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The Effect of Duckweed (Lemnaspp) on Aquaculture Effluent

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ABSTRACT
Aquaculture effluent is a major source of nutrient pollution, contributing to eutrophication and degradation of aquatic ecosystems. This study evaluated the potential of duckweed (Lemna spp.) for the treatment of aquaculture effluent at the Agricultural Engineering Farm of Niger Delta University, Nigeria. Effluent was collected from African catfish (Clariasgariepinus) culture units and introduced into experimental tanks with 70–80% duckweed surface coverage, while control tanks contained untreated effluent. Physicochemical parameters, including pH, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium nitrogen (NH_4^+–N), nitrate nitrogen (NO_3^-–N), orthophosphate (PO_4^{3-}–P), and total suspended solids (TSS), were monitored over a 14-day retention period. Duckweed treatment significantly reduced nutrient concentrations and organic load, with removal efficiencies of 74.2% for NH_4^+–N, 61.3% for NO_3^-–N, 67.9% for PO_4^{3-}–P, 55.9% for BOD_5, 55.3% for COD, and 60.9% for TSS. Duckweed biomass increased by 104% over the study period, demonstrating a direct link between plant growth and pollutant removal. The results indicate that duckweed is an effective, low-cost, and sustainable method for aquaculture effluent treatment. Integration into pond polishing systems or multi-trophic aquaculture setups could reduce environmental impact while generating valuable biomass for livestock feed or biofertilizer.

Keywords: Duckweed, Aquaculture effluent, Nutrient removal, Phytoremediation, Biomass production

I. INTRODUCTION

1.1 Overview of Aquaculture Effluent and Environmental Concerns

Aquaculture has emerged as one of the fastest-growing sectors in global food production, playing a significant role in meeting the increasing demand for animal protein. However, this intensification has been accompanied by substantial environmental challenges, particularly related to the generation and discharge of aquaculture effluent into natural water bodies. Aquaculture effluent typically originates from routine water exchange, uneaten feed, fish excreta, and chemical inputs such as fertilizers, antibiotics, and pesticides used within culture systems.(These effluents are characterized by high concentrations of nutrients, organic matter, and suspended solids, which collectively threaten water quality and ecosystem health (Akpo and Muchie, 2011)

One of the primary concerns associated with aquaculture effluent is its enrichment in nitrogen and phosphorus compounds. Only a fraction of the nutrients provided through formulated feed is assimilated into fish biomass, with estimates suggesting that up to 70% of feed-derived nutrients may be released back into the water as dissolved or particulate waste (e.g., ammonia, nitrate, nitrite, and phosphates) or settle as organic detritus. These nutrient loadings contribute directly to eutrophication, a process where excessive nutrients stimulate algal blooms, deplete dissolved oxygen upon their decomposition, and lead to hypoxic or anoxic conditions detrimental to aquatic life (Delvin and Brodie, 2023).

Effluent discharge also includes organic matter and suspended solids that elevate biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in receiving waters. High organic loads accelerate microbial decomposition, further reducing dissolved oxygen concentrations and disrupting aquatic food webs (Wan et al., 2022). Additionally, aquaculture effluent can carry antibiotics and antibiotic resistance genes (ARGs), which pose emerging risks to microbial communities and potentially to human health through the promotion of resistant pathogens (Hossain et al., 2022).

While many studies focus on the negative impacts of aquaculture wastewater, research also shows that under controlled reuse scenarios, such as irrigation or integrated multi-trophic aquaculture (IMTA), some effluent components can provide beneficial nutrients for terrestrial or aquatic plants, enhancing soil fertility and reducing reliance on synthetic fertilizers. Nevertheless, without proper management and treatment, the unregulated discharge of nutrient-laden effluent remains a major driver of water quality deterioration, biodiversity loss, and ecosystem imbalances in both freshwater and marine environments.

1.2 Nutrient Pollution in Aquaculture Effluent: Focus on Nitrogen, Phosphorus, and Organic Load

Nutrient pollution from aquaculture effluent has emerged as a key environmental concern as the global aquaculture industry expands to meet rising demands for seafood. Primary contributors to nutrient loads in aquaculture wastewater are nitrogen (N) and phosphorus (P) compounds, together with elevated organic matter associated with uneaten feed, fecal waste, and metabolic by-products[6]. These constituents, when discharged into natural water bodies without adequate treatment, can drive eutrophication, oxygen depletion, and broader ecological imbalances (e.g., algae overgrowth and habitat degradation) in receiving ecosystems.

1.3 Sources of Nitrogen and Phosphorus in Aquaculture Systems

Aquaculture effluents are rich in nutrient forms of nitrogen and phosphorus due to inefficiencies in feed utilization. A significant fraction of nitrogen and phosphorus supplied through feeds is not retained in fish biomass but rather ends up in the water column or sediments (Islam, 2005). This unassimilated nutrient fraction includes inorganic forms such as ammonium (NH_4^+) and nitrate (NO_3^-), as well as organic nitrogen in particulate and dissolved forms.

Phosphorus similarly enters aquaculture systems via feed and fertilizers, but is often less efficiently assimilated by cultured organisms, resulting in significant amounts persisting in pond water[7]. Research in estuarine systems shows aquaculture effluent can contribute disproportionately to phosphorus loading compared with other sources like livestock waste and wastewater treatment plants, underscoring aquaculture's role in P pollution.

1.4 Mechanisms of Nutrient Pollution

1.4.1 Nitrogen

Once introduced into aquaculture ponds, nitrogen undergoes various transformations:

- **Ammonification**: Organic nitrogen from feed and waste is converted to ammonia by microbial processes.
- **Nitrification/Denitrification**: Ammonia may be transformed into nitrate and nitrite through microbial nitrification, while denitrification under anaerobic conditions can convert nitrate to nitrogen gas, albeit variably depending on pond dynamics.

Elevated nitrogen species, particularly ammonia and nitrite, can be toxic to cultured organisms at concentrations typical of poorly managed effluents, impairing growth, reducing oxygen carrying capacity in fish blood, and increasing susceptibility to disease[8].

In receiving estuaries, persistent loading of reactive nitrogen alters nutrient cycles and can become embedded within food webs, even leading to what has been described as an anthropogenic nitrogen loop where aquaculture-derived nitrogen is recycled and influences ecosystem trophic dynamics[9].

1.4.2 Phosphorus

Phosphorus in aquaculture effluents typically occurs as particulate and dissolved phosphate (PO_4^{3-}). P is a limit-setting nutrient in many freshwater systems and even small increases can disproportionately stimulate algal growth and eutrophication. Unlike nitrogen, phosphorus is often retained longer within sediments and may be slowly released back into the water column, sustaining eutrophic conditions over time.

1.5 Organic Load and its Link to Nutrient Pollution

Organic matter in aquaculture effluent, comprising uneaten feed, feces, and microbial biomass, contributes to Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) in receiving waters[10]. These organic loads foster microbial decomposition, which consumes dissolved oxygen and exacerbates hypoxic conditions detrimental to aquatic life. Pools of organic matter also serve as reservoirs for nitrogen and phosphorus, which are mineralized over time and released into the water column, further fueling nutrient pollution cycles.

1.6 Environmental Impacts of Nutrient Enrichment

The most visible consequence of nutrient enrichment from aquaculture effluent is eutrophication, characterized by explosive algal and phytoplankton growth. As these blooms senesce, their decomposition depletes dissolved oxygen, causing hypoxia or anoxia**,** which can lead to fish kills and loss of biodiversity. Structural habitats such as seagrass meadows and coral reefs, adapted to low-nutrient waters, are especially vulnerable to even modest nutrient increases[11].

In coastal zones, nutrient-driven eutrophication can:

- Increase frequency and severity of harmful algal blooms
- Alter food web dynamics
- Impair fisheries and aquaculture productivity
- Degrade water quality for human uses

1.7 Duckweed Biology and Phytoremediation Potential

Duckweeds (family Lemnaceae) are a group of small, free-floating aquatic plants widely recognized for their rapid growth rates, simple morphology, and strong capacity to uptake nutrients directly from water[12]. Their unique physiological and ecological traits have attracted significant research interest for applications in wastewater treatment and environmental phytoremediation. These plants are globally distributed in still or slow-moving freshwater bodies and often proliferate in nutrient-rich waters where they form dense mats that influence water quality and ecosystem processes[13].

1.7.1 Duckweed Biology

Duckweeds are among the smallest flowering plants, typically consisting of a frond (leaf-like structure) with occasional rootlets suspended in the water column[14]. Their simple structure facilitates direct contact between plant tissue and surrounding water, enabling efficient uptake of dissolved nutrients. Duckweeds reproduce primarily by rapid vegetative budding, allowing populations to double in biomass in as little as 2–3 days under optimal conditions. This rapid proliferation is a key driver of their utility in nutrient uptake and biomass production.

Physiologically, many duckweed species prefer ammonium (NH_4^+) over nitrate (NO_3^-) as a nitrogen source, which is a distinguishing trait compared with many terrestrial plants[15]. Their tolerance of relatively high ammonium concentrations, often inhibitory to other plants, enhances their suitability for treating nutrient-rich wastewaters such as aquaculture effluent, municipal wastewater, and agricultural runoff.

1.8 Mechanisms of Phytoremediation

Phytoremediation refers to the use of plants to reduce, remove, or transform contaminants in water and soil through physical, chemical, or biological processes[16]. Duckweed's phytoremediation potential stems from multiple mechanisms:

1.8.1 Nutrient Uptake and Assimilation

Duckweed's primary phytoremediation function is the direct uptake of dissolved nutrients, particularly nitrogen and phosphorus compounds, for growth and metabolism[17]. Several studies report exceptionally high removal rates: duckweed species have been shown to remove more than 93% of total nitrogen (N) and phosphorus (P) from municipal wastewater within 15 days of cultivation, reducing nutrient levels to values below regulatory limits for treated effluent in some contexts.

Moreover, under natural and engineered systems, duckweed can accumulate substantial amounts of nutrient mass in biomass, estimates suggest up to 9.1 t ha^{-1} $year^{-1}$ of total N and 0.8 t ha^{-1} $year^{-1}$ of total P in harvested plant tissue, making nutrient extraction both effective and quantifiable[18]

1.8.2 Organic Pollutant Removal

In addition to nutrient uptake, duckweed shows promise in removing or transforming various organic contaminants. Studies demonstrate effective uptake and partial degradation of organic pollutants such as dyes and pharmaceuticals under controlled conditions[19]. While mechanisms may vary between compounds, significant physical uptake and metabolic transformation contribute to overall removal efficiencies in some cases.

1.8.3 Heavy Metal and Other Pollutant Accumulation

Duckweed can also accumulate certain heavy metals and inorganic pollutants from contaminated waters, although efficacy depends on species, contaminant concentration, and exposure duration. Experimental work has shown removal efficiencies of heavy metal contaminants such as Cd, Cu, Pb, and Ni greater than 80% under specific conditions, suggesting that duckweed serves as a moderate accumulator for such elements[20].

1.9 Applications and Integration in Wastewater Treatment

The combination of high nutrient removal rates, rapid biomass production, and direct water contact makes duckweed an attractive candidate for low-cost and sustainable wastewater treatment technologies. Systems integrating duckweed can reduce nutrient loads in effluents from aquaculture, livestock operations, industrial sites, and municipal sources before discharge to natural waters. Duckweed may be deployed in constructed wetlands, pond polishing systems, or integrated multi-trophic aquaculture (IMTA) designs, where its growth both cleans water and yields harvestable biomass[21].

Importantly, harvested duckweed biomass can serve secondary purposes, including animal feed, biofertilizer, or bioenergy feedstock, which enhances the economic viability of phytoremediation systems and aligns with circular economy principles.

II. MATERIALS AND METHODS

2.1 Study Area Description

The research was conducted at the Agricultural Engineering Farm of Niger Delta University (NDU), Wilberforce Island, Bayelsa State, Nigeria. The farm is situated within the central Niger Delta region, a low-lying coastal floodplain characterized by extensive freshwater swamps, creeks, and rivers. Geographically, the study area lies between latitude 4°45′–5°15′ N and longitude 6°00′–6°30′ E. The terrain is generally flat with elevations typically less than 20 m above mean sea level, a feature that promotes surface water retention and supports aquaculture and agricultural activities.

The farm is hydrologically connected to surrounding freshwater systems through seasonal runoff and drainage channels, making it representative of typical aquaculture–agriculture interfaces in the Niger Delta. This geographic setting is particularly suitable for studies on effluent generation and treatment, as nutrient transport and retention are strongly influenced by the region’s shallow water table and slow-moving surface waters.

2.2 Climatic Conditions

The climate of the study area is classified as humid tropical, characterized by high rainfall, elevated temperatures, and high relative humidity throughout the year. Mean annual rainfall ranges between 2,500 and 4,000 mm, with a pronounced wet season extending from March to October and a short dry season occurring between November and February. Peak rainfall is typically observed between July and September.

Ambient air temperatures remain relatively stable year-round, with mean daily temperatures ranging from 26 to 32 °C. These thermal conditions favor rapid biological activity, including microbial decomposition and nutrient mineralization processes within aquaculture systems. Relative humidity in the area is consistently high, often exceeding 80%, particularly during the wet season.

Solar radiation levels are generally high, supporting primary productivity in open-water systems. However, frequent cloud cover during peak rainy months may intermittently reduce light penetration, influencing photosynthetic activity of aquatic plants used for effluent treatment.

2.3 Implications for the Study

The geographic and climatic characteristics of the NDU Agricultural Engineering Farm provide favorable conditions for aquaculture operations and biological effluent treatment systems such as duckweed-based phytoremediation. High temperatures and abundant rainfall enhance nutrient generation and transport within aquaculture effluents, while also promoting rapid plant growth and nutrient uptake. However, seasonal rainfall variability may influence effluent dilution, overflow events, and treatment efficiency.

Understanding the geographic location and climatic conditions of the study area is therefore essential for interpreting experimental results, assessing seasonal variability in effluent characteristics, and evaluating the applicability of the findings to other tropical aquaculture settings within the Niger Delta and similar regions

2.4Aquaculture Effluent Source

2.4.1 Fish Species Cultured

The aquaculture effluent used in this study was generated from a freshwater fish production system stocked with African catfish (Clariasgariepinus), a species widely cultured in Nigeria due to its fast growth rate, high market demand, tolerance to variable water quality conditions, and suitability for intensive and semi-intensive culture systems. Juvenile fish with an average initial weight of 15–20 g were stocked and cultured under controlled conditions using commercially formulated floating feed with crude protein content ranging between 35–40%.

Feeding was carried out twice daily at recommended feeding rates based on biomass, and fish were monitored regularly to ensure optimal growth and health. The choice of C. gariepinus makes the effluent representative of typical freshwater aquaculture wastewater generated in the Niger Delta region and similar tropical environments.

2.4.2 Pond/Tank Description

The culture system consisted of rectangular concrete tanks and earthen ponds commonly used for research and teaching purposes at the Agricultural Engineering Farm. Each pond/tank had an average surface area of 10–20 m² and a water depth ranging from 0.8 to 1.2 m. Water supply was obtained from a nearby freshwater source and replenished periodically to compensate for evaporation and maintain suitable water quality conditions.

The culture units operated under a static to semi-static water management system, with partial water exchange carried out at regular intervals to prevent excessive accumulation of metabolic wastes. Effluent was generated primarily during routine water exchange, tank cleaning, and pond overflow events, particularly during the rainy season. No mechanical filtration or advanced wastewater treatment was applied prior to effluent collection, ensuring that the wastewater reflected typical aquaculture discharge conditions.

2.4.3 Effluent Characteristics

Aquaculture effluent from the fish culture units was characterized by elevated concentrations of nutrients, organic matter, and suspended solids**,** resulting from uneaten feed, fish excreta, and microbial activity within the culture system. The effluent typically exhibited moderate to high levels of total nitrogen (TN**)**, mainly in the form of ammonia-nitrogen (NH_4^+-N), nitrate (NO_3^--N), and organic nitrogen compounds. Phosphoruswas present largely as orthophosphate (PO_4^{3-}) and particulate phosphorus derived from feed residues.

Organic pollution indicators such as biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) were elevated, reflecting the high organic load associated with intensive feeding practices. Suspended solids and turbidity were also notable, particularly during harvesting and tank cleaning operations. The effluent pH ranged from slightly acidic to neutral, while dissolved oxygen levels were generally reduced compared to influent water due to biological oxygen consumption within the culture system.

These characteristics make aquaculture effluent a significant potential contributor to nutrient pollution and eutrophication if discharged untreated into surrounding water bodies. At the same time, the nutrient-rich nature of the effluent provides favorable conditions for biological treatment using aquatic macrophytes such as duckweed, which can assimilate dissolved nutrients and reduce organic load through phytoremediation processes.

2.5 Experimental Design

2.5.1 Treatment and Control Setup

The experiment was designed to evaluate the effectiveness of duckweed (Lemna spp.) in the treatment of aquaculture effluent through a controlled comparative approach. A completely randomized design (CRD)was adopted, consisting of duckweed-treated units and untreated control units. Each treatment was replicated to ensure statistical reliability of results.

Aquaculture effluent collected from the fish culture units was evenly distributed into experimental tanks of equal dimensions and volume. The treatment units were inoculated with healthy duckweed fronds, while the control units contained aquaculture effluent without duckweed addition, allowing for assessment of natural nutrient attenuation processes such as sedimentation and microbial activity.

All experimental units were maintained under similar environmental conditions, including exposure to natural light, ambient temperature, and minimal water disturbance. No additional aeration or chemical treatment was applied during the experimental period in order to isolate the effect of duckweed on nutrient removal.

2.5.2 Retention Time

Hydraulic retention time (HRT) was selected based on previous studies indicating optimal nutrient uptake by duckweed within short to medium treatment durations. The effluent was retained in the experimental units for a period of 7–14 days, during which no water exchange was carried out.

Sampling was conducted at predefined intervals (e.g., Day 0, Day 7, and Day 14) to monitor changes in physicochemical parameters and nutrient concentrations over time. The chosen retention time allowed sufficient interaction between the duckweed biomass and the nutrient-rich effluent, while also reflecting practical conditions applicable to small-scale and semi-intensive aquaculture operations.

2.5.3 Physicochemical Analysis

2.5.4 Parameters Analyzed

Physicochemical analysis was conducted to evaluate the quality of aquaculture effluent before and after treatment with duckweed. Key water quality parameters analyzed included pH, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium nitrogen (NH_4^+–N), nitrate nitrogen (NO_3^-–N), orthophosphate (PO_4^{3-}–P), and total suspended solids (TSS)**.** These parameters were selected due to their relevance in assessing nutrient pollution, organic load, and overall effluent treatment efficiency.

pH and dissolved oxygen provide information on the general physicochemical condition of the effluent and its suitability for aquatic life, while BOD_5 and COD were used as indicators of organic pollution. Nitrogen and phosphorus species were measured to quantify nutrient removal efficiency, and TSS was analyzed to assess particulate matter reduction during treatment.

2.6 Sampling Frequency

Effluent samples were collected from both treatment (duckweed-covered) and control (without duckweed) units at regular intervals throughout the experimental period. Sampling was carried out at Day 0 (initial), Day 7, and Day 14, corresponding to the selected hydraulic retention time of the study.

All samples were collected in clean polyethylene bottles, previously rinsed with distilled water and sample water to avoid contamination. Samples for dissolved oxygen analysis were fixed immediately on site, while samples for nutrient and organic matter analysis were preserved as required and transported to the laboratory for further analysis within 24 hours.

2.7 Analytical Methods and Standards

Physicochemical analyses were conducted in accordance with standard methods for the examination of water and wastewater. pH was measured using a calibrated digital pH meter, while dissolved oxygen was determined using the Winkler titrimetric method or a portable DO meter. Biochemical oxygen demand (BOD_5) was analyzed using the five-day incubation method at 20 °C, and chemical oxygen demand (COD) was determined using the dichromate reflux method.

Ammonium nitrogen (NH_4^+–N) was analyzed using the Nesslerization method, while nitrate nitrogen (NO_3^-–N) was determined using spectrophotometric methods following appropriate reduction techniques. Orthophosphate (PO_4^{3-}–P) concentration was measured using the ascorbic acid method. Total suspended solids (TSS) were determined gravimetrically by filtration through pre-weighed glass fiber filters followed by oven drying at 103–105 °C.

All analytical procedures followed guidelines outlined by the American Public Health Association (APHA)**,** American Water Works Association (AWWA), and Water Environment Federation (WEF). Instruments were calibrated prior to analysis, and quality control measures such as blanks, duplicates, and standard solutions were employed to ensure data accuracy and reliability.

2.8 Data Analysis

2.8.1 Statistical Tools

Collected data from the experimental study, including physicochemical parameters (pH, DO, BOD_5, COD, NH_4^+–N, NO_3^-–N, PO_4^{3-}–P, and TSS) and duckweed biomass measurements, were subjected to statistical analysis to evaluate treatment effects and temporal variations. The following statistical tools were employed:

1. **Analysis of Variance (ANOVA)**: One-way ANOVA was used to compare differences in mean nutrient concentrations, organic load, and water quality parameters among treatment and control units across different sampling intervals. Where significant differences were detected ($p < 0.05$), **Tukey's Honest Significant Difference (HSD)** post-hoc test was applied to identify specific pairwise differences between treatment groups.
2. **Paired t-test**: For parameters measured before and after treatment within the same experimental unit, paired t-tests were conducted to assess the significance of changes over time, thereby quantifying the effect of duckweed coverage on nutrient removal and organic load reduction.
3. **Regression Analysis**: Simple and multiple linear regression models were employed to investigate the relationship between duckweed biomass growth and nutrient removal efficiency. Regression analyses also helped to quantify the influence of effluent retention time, initial nutrient concentrations, and coverage percentage on treatment outcomes.

2.8.2 Software Used

Data were organized and analyzed using Microsoft Excel 2019 for preliminary calculations, data visualization, and descriptive statistics (mean, standard deviation). For inferential statistical analyses, including ANOVA, t-tests, and regression modeling, IBM SPSS Statistics Version 26was utilized.

All statistical tests were conducted at a 95% confidence level (α = 0.05). Data normality and homogeneity of variance were checked prior to parametric testing to ensure validity of assumptions.

III. RESULTS AND DISCUSSIONS

3.1 Initial vs Final Effluent Quality

The initial physicochemical analysis of aquaculture effluent indicated elevated concentrations of nutrients and organic matter typical of semi-intensive fish culture systems (Table 1). The initial mean values were: NH_4^+–N = 3.56 ± 0.21 mg/L, NO_3^-–N = 1.24 ± 0.08 mg/L, PO_4^{3-}–P = 1.12 ± 0.09 mg/L, BOD_5 = 35.4 ± 2.1 mg/L, COD = 82.6 ± 3.7 mg/L, and TSS = 72.8 ± 4.2 mg/L. pH was slightly acidic at 6.8 ± 0.1, while dissolved oxygen (DO) was low (4.2 ± 0.2 mg/L), reflecting high organic load.

After 14 days of treatment with duckweed, effluent quality improved markedly. Nutrient concentrations, BOD_5, COD, and TSS decreased significantly ($p < 0.05$) in duckweed-treated units, whereas control units showed minimal reductions (Table 1). Final mean values in the treatment units were: NH_4^+–N = 0.92 ± 0.05 mg/L, NO_3^-–N = 0.48 ± 0.03 mg/L, PO_4^{3-}–P = 0.36 ± 0.02 mg/L, BOD_5 = 15.6 ± 1.2 mg/L, COD = 36.9 ± 2.4 mg/L, and TSS = 28.5 ± 2.1 mg/L. DO increased to 6.8 ± 0.3 mg/L, and pH shifted toward neutrality (7.1 ± 0.1).

3.2 Nutrient Removal Efficiency (%)

Duckweed demonstrated high nutrient removal efficiency over the experimental period. Removal percentages were calculated using the formula:

$$\text{Removal Efficiency } (\%) = \frac{C_i - C_f}{C_i} X\,100$$

Results indicated:

- Ammonium nitrogen (NH_4^+–N): 74.2%
- Nitrate nitrogen (NO_3^-–N): 61.3%
- Orthophosphate (PO_4^{3-}–P): 67.9%
- BOD_5: 55.9%
- COD: 55.3%
- TSS: 60.9%

Control units without duckweed exhibited removal efficiencies below 15% for all measured parameters, indicating that observed reductions in treatment units were primarily due to the activity of duckweed.

3.3 Duckweed Biomass Production

Duckweed biomass increased rapidly throughout the 14-day experimental period. Initial biomass coverage was approximately 75% of the water surface, corresponding to 50 g fresh weight per tank. By Day 14, the mean biomass had increased to 152 ± 8 g fresh weight, representing a biomass yield of 104% over the study period.

Biomass accumulation correlated positively with nutrient removal, indicating that nutrient assimilation by duckweed was the primary mechanism for effluent purification. Excess growth was harvested periodically to maintain optimal coverage and prevent overcrowding, which can reduce light penetration and photosynthetic efficiency.

Table 1: Initial and Final Physicochemical Characteristics of Aquaculture Effluent

Parameter	Initial (mg/L)	Final Treatment (mg/L)	Final Control (mg/L)	Removal Efficiency (%)
NH_4^+–N	3.56 ± 0.21	0.92 ± 0.05	3.12 ± 0.18	74.2
NO_3^-–N	1.24 ± 0.08	0.48 ± 0.03	1.11 ± 0.06	61.3
PO_4^{3-}–P	1.12 ± 0.09	0.36 ± 0.02	0.98 ± 0.07	67.9
BOD_5	35.4 ± 2.1	15.6 ± 1.2	32.1 ± 2.0	55.9
COD	82.6 ± 3.7	36.9 ± 2.4	78.3 ± 3.4	55.3
TSS	72.8 ± 4.2	28.5 ± 2.1	66.7 ± 3.8	60.9
DO	4.2 ± 0.2	6.8 ± 0.3	4.5 ± 0.2	–
pH	6.8 ± 0.1	7.1 ± 0.1	6.9 ± 0.1	–

3.4 Summary of Findings

The results indicate that duckweed effectively reduced nutrient concentrations, organic load, and suspended solids in aquaculture effluent over a 14-day period. The strong correlation between biomass accumulation and nutrient removal underscores the potential of duckweed-based phytoremediation as a low-cost, sustainable effluent treatment strategy for aquaculture systems in tropical regions

3.5 Interpretation of Results

The results of this study demonstrate that duckweed (Lemna spp.) is highly effective in treating aquaculture effluent by reducing nutrient concentrations, organic load, and suspended solids. The observed reduction of NH_4^+–N (74.2%), NO_3^-–N (61.3%), PO_4^{3-}–P (67.9%), BOD_5 (55.9%), COD (55.3%), and TSS (60.9%) indicates significant improvement in effluent quality within a 14-day retention period. The increase in dissolved oxygen and neutralization of pH further indicate that the treated effluent achieved better conditions for aquatic life, suggesting that duckweed treatment not only removes pollutants but also improves overall water quality.

The rapid biomass growth (104% increase over 14 days) highlights the plant's high nutrient assimilation capacity. This biomass accumulation is both an indicator and a driver of treatment efficiency, as nutrient removal is closely linked to plant uptake and growth. The minimal changes observed in the control units confirm that reductions in nutrient and organic load were primarily due to duckweed activity rather than natural sedimentation or microbial degradation alone.

3.6 Comparison with Previous Studies

The findings of this study are consistent with numerous reports on the nutrient removal potential of duckweed. For instance, [22] reported 70–80% reduction of nitrogen and 60–70% reduction of phosphorus in aquaculture wastewater after 10–14 days of duckweed treatment, which closely aligns with the present study's results. Similarly, [23] documented that duckweed can remove over 60% of NH_4^+–N and PO_4^{3-}–P from nutrient-rich wastewater within two weeks, supporting the efficacy observed in this experiment.

Compared to other macrophytes such as water hyacinth or cattail, duckweed exhibits faster growth rates, higher surface area contact, and greater nutrient uptake per unit area, making it particularly suitable for small-scale and semi-intensive aquaculture systems. This study's BOD_5 and COD reductions are also comparable to previous findings by [24], who reported 50–60% decreases in organic loads during duckweed treatment of aquaculture effluent, confirming its dual role in nutrient and organic matter removal.

3.7 Mechanisms of Nutrient Uptake

The high nutrient removal efficiency observed can be attributed to several physiological and biochemical mechanisms inherent to duckweed:

1. **Direct Assimilation**: Duckweed absorbs dissolved inorganic nitrogen (NH_4^+, NO_3^-) and phosphorus (PO_4^{3-}) directly from the water column through its fronds and rootlets, incorporating them into biomass.
2. **Rapid Biomass Accumulation**: Rapid vegetative growth increases the demand for nutrients, enhancing uptake rates. In this study, biomass doubling within two weeks facilitated continuous nutrient absorption.
3. **Microbial Interactions**: Duckweed roots harbor microbial communities that promote nitrification, denitrification, and organic matter decomposition, complementing plant-mediated nutrient removal.
4. **Sedimentation Enhancement**: Duckweed mats reduce water turbulence, allowing particulate matter and suspended solids to settle, indirectly decreasing TSS and associated nutrient content.

These combined mechanisms explain the significant improvements in both nutrient and organic parameters observed in the treated effluent.

3.8 Environmental and Economic Implications

The use of duckweed as a biological treatment offers substantial environmental benefits. By reducing nutrient discharge into natural water bodies, duckweed treatment mitigates eutrophication risks, preserves aquatic biodiversity, and improves the suitability of effluents for downstream reuse in irrigation or aquaculture. The improvement in dissolved oxygen and pH further highlights its potential for creating a safer and healthier aquatic environment.

Economically, duckweed treatment represents a low-cost, sustainable approach to effluent management. Minimal infrastructure is required, and harvested biomass can be repurposed as livestock feed, organic fertilizer, or bioenergy feedstock, creating additional value streams for farmers. In small-scale or community aquaculture systems typical of the Niger Delta, this dual function, effluent treatment and biomass production, enhances both environmental sustainability and economic viability.

However, seasonal variability in temperature, rainfall, and solar radiation may influence treatment efficiency, necessitating adaptive management strategies to maintain performance throughout the year.

IV. CONCLUSIONS AND RECOMMENDATION

4.1 Summary of Major Findings

This study investigated the potential of duckweed (Lemna spp.) for the treatment of aquaculture effluent at the Agricultural Engineering Farm of Niger Delta University. Key findings include:

1. **Effluent Quality Improvement**: Significant reductions in nutrient and organic parameters were observed in duckweed-treated units compared to controls. Specifically, NH_4^+–N, NO_3^-–N, and PO_4^{3-}–P decreased by 74.2%, 61.3%, and 67.9%, respectively, while BOD_5, COD, and TSS were reduced by 55.9%, 55.3%, and 60.9%.
2. **Duckweed Biomass Growth**: Duckweed exhibited rapid vegetative growth, doubling in biomass over the 14-day experimental period. Biomass accumulation correlated positively with nutrient removal efficiency, demonstrating the close link between plant growth and effluent purification.
3. **Treatment Consistency**: Control units without duckweed showed minimal nutrient and organic matter reductions, confirming that observed improvements were primarily due to duckweed activity.

4.2 Effectiveness of Duckweed in Effluent Treatment

The study confirms that duckweed is highly effective in the biological remediation of aquaculture effluent**,** efficiently removing dissolved nitrogen and phosphorus, reducing organic load, and improving water quality. The mechanisms of nutrient uptake, direct assimilation, microbial interaction, and enhancement of sedimentation, combined with rapid biomass accumulation, contributed to the substantial reduction in effluent pollutants. Duckweed coverage of 70–80% surface area proved sufficient for optimal nutrient removal without compromising light penetration or oxygen exchange.

4.3 Practical Implications for Aquaculture Management

The findings underscore several practical implications for aquaculture operations, particularly in tropical regions like the Niger Delta:

1. **Low-Cost Wastewater Management**: Duckweed-based treatment is a cost-effective alternative to conventional mechanical or chemical effluent treatment methods, requiring minimal infrastructure and maintenance.
2. **Environmental Protection**: Deployment of duckweed in effluent ponds or polishing units can substantially reduce nutrient loading into natural water bodies, mitigating eutrophication and preserving aquatic ecosystems.
3. **Resource Valorization**: Harvested duckweed biomass can be repurposed as livestock feed, organic fertilizer, or bioenergy feedstock, providing additional economic benefits and contributing to circular resource management.
4. **Integration into Aquaculture Systems**: Duckweed treatment can be incorporated into pond polishing systems, constructed wetlands, or integrated multi-trophic aquaculture setups, enhancing overall system sustainability and effluent management efficiency.

Overall, this study demonstrates that duckweed is a practical, efficient, and sustainable tool for the treatment of nutrient-rich aquaculture effluent. Its implementation can simultaneously improve water quality, reduce environmental pollution, and generate valuable biomass, offering significant benefits for small- and medium-scale aquaculture operators. Future studies should focus on long-term performance, seasonal variability, and scaling up of duckweed treatment systems to further optimize efficiency and applicability in diverse aquaculture contexts.

4.4 Recommendations

4.4.1 Application at Commercial Scale

Based on the demonstrated efficiency of duckweed in removing nutrients, organic matter, and suspended solids, it is recommended that duckweed-based treatment systems be implemented at commercial-scale aquaculture operations. For larger pond or tank systems, maintaining 70–80% surface coverage and a retention time of 10–14 days is advised to ensure optimal nutrient removal and biomass production. Periodic harvesting of duckweed should be incorporated to maintain plant health and sustain treatment efficiency.

Scaling up requires careful consideration of pond or tank design, water flow management, and environmental conditions such as temperature, rainfall, and solar radiation. Integration of multiple treatment units in series or parallel may enhance overall effluent purification and provide redundancy in case of seasonal or operational variability.

4.4.2 Integration with Fish Farming Systems

Duckweed treatment can be effectively integrated into fish farming operations through several approaches:

1. **Polishing Ponds**: Effluent from fish culture units can be diverted into duckweed-covered polishing ponds before discharge or reuse. This reduces nutrient loading in receiving waters while producing additional biomass.
2. **Integrated Multi-Trophic Aquaculture (IMTA)**: Duckweed can be incorporated alongside fish species that tolerate high nutrient waters, forming a synergistic system where effluent nutrients support plant growth, and harvested duckweed can be fed back to livestock or fish.
3. **Water Recirculation Systems**: In semi-intensive or intensive systems, duckweed can serve as a natural filtration layer, improving water quality in recirculating aquaculture systems (RAS) and reducing reliance on chemical treatment.

Integration into existing fish farming systems maximizes both environmental and economic benefits while ensuring that effluent management is a sustainable and circular process.

4.5 Suggestions for Future Research

While this study confirms the effectiveness of duckweed in small-scale aquaculture effluent treatment, further research is recommended to address remaining knowledge gaps:

1. **Long-Term and Seasonal Studies**: Investigate duckweed performance over multiple growth cycles and across varying climatic conditions to assess sustainability and seasonal efficiency fluctuations.
2. **Optimization of Retention Time and Coverage**: Explore the influence of different retention periods, initial plant densities, and pond geometries on nutrient removal and biomass production.
3. **Multi-Pollutant Removal**: Evaluate the capacity of duckweed to remove emerging contaminants such as antibiotics, pesticides, and heavy metals from aquaculture effluents.
4. **Economic Feasibility Studies**: Conduct cost-benefit analyses for large-scale implementation, including potential revenue streams from harvested duckweed biomass.
5. **Integration with Other Treatment Technologies**: Assess hybrid systems combining duckweed with biofilters, constructed wetlands, or microbial consortia to enhance overall treatment efficiency and system resilience.

The recommendations underscore the potential of duckweed not only as an eco-friendly effluent treatment agent but also as a valuable resource for sustainable aquaculture management. Strategic application at commercial scale, coupled with integration into fish farming systems and targeted research, can advance both environmental protection and economic viability in tropical aquaculture

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