (2017) investigated the use of duckweed sewage treatment from a molasses-based distillery. The study reported significant reductions in organic matter and color, with removal efficiencies

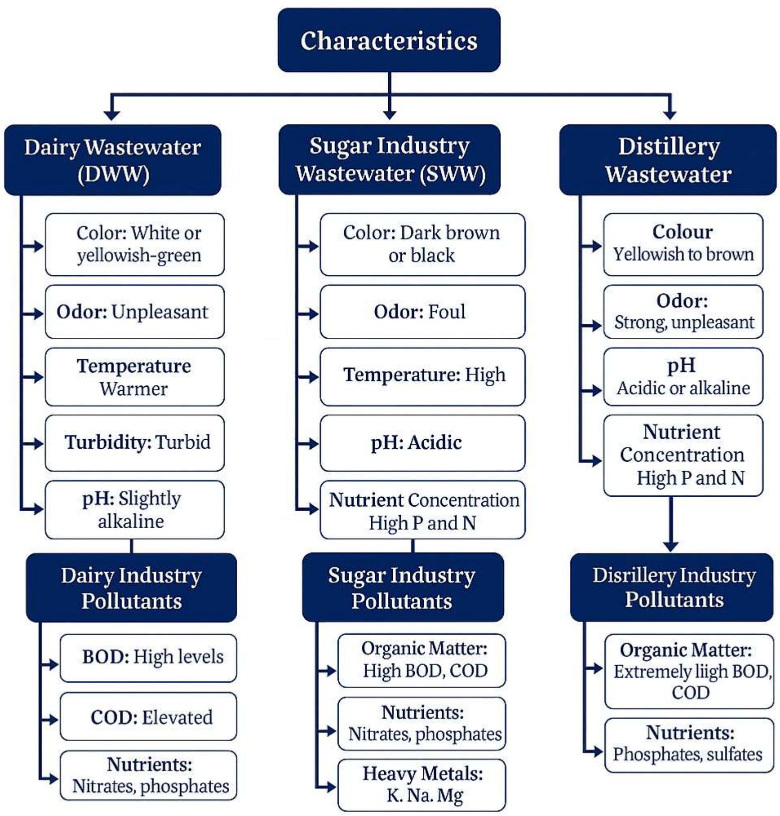


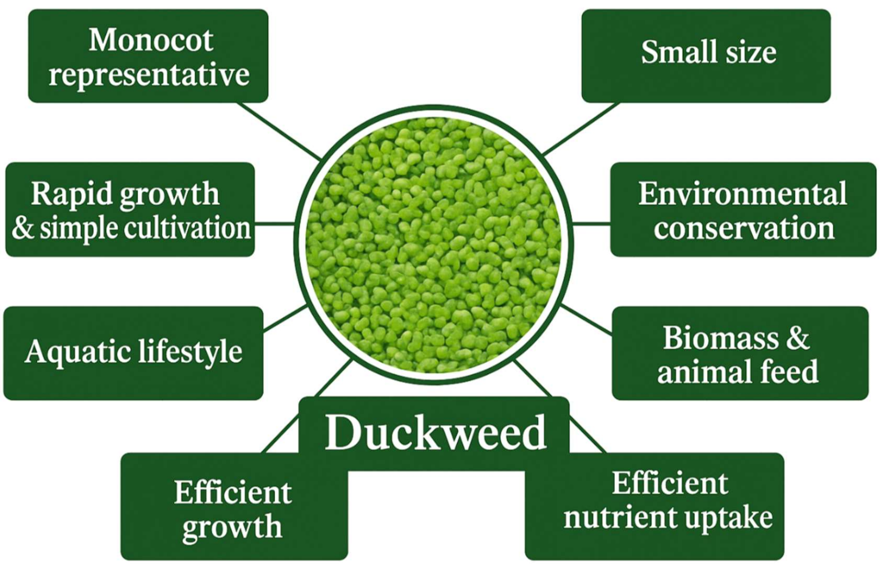
Fig. 2: Comparative physicochemical characteristics and major pollutants found in dairy (DWW), sugar industry (SWW), and distillery wastewater (DStWW).Source: Own creation based on compiled data from Kolev Slavov (2017), Malik et al. (2019), Kumar et al. (2020), Shashikanth et al. (2019), Fito et al. (2019), Ahmad and Mahmoud (1982), Sahu et al. (2008).

exceeding 80%. The treated effluent met the discharge standards set by regulatory authorities, demonstrating the feasibility of duckweed for distillery wastewater treatment (Joshi et al. 2017). Singh et al. (2015) further confirmed the effectiveness of duckweed in distillery wastewater treatment. The researchers reported that duckweed could substantially reduce BOD, COD, and phenolic compounds, with removal efficiencies comparable to conventional treatment methods. The harvested biomass was analyzed for its nutritional composition and found to be suitable for use as animal feed (Singh et al. 2015).

Duckweed Treatment Mechanism

Growth characteristics and nutrient uptake: Lemnaceae, the official name for duckweed (genus Lemna), are monocots (like grasses and palms) that are classified into five genera: Landoltia, Wolffiella, Spirodela, Lemna, and Wolffia (Asolekar et al. 2014, Thingujam et al. 2024). It floats on the surface of still-moving lakes, ponds, and sloughs and is no longer than ¼ of an inch. It exhibits rapid growth, with some species capable of doubling their biomass in just a few days under optimal conditions (Fig. 2). Duckweed is highly efficient in nutrient uptake, particularly nitrogen and phosphorus, making it an excellent candidate for wastewater treatment (Xu et al. 2023). It can thrive in varied environmental conditions, further enhancing its potential for use in wastewater treatment (Cheng et al. 2002, Culley Jr & Epps 1973, Hillman & Culley 1978). Duckweed's high nutrient uptake capacity is attributed to its physiological characteristics, including a high surface area-to-volume ratio and efficient nutrient transport mechanisms (Landolt & Kandeler 1987, Leng 1999). Duckweed can absorb nutrients directly from the water column, assimilating them into its biomass and reducing the nutrient load in the wastewater (Verma & Suthar 2015). In high-strength swine wastewater, Cheng & Stomp (2009) found that *L. minor* grew at a rate of about 29 $gm.^{-2}.day^{-1}$, but duckweed absorbed 90% of the total Kjeldahl Nitrogen (TKN) and 88.6% of the total Phosphorus (TP) (Cheng & Stomp 2009). Another study revealed the phosphorus uptake of 13 to 58 mg P m^{-2} d^{-1} and found that phosphorus uptake by duckweed was dependent on nitrogen concentration and the depth of the growth pond (Landolt & Kandeler 1987). Typical duckweed can have protein concentrations of up to 45% of its dry bulk. The gathered duckweed has a high protein content, making it a viable food source for animal and human feed (Iqbal et al. 2019).

Duckweed mechanisms of pollutant removal: Duckweed is highly effective in removing pollutants from water through various mechanisms, as supported by extensive research. These mechanisms include direct assimilation of nutrients into its biomass, microbial degradation of organic compounds in the rhizosphere (root zone), and sedimentation of particulate matter. The floating mat of duckweed also helps reduce light penetration, thereby limiting the growth of algae and other phototrophic organisms (Zhao et al. 2020, 2014). Duckweed root-associated microbial communities are essential for the breakdown of organic materials and the conversion of nutrients. These microbial processes enhance the whole pollutant removal efficacy, making duckweed-



Source: Own creation, adapted from Coughlan et al. (2022), Xu et al. (2023), and Zhou et al. (2023a).

Fig. 3: Key characteristics of duckweed (*Lemna* spp.).

based systems highly effective for wastewater treatment (Landesman et al. 2005).

Research has demonstrated the effectiveness of duckweed in eradicating a wide range of contaminants (Muradov et al. 2014). The combination of direct nutrient uptake, microbial degradation, and physical filtration makes duckweed a versatile and efficient biological treatment agent. Duckweed enhances organic matter degradation through oxygen supply and provides an exterior for bacterial growth, leading to substantial N and P removal (Körner et al. 2003). The growth rates of various *L. Minor* species vary, influencing their efficiency in wastewater treatment (Khare et al. 2021). Duckweed is an effective tool for phytoremediation of wastewater, capable of removing nutrients and pollutants like nitrate, phosphate, BOD, and ammonia with high efficiency (Frédéric et al. 2006). Duckweed is easy to harvest and has a high protein content, making it a valuable byproduct of the phytoremediation process. - Duckweed-based systems can remove 73-97% of nitrate and 63-99% of phosphate, as well as 96% of BOD and 99% of ammonia within 3 days (Gupta & Prakash 2013). These mechanisms collectively enable duckweed systems to achieve 85–95% pollutant removal efficiency**,** making them a cost-effective solution for wastewater treatment, eutrophication control, and phytoremediation.

Case Studies and Comparative Analysis

Nutritional composition of duckweed: The most successful decades for research on duckweed as a protein source were the 1970s and 1980s (Cheng & Stomp 2009), making it a fantastic option for animal feed. It contains 20–40% protein on a dry weight basis (Hughey 1995), with a high-quality amino acid (AA) profile comparable to soybean, including vital AAs like lysine, methionine, and tryptophan, which are vital for animal growth (Appenroth et al. 2018). Duckweed also provides 4–7% lipids, including omega-3 and omega-6, which improve animal health and product quality, such as enriched eggs or milk. Its carbohydrate content ranges from 25–35%, serving as a reliable energy source, while its 5–15% fiber aids digestion (Sońta et al. 2019, Xu et al. 2023). Additionally, it is rich in vitamins (A, B-complex, and C) and minerals like calcium, phosphorus, potassium, and magnesium, and trace elements such as zinc and iron (Pagliuso et al. 2022). Duckweed also contains beneficial phytochemicals like polyphenols and flavonoids, which offer antioxidant benefits. With low levels of anti-nutritional factors, it is highly digestible and suitable for various animals. The possible uses of duckweeds in aquaculture and animal feed may be affected by the presence of carotenoids such as lutein, astaxanthin, and β-carotene (Zhao et al. 2020). It is widely used in livestock, including poultry, fish, and ruminants, and in aquaculture. Duckweed also supports sustainable farming practices due to its rapid development, minimal land requirements, and ability to utilize nutrients from wastewater (Coughlan et al. 2022). Appenroth et al. have shown duckweed's nutritional worth as animal feed. The research reported that its biomass contains major amounts of protein, fiber, and essential nutrients, making it a suitable feedstock for poultry and fish. The researchers also highlighted the environmental benefits of using duckweed as feed, as it reduces the reliance on conventional feed ingredients and promotes sustainable agriculture (Appenroth et al. 2018). Cheng & Stomp (2009) explained that the grown duckweed can be used to make value-added products such as fuel ethanol and animal feed, and it can also be a good source of proteins and carbs. When yeast was used to ferment the hydrolysate, 25.8% of the initial dry duckweed biomass was converted to ethanol. According to these findings, duckweed biomass can yield sizable amounts of starch that are easily transformed into ethanol (Cheng & Stomp 2009).

Processing techniques: Processing techniques are crucial for converting duckweed biomass into safe, nutritious, and cost-effective animal feed while minimizing waste and maximizing sustainability (Ujong et al. 2025). Steps such as drying, grinding, and pelletizing enhance feed quality by preserving nutrients, reducing moisture content to prevent spoilage, and transforming raw biomass into a uniform, easy-to-consume format that reduces wastage. Additional methods like fermentation, ensiling, extrusion (Ujong et al. 2025, Zhao et al. 2014), and fortification improve digestibility and nutritional value while cleaning, disinfection, and testing ensure compliance with safety standards. Efficient processing not only optimizes the use of harvested duckweed but also positions it as a sustainable alternative to conventional feed sources like soy or fishmeal (Takács et al. 2025). Using a Box-Behnken experimental design, Mirón-Mérida et al. (2024) improved the alkaline protein extraction from *Lemna minor* using ultrasound.

Additionally, an investigation of how ultrasound affects the extracted protein's morphological, structural, and functional characteristics was conducted. They concluded that more protein may be extracted because of the cellular disturbance caused by ultrasonography. Additionally, the use of ultrasonography during the protein extraction process altered the duckweed protein's structure and color, improving its characteristics.

When taking into account the use of duckweed in various food products, these findings are encouraging (Mirón-Mérida et al. 2024). A non-thermal processing method called high hydrostatic pressure technology (HHPT) has demonstrated potential in improving the bioavailability and bioaccessibility of bioactive substances in a range of food systems. However, little research has been done on how high hydrostatic pressure affects duckweed's bioactive qualities (Chen et al. 2018). Abdullahi AI et al. showed how various processing techniques affected Lemna paucicostata's nutritional makeup and anti-nutritional characteristics. Four different processing techniques were applied to Lemna paucicostata. While all of the processing techniques employed in this study decreased L. paucicostata's anti-nutritional components, the blanching procedure is the most effective at enhancing the plant's nutritious content (Abdullahi et al. 2022). Lam et al. (2017) investigated the use of extrusion technology to process duckweed biomass into pellets. The study reported that extrusion significantly improved the texture and nutritional composition of duckweed feed, making it suitable for use in livestock diets. The researchers also highlighted the economic benefits of using extrusion technology, as it reduces processing costs and enhances the shelf life of duckweed feed (Lam et al. 2017). Table 1 lists the comparison of duckweed with other nature-based phytoremediation solutions.

Biomass Valorization

Environmental impact: Duckweed has a profound positive impact on the environment due to its ability to address multiple ecological challenges. It improves water quality by efficiently absorbing excess nutrients such as N and P, which helps prevent eutrophication and supports healthier aquatic ecosystems (Fig. 3). Its role in wastewater treatment is particularly notable, as it thrives in nutrient-rich environments and removes contaminants, heavy metals, and organic pollutants, making water safe for reuse (Jaimes Prada et al. 2024). Duckweed's rapid growth rate enables it to act as a carbon sink, absorbing major amounts of carbon dioxide and causative to climate change mitigation. As a sustainable, high-protein biomass, it serves as an eco-friendly option to conventional feed sources like soy and fishmeal, thereby reducing overfishing, deforestation, and greenhouse gas emissions associated with traditional feed production.

Additionally, its cultivation requires minimal freshwater and no arable land, making it a resource-efficient crop that aligns with global efforts to conserve natural resources and promote sustainable agriculture (Vu et al. 2020). Utilizing duckweed to produce biomass and remediate wastewater contributes to reducing nutrient pollution in water bodies, mitigating eutrophication, and providing a sustainable alternative to chemical fertilizers. Additionally, biomass production provides a renewable source of nutrients that can be utilized as animal feed or organic fertilizer, reducing the reliance on synthetic fertilizers and promoting sustainable agriculture (Zhou et al. 2023a).

Economic Viability

Duckweed demonstrates strong economic viability with significant potential for revenue generation across multiple

Table 1: Comparison of duckweed with other nature-based phytoremediation solutions.

Parameter	Duckweed (*Lemna spp.*)	Algae	Water Hyacinth	Constructed Wetlands	References
Growth Rate	Very fast (doubling time ~1.5–3 days)	Fast, but strain-dependent	Slower (7–14 days)	Slow (~weeks)	Cheng and Stomp (2009), Zhao et al. (2020), Hillman and Culley (1978)
Nutrient Uptake	High N & P removal (up to 90–95%)	High N uptake, limited P in some species	Moderate N and P	Variable, depends on plant species and substrate	Gupta and Prakash (2013), Körner et al. (2003), Pant and Adholeya (2007)
Biomass Use	Feed, bioethanol, compost	Biofuel, compost	Compost, mulch, biogas	Rarely used, sometimes for compost	Appenroth et al. (2018), Zhao et al. (2014), Pant and Adholeya (2007)
Harvesting	Very easy, surface floating	Difficult (microscopic cells)	Bulky, manual/ mechanical	Not practical, rooted plants	Zhou et al. (2023a), Gupta and Prakash (2013)
Space Requirement	Low (compact growth in small ponds)	High (needs open, sunlit area)	Moderate	High (land-intensive)	Coughlan et al. (2022), Pant and Adholeya (2007)
Pollutant Removal Efficiency	85–95% for nutrients and organics	70–90% depending on species	60–85%	50–80%	Gupta and Prakash (2013), Zhao et al. (2014), Pant and Adholeya (2007)
Operational Cost	Low setup and maintenance	Moderate (needs light, nutrients)	Moderate, but biomass needs disposal	High (construction and maintenance)	Calicioglu et al. (2021), Pant and Adholeya (2007)
Challenges	Sensitive to pH and seasonal variation	Prone to crashes, harvesting issues	Invasive species risk	Clogging, mosquito breeding	Zhou et al. (2023a), Pant & Adholeya (2007), Gupta & Prakash (2013)

industries due to its low production costs, high biomass yield, and versatile applications (Calicioglu et al. 2021). The global duckweed protein market was valued at USD 72.7 million in 2024 and is projected to grow at a compound annual growth rate (CAGR) of over 7.9% during 2025–2034 (Global Market Insights, 2024). Similarly, overall duckweed sales are expected to grow at a CAGR of 10.8% between 2023 and 2033, reaching approximately USD 195.4 million by 2033 (Future Market Insights, 2023; Fig. 4 & 5). The global market for sustainable animal feed ingredients, biofuels, and organic fertilizers is expanding rapidly, creating a lucrative opportunity for duckweed-based products. As a high-protein biomass, it provides a cost-effective alternative to traditional feed ingredients like soy and fishmeal, meeting the rising demand in the livestock and aquaculture sectors (Pagliuso et al. 2022). The biofuel market, valued at over $100 billion, offers additional revenue streams, as duckweed can serve as an efficient feedstock for bioethanol production. Furthermore, its use in wastewater treatment and bioplastics aligns with the increasing global demand for eco-friendly solutions, supported by government incentives and corporate investments in green technologies. Duckweed farming also

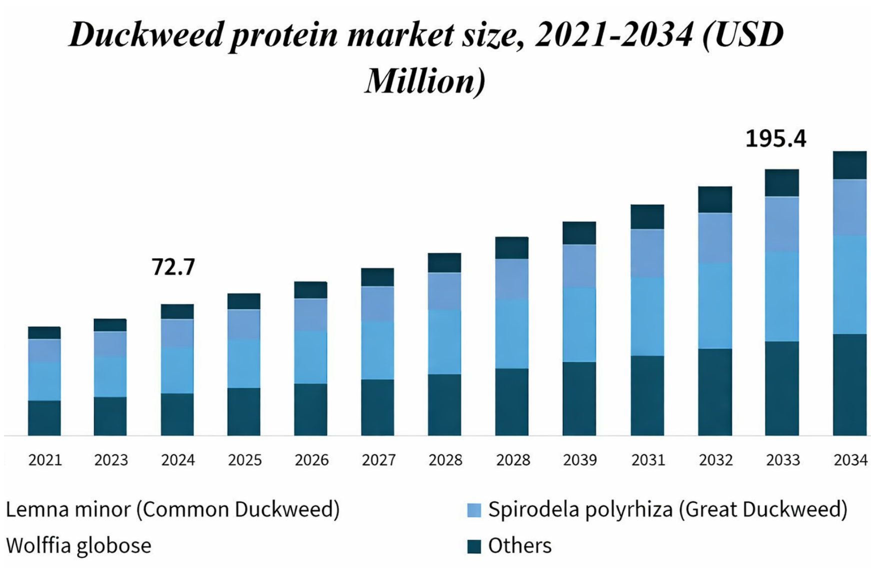


Fig. 4: Duckweed protein market size (Own creation) (https://www.futuremarketinsights.com/reports/duckweed-market).

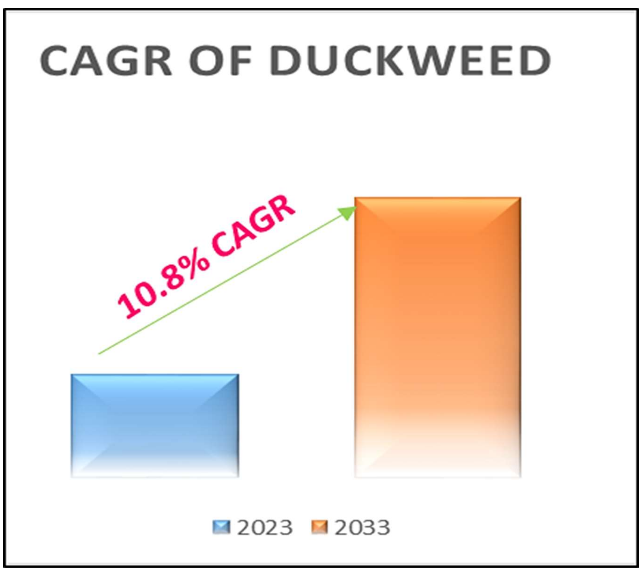


Fig. 5: Growth rate of duckweed (Own creation). (https://www.futuremarketinsights.com/reports/duckweed-market).

creates opportunities for rural development, employment, and export potential, particularly in regions with limited agricultural resources (Yang 2022). Comprehensive market analysis indicates that increasing awareness of sustainable practices and the rising cost of conventional feed and energy sources will continue to drive the adoption of duckweed, ensuring its long-term profitability and market expansion.

Challenges and Future Perspectives

Operational challenges: Duckweed wastewater treatment, though promising, faces several operational challenges that impact its scalability and efficiency. Duckweed growth is highly sensitive to environmental conditions such as temperature, light, pH, and nutrient availability, which may ensure optimal performance (Pasos-Panqueva et al. 2024). Harvesting and managing excess biomass is another hurdle, as overgrowth may lead to oxygen depletion, and disposal or utilization of the biomass requires further processing (Zhou et al. 2023a). Variability in water quality, contamination risks from absorbed pollutants like heavy metals, and difficulties in integrating with conventional treatment methods add to the complexity. Seasonal variations, especially in colder climates, can further hinder consistent performance.

Additionally, the economic viability of scaling up such systems is questionable, as it requires frequent monitoring, control, and maintenance to ensure optimal conditions for efficient treatment (Coughlan et al. 2022). The differences in the distribution and amount of bioactive chemicals within duckweed present another difficulty. Growth conditions, processing techniques, and the source or species can all have a big impact on these chemicals' concentration and bioavailability (Takács et al. 2025). Addressing these challenges is essential for the broader adoption of duckweed-based wastewater treatment.

Research gaps and future directions: Despite its potential, several research gaps limit the full-scale application of duckweed in wastewater treatment, paving the way for future exploration. Limited studies focus on optimizing duckweed's growth under diverse wastewater conditions, including high pollutant loads and variable climates, to enhance its resilience and efficiency. More research is needed on nutrient recovery mechanisms and the fate of absorbed contaminants to ensure environmental safety. Additionally, scalable and cost-effective systems for biomass harvesting, processing, and utilization, such as bioenergy production or bioproduct synthesis, remain underexplored. The integration of duckweed treatment with conventional technologies and its application in decentralized wastewater systems also requires further investigation. Integrating advanced technologies, such as hydroponic systems and automated harvesting, could enhance the efficiency of duckweed-based wastewater treatment. Forthcoming investigations should focus on genetic engineering to improve growth rates, pollutant uptake, and stress tolerance while leveraging advanced monitoring systems for automation and real-time control. Expanding these areas can unlock the potential of duckweed as a sustainable and scalable solution for WW treatment (Coughlan et al. 2022, Thingujam et al. 2024, Ujong et al. 2025). Further investigations into the potential of *L. minor* as a feedstock for biofuel production and bioremediation of emerging pollutants, such as pharmaceuticals and microplastics, could expand its applications. Additionally, future research should address the regulatory and policy frameworks needed to support the large-scale implementation of duckweed-based systems. Developing guidelines for the safe use of duckweed feed and establishing standards for wastewater treatment and biomass production are essential for promoting sustainable and economically viable practices (Zhou et al. 2023b).

Policy and Implementation Discussion

To enable large-scale implementation of duckweed-based treatment systems, policy frameworks must support integration with existing treatment infrastructure. Key considerations include establishing regulatory standards for effluent reuse, protocols for biomass utilization (e.g., as animal feed or fertilizer), and incentives for decentralized treatment models. Collaborative efforts between environmental agencies, municipalities, and industry stakeholders are essential to overcome institutional and economic barriers.

CONCLUSIONS

Duckweed-based wastewater treatment is a sustainable and innovative approach that effectively addresses water pollution while promoting resource recovery. Its rapid growth on nutrient-rich wastewater and high efficiency in removing pollutants such as nitrogen, phosphorus, COD, and BOD make it a promising biodegradable choice to conventional treatment approaches. Additionally, the nutrient-rich biomass produced during the process has immense potential for reuse, particularly as animal feed and biomass for bioenergy production, contributing to a circular economy. However, successful implementation of duckweed systems requires addressing challenges such as environmental variability, water quality fluctuations, and scalability. Standardized protocols for optimizing duckweed growth, nutrient absorption, and biomass utilization across diverse wastewater sources are crucial for maximizing its benefits.

Further research should also explore integrating duckweed systems with existing treatment technologies and their potential for decentralized wastewater management. By adopting duckweed-based treatment systems, communities can not only enhance water quality and reduce treatment costs but also generate valuable by-products like animal feed and biomass.

This dual-purpose approach offers a cost-effective and environmentally sustainable solution, paving the way for broader applications in wastewater management and resource recovery, ultimately contributing to global environmental and economic sustainability.

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