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Phytoremediation of Grey Water using Duckweed (Lemnaspp) New

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Abstract-- **The issue of global water scarcity along with the increase of gray water produced from domestic activities such as bathing, laundry and kitchen use are major environmental challenges particularly in the developing world. In this regard, the study focused on evaluating the phytoremediation potential of duckweed (Lemna spp.) for grey water treatment as a low-cost and sustainable alternative to conventional systems. An experiment was run at the Agricultural Engineering Laboratory, Niger Delta University wherein duckweed ponds were designed to test the removal of pollutants over a span of 14 days. Physicochemical parameters like pH, DO, BOD, COD, TSS, nitrates, phosphates, and surfactants were analyzed according to APHA (2017) methods. The results showed that there was a huge decline in BOD (up to 85%), COD (82%), TSS (76%), nitrates (70%), and phosphates (68%), which means that the removal of pollutants was very efficient. Duckweed growth was observed to be positively correlated with the decline of pollutants, thus suggesting active nutrient uptake and microbial symbiosis in the rhizosphere. The study concludes that duckweed is a viable technology for decentralized gray water treatment, facilitating water reuse for irrigation and other non-potable applications. More studies are suggested on seasonal variation, hydraulic loading optimization, and economic feasibility to improve scalability and integration into rural and peri-urban wastewater management systems.**

Keywords-- **Phytoremediation, Duckweed (Lemna minor), Grey water, Wastewater treatment, Nutrient removal, Sustainable sanitation**

I. INTRODUCTION

1.1 Background of the Study

1.2 Global Water Scarcity and Pollution Challenges

Water scarcity and pollution are still the main global problems that severely affect the sustainability of human life and development. As the United Nations World Water Development Report [1] suggests, more than two billion people live in countries with very high-water stress, and in the coming years, the demand for fresh water could be up to 40% more than supply by 2030. Water pollution resulting from urbanization, industrialization, and population growth has been a major problem, especially in areas where domestic, agricultural, and industrial waste come together [2].

The problem of using or treating the water so badly that it is discharged into rivers lakes and reservoirs causing ecological disasters, loss of species, and public health risks is most serious in developing countries where most of the country's population does not have access to proper health infrastructure [3].

1.3 Increasing Generation of Grey Water in Domestic Settings

Grey water, which is the wastewater that comes from bathing, washing, and cooking accounts for 50–80% of the total domestic waste water [4]. It has been the global increase in the use of detergents, soaps, and cleaning agents in daily domestic routines, which is one of the biggest contributors to the increase in grey water volume. Grey water is in general non- fecal contaminated but it does consist of a good deal of organic matter, surfactants, nutrients, and oils [5]. In developing countries like Nigeria, grey water is often let out untreated into open drains and water bodies because of insufficient waste water management systems [6]. This practice causes environmental degradation, eutrophication,and groundwater contamination.

1.4 Environmental Implications of Untreated Discharge

The unregulated discharge of untreated grey water causes both environmental and socio-economic problems. One of the major ecological impacts of nutrient-rich grey water is the growth of algal blooms, which consume dissolved oxygen and disturb aquatic habitats [7]. Water chemistry is changed and microbial and aquatic life are inhibited by surfactants and chemical additives. The land might become salty, the crops could get less productive, and the humans might get sick from the contaminated water if these pollutants are around for a long time [8]. Low-income populations are hardest hit, as in these communities untreated domestic wastewater often stagnant near house contributes to bad smell and spreads the diseases carried by insects [9]. These difficulties highlight the pressing demand for cheap, decentralized, and ecologically sound grey water treatment systems. Phytoremediation, a natural process using aquatic macrophytes like Lemna spp. (duckweed), presents a great opportunity for the removal of nutrients and pollutants especially in impoverished areas [10].

1.5 Duckweed and Its Phytoremediation Potential

1.5.1 Botanical Overview of Lemna spp.

Duckweed (Lemna spp.) is tiny, free-floating aquatic macrophyte of the family Araceae (subfamily Lemnoideae). It is also one of the fastest-growing flowering plants all over the world, and it has a simple structure made up of fronds (leaf-like parts) and short roots that go into the water column [11]. The plant grows best in visually impaired, stagnant or not moving freshwater areas teeming with nutrients and forms thick green mats on the surface of the water.

Lemna minor, Lemnagibba and Spirodelapolyrhiza are among the species that are very widespread in the tropical and subtropical areas, and the Niger Delta region of Nigeria is also included in that area [12]. The whole Lemna genus of plants gets propagated quickly by vegetative budding which makes it possible for them to have exponential biomass accumulation during the very good conditions of light, temperature, and nutrient availability [13]. Because it is rich in protein, it is able to survive in polluted environments and moreover it can withstand various conditions of wastewater; it is for these reasons that duckweed has become a global focus for its applications in wastewater treatment, animal feeding, and energy production [14].

1.5.2 Growth Characteristics and Nutrient Uptake Capacity

Duckweed is characterized by its amazing growth and nutrient taking-in properties which are the reasons behind its application in wastewaters' cleaning. The plant under the best environmental conditions can increase its weight twice in 2–3 days [15]. The high surface-area-to-volume ratio of the plant facilitates the nutrient uptake, so especially that for nitrogen (N) and phosphorus (P) which are the nutrients the grey water mainly contain. Duckweed takes up ammonium (NH_4^+) and phosphate (PO_4^{3-}) directly from the water column for their growth by incorporating them into cellular proteins and nucleic acids [16]. The removal efficiencies of nitrogen up to 70–90% and reduction of phosphorus in the amount of 80% and above have been reported in duckweed-based systems [17]. The floating nature of the plant allows it to get continuously the light which supports both photosynthesis and oxygenation processes that help in the growth of microbes in the vicinity of the root zone, and thus the plant's contribution to the overall process of nutrient removal is enhanced.

What is more, the method of harvesting duckweed is so simple that it enables the removal of the accumulated biomass very easily, thus not allowing the nutrients to get released back into the water body. The biomass that is harvested can be used as an organic fertilizer, a substrate for biogas production, or as feed for livestock, thus aiding in the creation of a circular economy principles in wastewater management [11].

1.5.3 Previous Research on Duckweed in Wastewater Treatment

Duckweed has been proven by several research works to be a highly effective treatment option for different types of wastewaters like the domestic grey water, agricultural runoff, and the industrial effluents. [18] noted that the duckweed ponds over 80% biochemical oxygen demand (BOD) and 75% of total suspended solids (TSS) removal in just 10 days of retention. Likewise, Lemna minor was municipal wastewater nitrogen and phosphorus levels with removal efficiencies equal to constructed wetlands but at a significantly lower cost of operation [19]. In places where the sanitation situation is not well-developed, the use of the duckweed-based systems is often recognized as cheap and decentralized wastewater treatment options. For example, the studies carried out in Ghana and Nigeria indicated that the plant has great potential in the treatment of household grey water, meeting the requirements for irrigation and aquaculture reuse [7], [20]. Moreover, the only factor that is limiting its use in the area where conventional wastewater management is lacking is its ability to withstand high pollutant loads and survive under tropical climatic conditions. Fresh developments in wastewater management include the combination of duckweed systems with biofilm reactors and anaerobic digesters for better overall pollutant removal and energy recovery [13]. These breakthroughs point to the plant's many-sidedness in supporting sustainable water management, resource recovery, and ecological restoration.

1.5.4 Summary

The fast growth and high nutrient uptake capacity along with the partnership with the rhizospheric microorganisms are the main reasons why Lemna spp. is considered the most effective plant for the phytoremediation process. Its low energy requirement, minimal maintenance, and versatility with different types of wastewater make it a promising green technology for the decentralized treatment of grey water in developing countries.

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So, duckweed-based treatment systems support the global movement towards Sustainable Development Goal 6 (Clean Water and Sanitation) not only by the reuse of water but also by the conservation of the environment.

1.6 Study Justification and Objectives

1.6.1 Need for low-cost, decentralized grey water treatment methods

The global menace of water shortage, made worse by population increase, urban development and climate change, has made the search for new sources of water and sustainable wastewater management less severe (United Nations World Water Development Report, 2023). In numerous developing areas, especially in sub-Saharan Africa, there is still a lack of access to centralized wastewater treatment plants, which is mainly due to expensive installation and operating costs, unstable power supply, and poor institutional support [21], [22]. As a result, a large volume of domestic grey water, which comes from bathing, laundry and kitchen activities, is dumped untreated, causing nutrient enrichment, foul smell, and health risks [4], [5].

The traditional methods of treating wastewater, like activated sludge and membrane bioreactors, are highly effective, but their high cost of construction and operation makes them impractical for small towns and rural areas [23]. This has created a great necessity for treating household or community grey water effectively with easy, low-cost, and nature-friendly technologies that are not highly reliant on electricity or complicated machinery [24]. In addition, environmentally friendly approaches such as phytoremediation have the power to completely transform wastewater management particularly in developing countries where cost and technical competence are the two main hindrances [25],[26]. Particularly, Duckweed systems could provide most of the unique benefits for such applications. Their fast-growing nature, high rate of nutrient uptake, and ability to flourish even in nutrient-rich waters make them the most suitable microorganisms for the removal of organic matter, nitrogen, phosphorus, and suspended solids from grey water with very low operational cost [27],[28]. In addition to that, the biomass obtained can be used as animal feed, compost material, or bioenergy substrate thus contributing to sustainability and drawing acceptance from the community [29].

1.6.2 Objectives

This research work is focused on the huge aim of the study of the rate of duckweed (Lemna spp.) removal of pollutants from the treatment of domestic grey water.

To be precise, the research intends to: the evaluation of duckweed's ability to remove main contaminants nutrients (nitrogen and phosphorus), organic matter (as BOD and COD), and suspended solids from domestic grey water, observing and assessing the growth and productivity of biomass of duckweed under exposure to grey water, and finally the ratification of duckweed's suitability.

The research is a contribution to the development of the United Nations Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation) and 12 (Responsible Consumption and Production) in the direction of eco-friendly and resource-efficient wastewater treatment methods.

II. Materials and Methods

2.1 Study Area

The experiment was performed at the Soil & Water Laboratory, Department of Agricultural & Environmental Engineering, Niger Delta University (NDU) at Wilberforce Island, Bayelsa State, Nigeria, and at AI Barr Laboratory Services, Yenagoa, which has the capability of conducting environmental and water quality analysis. This laboratory is also equipped with the necessary apparatus for physicochemical testing such as pH, turbidity, biochemical oxygen demand (BOD), and chemical oxygen demand (COD), besides nutrient (nitrogen and phosphorus) determination. The weather of Wilberforce Island is usually humid tropical, having high annual rainfall (2,000–3,500 mm) and temperatures of 25°C to 33°C. Such environment is favorable for aquatic plant growth and experimental studies involving macrophytes like duckweed (Lemna spp.).

2.2 Description of Grey Water Collection Site

The gray water utilized in this experiment was sourced from a house in the Niger Delta University staff quarters representing a typical grey water source of semi-urban communities. The site chosen generates grey water from bathrooms, washing activities, and cooking areas, but no black water (toilet effluent) is included. This separation guaranteed that the involved wastewater had a lower pathogen content than that of black water hence it was appropriate for the controlled phytoremediation research [4], [5].

The household selected for this study had the characteristics of being easily accessible, having a constant grey water discharge, and being close to the laboratory to avoid sample degradation during transportation.

The average daily grey water generation was approximately 80 to 120 liters per day, a figure that matches the corresponding domestic consumption in developing regions [30].

2.3 Grey Water Collection and Pre-Treatment Procedure

The manual collection of the grey water samples was done using a 25-liter keg that was previously rinsed with distilled water to eliminate the possibility of contamination. The sampling occurred in the morning to take advantage of the household's initial discharge flow. The collected water was promptly transported to the Soil and Water Laboratory, Department of Agricultural & Environmental Engineering for pretreatment and setting up the experiment. Before using the grey water in the phytoremediation system, a simple pre-treatment process was applied to remove large debris, oil films, and solids that could hinder duckweed growth. The pre-treatment consisted of the following steps:

1. *Screening:* The raw grey water was filtered using a 1-mm stainless steel mesh sieve to eliminateabrasive particles constituted of food wastes, hair, and fabric lint.
2. *Sedimentation:* The water after screening was left in a sedimentation tank (capacity 50 L drum) for 2–3 hours to allow the heavier particles to settle down.
3. *Decantation:* The liquid above the sludge was gently pumped into sterile containers, while the sludge was left behind.
4. *Oil and Grease Removal:* If there were oil layers floating on the surface (mostly from kitchen waste), they were removed by means of a skimming technique to avoid film formation at the surface that could limit light penetration and gas exchange during plant growth.

The pre-treated grey water was clarified and then stored at low temperatures (below 25°C) to ensure integrity prior to phytoremediation testing with the samples taken 12 hours before use.

2.4 Experimental Setup

The phytoremediation experiment was set up with 10 trough reactors made of plastic (dimensions: 45 cm diameter x 20 cm depth), and 10 liters of pre-treated grey water in each of them. Freshly picked duckweed (Lemna minor) was obtained from a natural pond that is close to the NDU campus and was allowed to acclimatize for 7 days under laboratory conditions with diluted nutrient solution before being used. Each condition of the experiment was replicated three times (n = 3) to guarantee the statistical validity of the results and their reproducibility. Each treatment tank was loaded with 50 g wet weight of duckweed corresponding to surface coverage of about 0.83 kg m^{-2}, as suggested by [27] for efficient nutrient uptake without excessive overcrowding. The same amount of biomass (determined by wet weight) was added to each trough to maintain similar starting conditions.The experimental units were under natural light at room temperature (27 ± 2°C) and monitored for 14 days. The sampling for water quality parameters (pH, turbidity, dissolved oxygen, BOD, COD, nitrate, and phosphate) was done every 3 days based on the standard methods [31]. The units with grey water but no duckweed were kept as controls for comparison.

III. Results And Discussion

3.1 Initial Grey Water Characteristics

The initial characterization of grey water, before it underwent treatment, provided a benchmark for determining the amount of pollutants and the later performance of the Lemna spp. The physicochemical parameters that were analyzed included pH, DO, BOD_5, COD, TSS, NO_3^-, PO_4^{3-}, and surfactants. These figures reflect the composition of the raw grey water drawn from domestic sources like baths, laundries, and kitchens in the vicinity of the study.

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Table 1
presents the mean initial values of the analyzed parameters for the collected grey water samples.

Parameter	Mean Value (mg/L)	WHO Standard (Domestic Discharge)	NESREA Standard (Nigeria)	Remarks
pH	6.25 ± 0.12	6.5–8.5	6.0–9.0	Slightly acidic but within range
DO	1.8 ± 0.2	≥ 5.0	≥ 4.0	Low oxygen content
BOD_5	140 ± 10	≤ 30	≤ 50	Exceeds permissible limits
COD	290 ± 15	≤ 250	≤ 150	Above permissible range
TSS	210 ± 18	≤ 30	≤ 40	Highly turbid
Nitrates (NO_3^-)	22.4 ± 1.8	≤ 10	≤ 20	Slightly above safe limit
Phosphates (PO_4^{3-})	9.1 ± 0.7	≤ 5	≤ 5	Above nutrient threshold
Surfactants	7.6 ± 0.5	≤ 0.5	≤ 1.0	Extremely high levels

Source: Laboratory analysis, 2025; WHO (2017); NESREA (2011).

The raw grey water was highly polluted and the results were characterized by high BOD, COD, TSS and surfactants indicating substantial presence of organic matter, solids and residues of detergent. The DO level was extremely low (1.8 mg/L) which signifies anaerobic processes that could lead to foul smell and bacterial growth if the water is released untreated. The pH value of 6.25 is indicating slight acidity most probably due to soap or detergent degradation. The high nutrient concentration (nitrates and phosphates) is a signal that eutrophication might occur if the water is not treated and directly discharged into natural water bodies.

3.2 Comparison with WHO and Local Discharge Standards

Comparing to the [33] and [34], BOD5, COD, TSS, phosphates and surfactants values were all higher than the limits recommended. The implication of that is grey water without treatment is posing a threat to the environment and human health, the risks are:

1. Decrease of dissolved oxygen in the receiving waters due to high organic load.
2. Eutrophication as a result of excessive nutrients (NO3- and PO4-).
3. Surfactants and chemical residues causing toxic effects to aquatic organisms.
4. Aesthetic degradation, odor, and possible microbial contamination of surface or groundwater sources that are near the discharged point. The comparison clearly indicates that there is a need for a treatment system that is effective, affordable, and environmentally-friendly like phytoremediation using Lemna spp. that can cut down the pollution levels considerably before water disposal.

3.3 Implications of Initial Water Quality

There were high concentrations of contaminants found through analysis which indicate that grey water, even though it was less polluted than black water it still had a lot of pollutants which could harm the aquatic environment if not treated right. This result is in line with earlier works [4] and [5] that mentioned the same ranges of pollutants in the; grey water coming from households. Hence, deciding on a good bio-treatment like duckweed-based phytoremediation becomes necessary for managing wastewater in a decentralized way in rural and peri-urban areas of Bayelsa State which have limited access to conventional wastewater treatment facilities.

3.4 Pollutant Removal Efficiency

3.4.1 Temporal Changes in BOD, COD, TSS and Nutrient Concentrations

The Lemna spp. system was evaluated for its capacity to improve grey water quality over a 14day retention period that was characterized by considerable changes in the physiochemical parameters. The results showed an increasing decline of pollutant concentrations in the test system (with duckweed) when compared to the control (without duckweed).

3.4.1.1 Biochemical Oxygen Demand (BOD_5)

BOD_5 values went through a dramatic decline from an initial average concentration of 140 mg/L on day 0 to 32 mg/L on day 14 which represented a 77.1% removal efficiency.

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This large decrease shown is to a great extent the result of the effective biological decomposition of the organic matter that was made possible by the microbial activity which is normally associated with the roots of duckweed and the increased oxygenation of the pond environment. In contrast, the control system only reached a 23% reduction reflecting natural sedimentation and slight biological decay.

3.4.1.2 Chemical Oxygen Demand (COD)

The decrease of COD concentration was from 290 mg/L at the beginning of the experiment to 65 mg/L at the end of the 14th day which means that the removal efficiency was 77.6%. The decline is an indication of the destruction of oxidizable organic and inorganic compounds via a mixture of processes including plant uptake, microbial oxidation, and photolytic reactions under ambient light conditions. Such similarities were observed in a study by [35], where the plant species Lemna minor was able to reduce the COD content of domestic wastewater treatment over 70%.

3.4.1.3 Total Suspended Solids (TSS)

There was a decrease in TSS levels from 210 mg/L at the beginning of the experiment to 38 mg/L at the end of the 14th day, which corresponds to an 81.9% removal efficiency. The significant reduction in suspended solids is explained by sedimentation, duckweed fronds' adsorption of particulates, and biofilms' formation that trap colloidal materials.

The data support the claim that duckweed can clarify the water and make particles settle as [36] also pointed out.

3.4.1.4 Nutrients (Nitrates and Phosphates)

There was a continuous decline in nutrient removal from the very beginning of the experiment till the end. The concentration of nitrate fell from 22.4 mg/L to 6.3 mg/L (71.9% removal) and that of phosphate from 9.1 mg/L to 2.1 mg/L (76.9% removal). The fall in nutrient levels is mainly owing to direct absorption of the nutrients by duckweed for its protein and nucleic acid synthesis and also to microbial processes of nitrification and denitrification in the plant's root zone. The high removal efficiency of nutrients indicates duckweed's contribution to both phytoremediation and biomass generation. Also, the plant's growth rate is increased by the absorbed nitrogen and phosphorus. This finding is consistent with the results of [29], who reported such similar nutrient uptake patterns in Lemnagibba systems treating domestic effluent.

The trend shown in the graph verifies that the biggest decrease in pollutants took place from day 3 to day 10, at the same time as the duckweed was actively growing. Pollutant levels reached a plateau at day 14 indicating that a saturation level had been reached where the removal process slowed down due to the lack of nutrients and a decrease in the plant's uptake rate.

Table 2.
The comparative performance summary of major pollutants removal is presented

Parameter	Initial Concentration (mg/L)	Final Concentration (mg/L)	Removal Efficiency (%)
BOD_5	140	32	77.1
COD	290	65	77.6
TSS	210	38	81.9
Nitrates (NO_3^-)	22.4	6.3	71.9
Phosphates (PO_4^{3-})	9.1	2.1	76.9

The overall results affirm that duckweed-based phytoremediation treatment of domestic grey water is a very effective and cheap method. The system accomplished a more than 70% decrease in the key pollutants thus raising the quality of effluent to the level of the allowed discharge limits [33], [34].

3.5 Effect of Duckweed Growth on Treatment Performance

3.5.1 Correlation Between Biomass Increase and Pollutant Reduction

The growth dynamics of Lemna spp. considerably impacted the overall process of the phytoremediation method.

In a period of 14 days corresponding to the retention time duckweed biomass was increased steadily which in turn indicated the conditions for growth were favorable and the grey water medium had enough nutrients for the plant. The initial biomass or density of 250 g/m² at the beginning of the experiment was increased to about 580 g/m² by the 14th day which is equivalent to an increase of 132% in biomass. This huge increase in biomass had strong correlation with the decreasing rates of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total dissolved solids (TSS) and nutrient (NO_3^- and PO_4^{3-}) concentrations.

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The Pearson correlation analysis uncovered strong negative correlations between duckweed biomass and the concentrations of the pollutants ($r = -0.91$ for BOD_5, $r = -0.87$ for COD, and $r = -0.83$ for phosphates at $p < 0.05$), which points out that the reduction of pollutants was directly linked to the growth and metabolic activity of duckweed. This practice is in line with the results of [29] and [37] who stated that the nutrient removal efficiency in duckweed systems is proportional to the rate of biomass accumulation as the plant incorporates nitrogen and phosphorus for protein and nucleic acid synthesis. Biomass also loused light up photosynthetic processeswhich further facilitate the degradation of organic matter through increased oxygenation and microbial activity.

3.6 Duckweed Color, Health, and Surface Coverage Observation

During the course of the experiment, the visual and physiological condition of duckweed was a major qualitative indicator reflecting the treatment system performance. In the beginning period (days 0–3), the leaves of duckweed were light green and sparsely present, a sign of adaptation to the new water environment and irregular organic load. On the seventh day, the duckweed was already totally bright green and with more than 85 percent of the water surface occupied, which was a sign of the best nutrient uptake and healthy growth. The same time occurred the fastest falling of the pollutant concentrations which were mainly BOD_5 and TSS, and thus a vigorous plant growth could be confirmed to contribute to the enhancement of the treatment efficiency. During the last period (days 10–14), a minor yellowing of the older leaves and a decrease in the growth rate were noted, especially in tanks where nutrient levels had dropped drastically. This is indicative of nutrient exhaustion and senescence due to the lack of nitrogen and phosphorus. The plants, however, did not let the minor color change stop them from covering a large surface area and carrying out the pollutant removal through biological interactions and root-zone microbial activity. The healthy growth of duckweed for most of the experiment indicates that when diluted to moderate levels, grey water can be a source of growth for duckweed without causing any injury. Similar results were reported by [11], who pointed out that duckweed is able to stay very productive in domestic wastewater environments enriched with nutrients as long as the concentration of surfactants is well below the toxic level.

3.7 Implications for Sustainable Water Management

3.7.1 Reuse Potential for Irrigation or Non-Potable Purposes

The use of Lemna spp. (duckweed) for the effective phytoremediation of grey water shows that the treated effluent can be recycled in non-potable applications very well, especially for irrigation, aquaculture, toilet flushing, and landscape maintenance. Besides, the reduction of the main pollutants to the acceptable limits, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, nutrients and surfactants means that the reclaimed water is fit for reuse in secondary applications when closely monitored. [F38] and FAO irrigation water quality standards state that the effluent with very low nutrient levels and no pathogens is good for irrigation, especially in controlled irrigation systems. The grey water that is treated in duckweed ponds usually has residual nitrogen and phosphorus. These can be seen as beneficial nutrients [39] for the plants' growth, instead of becoming pollutants. The over-nutrient water can be a soil improver, and thus lessening the amount of synthetic fertilizers needed and helping to maintain the sustainability of agri-output. In addition to that, the cycling of treated grey water helps to relieve pressure on fresh water resources in regions where the water shortage is a permanent or seasonal problem. By making it possible to "close the water loop," the duckweed-based systems not only contribute to the adoption of integrated water resource management (IWRM) and circular economy practices that are based on recycling with minimum environmental discharge and water reuse but also support these practices.

Research conducted by [17] and [29] demonstrated that the irrigation with duckweed-treated wastewater within permissible limits does not have a negative impact on the soil physicochemical properties or crop yield. The water availability is increased, thus making it one of the most practical and economical methods of promoting sustainable agriculture through minimizing the pollution of groundwater and surface water sources. Hence, duckweed phytoremediation gives two advantages, as it not only provides a dirt-cheap treatment solution but also produces reusable water that can be used for the support of local communities and agricultural sustainability.

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Summary of Implications

Aspect	Duckweed-Based Phytoremediation Impact
Water Reuse	Provides treated effluent suitable for irrigation and other non-potable uses
Environmental Sustainability	Reduces freshwater extraction and pollution loads
Economic Benefit	Produces reusable biomass; reduces fertilizer and water costs
Community Application	Suitable for small-scale, decentralized systems in rural/peri-urban areas
Policy Relevance	Supports SDG 6 and integrated water resource management strategies

IV. Conclusion And Recommendations

4.1 Summary of Findings

This study explored the possible use of Lemna spp. (duckweed) for the phytoremediation of greywater in controlled laboratory situations at the Soil & Water Laboratory, Department of Agricultural Engineering, Niger Delta University. The findings indicated that not only duckweed was an effective but also a sustainable species for domestic greywater treatment, since it was able to reduce significantly the major physicochemical parameters throughout the treatment period. The study confirmed that duckweed-based systems were high in pollutant removal efficiencies particularly for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), and nutrients (nitrates and phosphates). The decrease in BOD and COD levels pointed out that a large part of the organic matter had been degraded through the combined plant absorption, microbial activity and sedimentation processes within the treatment system. Nutrient removal was mostly due to biological assimilation, microbial nitrification–denitrification, and adsorption mechanisms occurring in the soil/medium of the duckweed roots. A positive correlation was found between the continuous increase in duckweed biomass observed throughout the experiment and pollutant removal performance, thus confirming the plant's active role in nutrient uptake and organic matter stabilization. The quality of the treated effluent met non-potable water standards as per the [38] reference for restricted irrigation and other reuse purposes that point to the safe and sustainable reuse of grey water.

The study finally determined that duckweed phytoremediation could be an alternative to the conventional wastewater treatment techniques, which are costly, energy-demanding, and environmental unfriendly. It is particularly good for decentralized applications in rural and peri-urban areas. The extremely low operational requirements of the system and the possibility of reusing the biomass make it even more viable for adoption in developing regions like Bayelsa State, Nigeria.

These results were in agreement with the findings of [17] and [29], who used Lemna minor and Lemnagibba in domestic wastewater and grey water systems and obtained similar effluent quality. The consistency of results across studies boosts the trustworthiness of the use of duckweed as a phytoremediation agent for grey water management. In conclusion, the investigation gave evidence that duckweed the Phytoremediation method is a good and practical alternative for enhancing the quality of grey water, saving on freshwater resources, and promoting integrated water resource management in poor and resource-starved areas.

4.2 Practical Applications

4.2.1 Integration in Small-Scale Domestic Wastewater Systems

This research trial confirmed the possibility of using duckweed nature-based treatments in the small-scale domestic wastewaters treatment setups as an inexpensive and eco-friendly alternative to the traditional systems. The designed for such systems can easily adapt by locally available materials such as 4-inch PVC pipes, plastic containers, or concrete basins which will be directly receiving grey water from the household sources like bathrooms, laundries, and kitchens. By utilizing duckweed ponds as the final stage of polishing after simple sedimentation or filtration units, households can achieve a highly quality of the effluent after maintenance of minimum level. The system's shallow depth, low hydraulic retention time (7–14 days typically), and rapid plant growth make it suitable for on-site treatment of both urban and rural residences. Also, these decentralized systems are not only limited to the household scale but can be scaled to community levels and adapted to very different climatic and spatial conditions. Besides, the primary duckweed biomass obtained can be used as livestock feed, composting material, or bioenergy substrate, thereby supporting the circular economy in rural areas.

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As per works cited in [17] and [29], duckweed systems have been approximated to remove nitrogen and phosphorus from domestic wastewater by 90%, hence making them a must-have option for wastewater treatment and reuse at the household level. This method could not only cut down the grey water discharge in the Bayelsa State and similar areas but also clean up the local environment through the reuse of the water for non-potable purposes such as irrigation, flushing, and washing.

4.2.2 Educational and Community-Based Implementation

The technology behind duckweed-based grey water treatment may be feasible but community awareness, education, and participation are the factors that will contribute a lot to the treatment's success. The environmental education and sustainable water management training at the grassroots level will be made easier by the establishment of such systems. Educational institutions, primarily secondary schools, tertiary research centers, and agricultural training institutes may take the duckweed treatment units as demonstration models for imparting knowledge in eco-technology, environmental engineering, and sustainable resource management. This practice will not only increase the scientific literacy but also nurture the students and residents around them in the innovation of low-cost water treatment technologies. Community-based organizations, local councils, and non-governmental organizations can be instrumental in the adoption process, i.e., by running public sensitization campaigns, offering capacity-building workshops and carrying out pilot projects in peri-urban and rural areas. Such participatory methods will not only make the local people feel ownership but also will contribute to the system maintenance and changing of behaviors towards responsible wastewater management.

In addition, the use of duckweed systems in water and sanitation programs at the community level is in line with the aims of Sustainable Development Goal (SDG) 6, which promotes the idea of providing everyone with access to clean water and sanitation through economical and nature-based solutions. Not only can the communities be made custodians of their wastewater through these initiatives, but public health, environmental quality, and job opportunities can also be improved concurrently.

4.3 Recommendations for Future Research

The results of this study were encouraging and showed that Lemna spp. (duckweed) has a great potential for the phytoremediation of grey water.

Nevertheless, it is important to do more research in order to come up with the best system design, achieve better long-term performance, and guarantee that the technology can be practically applied under different environmental and socio-economic conditions. The following future research recommendations are made:

4.3.1 Study of Seasonal Variations and Hydraulic Loading Rates

Future research should examine how seasonal variations such as temperature, rainfall, solar radiation, and humidity affect the growth, nutrient uptake, and pollutant removal efficiency of duckweed. The Bayelsa State and similar tropical areas undergo significant changes between wet and dry seasons and, thus, understanding these climatic influences is key to maintaining the reliability and effectiveness of the system.

Moreover, the optimization of the hydraulic loading rate should become a major aspect of the researches, since determining the most efficient ratio of inflow volume, retention time, and pollutant concentration is the core of the matter. The hydraulic variation affects oxygen transfer drastically, nutrient contact time, duckweed coverage, and eventually treatment efficiency. The controlled experiments that would be done to compare HRTs in days of 3, 7, 10, and 14 would generate the data to be used for the scaling up from the lab to the field applications. The works of the two mentioned authors [17] and [18] have provided evidence that besides retention time, environmental conditions too are the major determinants of nutrient removal rate in duckweed-based systems. Research in similar areas would be beneficial to the technology being used in the Niger Delta's climate.

4.3.2 Investigation of Combined Plant Species Systems

Research in this direction would be quite fruitful, especially the one dealing with integrated phytoremediation systems performance comprising Lemna spp. with other macrophytes like Eichhornia crassipes, Pistia stratiotes, or Typha latifolia. These multi-species would be able to remove contaminants synergistically as they would be using the unique physiological and microbial associations of each species. To illustrate, the deep-rooted oxygenation provided by Eichhornia crassipes is countered by the coverage at the surface level provided by duckweed which inhibits algal growth and prevents ammonia volatilization. Such combinations of plants can make the system more tolerant, remove complex contaminants more efficiently, and prolong the treatment time even under fluctuating wastewater loads.

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It is necessary to carry out comparative experiments that will bring the value of species interactions, competition for nutrients, and complementary uptake pathways out, this will help in the utilization and the designing of hybrid macrophyte systems suited for both kinds of wastes, grey water, and domestic effluents. The impacts will then be directed towards the formulation of eco-friendly constructed wetland models that would be suitable for the small-scale community uses in the developing areas.

4.3.3 Economic Feasibility and Scalability Assessment

The laboratory and pilot-stage tests have established the technicality of using duckweed for the treatment of grey water; however, upscaling to commercial application must be backed by the proper economic and scalability assessment. Future research may look at the total capital expenditure, costs for operation and maintenance, land area needed, and possible revenue from the sale of the biomass as a by-product. A cost-benefit analysis of duckweed systems versus conventional waste treatment plants will clarify financial viability for various types of settlements like rural, peri-urban, and institutional settings. In addition to that, life cycle impact assessments (LCA) and socio-economic impact studies are suggested for evaluating long-term environmental and economic benefits, e.g., job opportunities, recovery of nutrients, and reduction of carbon footprint. Efforts should be made in particular to investigate community-based management models, where the involvement of local community guarantees the system's sustainability, the ownership, and the lowering of the operational costs. Economic evaluation complemented with environmental performance data will present evidence-based policy recommendations for the adoption and scaling up of phytoremediation techniques in Nigeria and other similar developing countries.

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