SAND FILTRATION PERFORMANCE OF WASTEWATER AND ITS ECOLOGICAL REUSE IN AN ALGERIAN SAHARAN REGION: CASE STUDY OF THE TIDMAINE STATION

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ABSTRACT

In arid regions with light, highly permeable soils, wastewater accumulation and discharge sites can be a significant source of environmental and groundwater contamination. These waters are heavily loaded with organic pollutants and heavy metals. Physical filtration through sand barriers is the focus of this study. This study assesses the efficacy of the Tidmaine wastewater treatment lagoon system in a hyper-arid region of southern Algeria and investigates the potential for reusing the treated effluent. Physicochemical analyses showed a progressive increase in pH from 7.06 to 8.22, consistent with active photosynthetic and bacterial processes. Electrical conductivity increased from 3.44 to 5.90 mS/cm, indicating higher salinity from evaporation and possible groundwater exchange. The turbidity decreased from 4.11 to 1.69 NTU. The sand filtration lagoon had the biggest drop, at 81.3%. Chemical pollution indicators showed that ammonium (NH_4^+) levels significantly reduced from 4.52 to 1.07 mg/L and orthophosphate (PO_4^{3-}) levels dropped from 25.52 to 3.20 mg/L. This shows the good efficiency of the biological and physicochemical removal process. Organic matter degradation was demonstrated by reductions in COD (Chemical Oxygen Demand) and BOD_5 (Biochemical Oxygen Demand (5 days)) from 288.1 and 162 mg/L to 103.8 and 25 mg/L, respectively. Despite these improvements, elevated salinity and residual organic loads exceeded some discharge standards. Technical corrections, including pond impermeabilization, biological enhancement with active sludge, macrophytes, microalgae, and additional sand filtration units, are proposed. The treated effluent shows promising potential for agricultural irrigation and industrial reuse while contributing to habitat enrichment and local biodiversity around the lagoon site.

Keywords: Wastewater, Sand filtration, Reuse, Arid environment, Biodiversity.

INTRODUCTION

Water scarcity is a great challenge in arid and semi-arid regions, where precipitation is minimal and evaporative demand is high. In such contexts, conventional freshwater sources are inadequate to meet agricultural, industrial, and domestic demands. Consequently, reusing treated wastewater has become a practical and sustainable way to help cover the water deficit (Calabrò, 2024; Silva, 2023; Tabatabaei et al., 2020).

Small- to medium-sized communities use lagoons, whether facultative, maturation, or polishing, because they are cheap, easy to operate, and perform well in warm climates (Calabrò, 2024). These natural treatment systems use a combination of physical, biological, and chemical processes to remove organic matter, nutrients, and pathogens from wastewater (Boleydei et al., 2024; Calabrò, 2024). These processes include settling, microbial degradation, algal-driven oxygenation, and photochemical reactions. Lagoon systems are especially useful in arid and semi-arid areas because they require little energy or operational knowledge and often perform better at higher temperatures (Bachi et al., 2022; Ouhammi et al., 2024). The treated effluent can also be reused for crop irrigation or ecological restoration, supporting sustainable water management and benefiting the entire lifecycle in places where water is scarce (Calabrò, 2024; Thompson & Dvorak, 2024). In areas like southern Algeria, where infrastructure and energy resources may be limited, their use is especially appealing. But lagoon-based systems often struggle to meet strict effluent quality standards, particularly for turbidity, nutrient removal, and salinity control (Bachi et al., 2022; Calabrò, 2024).

An important enhancement to lagoon systems is the addition of sand filtration as a tertiary or polishing stage. Slow sand filters can further reduce suspended solids, improve clarity, and provide biofilm-mediated nutrient transformations (Cooper et al., 1994; Reed et al., 1995; Torrens et al., 2009). In arid regions where evaporation concentrates salts, the sand filter can also help stabilise ionic loads and improve water quality through physical retention and adsorption (Garcia et al., 2000; Torrens et al., 2009).

The Tidmaine lagoon system, located in the Algerian Sahara, treats domestic wastewater in very extreme environments. While conventional lagooning offers substantial removal of organic and suspended matter, challenges remain in meeting discharge standards and enabling reuse. The present study aims to (i) evaluate the lagoon system's performance across physico-chemical and biological parameters, (ii) assess the polishing effect of a downstream sand filtration unit, and (iii) propose improvements and evaluate the potential for safe, reusable repurposing of the treated effluent for agriculture, industry, and ecological enhancement.

MATERIALS AND METHODS

In the Adrar region of southern Algeria, the Tidmaine lagoon system is situated in a hyper-arid Saharan environment characterised by high evaporation rates, scarce rainfall, and pronounced temperature fluctuations. The system comprises sequential ponds: a primary settling pond, facultative and maturation basins, a discharge lagoon, and a sand filtration unit. Water samples were collected from six points along the treatment process: inlet, primary decantation, facultative basin, maturation basin, discharge lagoon, and sand filter outlet. Standard methods were used to analyse the physicochemical parameters, such as pH, electrical conductivity, total dissolved solids, and turbidity, as well as pollution indicators like NH_4^+, NO_2^-, PO_4^{3-}, BOD_5, and COD. (Rodier, 1996; (Hespanhol, 1994). Data were compared with Algerian discharge and irrigation standards.

RESULTS AND DISCUSSION

The lagoon showed progressive improvement in effluent quality. The pH levels increased from 7.06 to 8.22, indicating the presence of high activity of microbes and algae. The electrical conductivity also increased from 3.44 to 5.90 mS/cm due to the water elevating the salt concentration. The turbidity decreased from 4.11 to 1.69 NTU, which is an efficiency of 58.68%. After sand filtration, the turbidity decreased to 81.3%.

Ammonium levels decreased from 4.52 to 1.07 mg/L, and orthophosphate levels decreased from 25.52 to 3.20 mg/L, indicating that both biological and physicochemical removal processes worked well. The decreases in COD and BOD_5 (from 288.1 and 162 mg/L to 103.8 and 25 mg/L, respectively) indicate that biodegradation is working well. But the high salinity and some organic pollution show that optimisation and technical improvements are needed.

A comparison of the physicochemical parameters at the six sampling points showed that effluent quality improved along the treatment line. The most significant variation was found at Point P5, which is influenced by the lagoon outlet after sand filtration.

Physiological and chemical Parameters

Table 1. Variation of Physicochemical Parameters (pH, Conductivity, Total Solids, and Turbidity).

Sampling Point	Inlet	1st Settling Pond	Facultative Pond	Maturation Pond	Sand Filter Lagoon	Surface Discharge Lagoon
Electrical Conductivity (mS/cm)	3.44 ± 0.12	4.79 ± 0.19	4.35 ± 0.26	4.70 ± 0.18	4.39 ± 0.20	5.90 ± 0.29
pH	7.06 ± 0.21	7.25 ± 0.33	7.60 ± 0.25	7.35 ± 0.20	8.22 ± 0.32	7.27 ± 0.22
Total Dissolved Solids at 110 °C ×10³ (mg/L)	2.15 ± 0.11	2.98 ± 0.15	2.72 ± 0.13	2.95 ± 0.10	2.75 ± 0.14	3.67 ± 0.16
Turbidity (NTU)	4.11 ± 0.23	3.98 ± 0.19	2.15 ± 0.09	1.94 ± 0.08	0.77 ± 0.04	1.70 ± 0.07

pH

The pH of the wastewater increased steadily as it passed through the lagooning process, rising from 7.06 at the inlet to 8.22 at the sand filter outlet (tab. 1). The pH at P5 (≈8.2) showed a small but steady increase relative to earlier stages (7.0–7.6). This means that photosynthesis and microbial activity were both higher. This alkalinization is usually linked to the use of CO_2 during algal growth and active biological stabilisation. Microalgae and autotrophic bacteria that do photosynthesis use dissolved CO_2 and change the carbonate balance to make it more alkaline (El Hachemi, 2012; Kansiime & Nalubega, 1999). Such a pH increase is typical in stabilisation ponds due to important biological productivity and oxygenation. (Abdel-Raouf et al., 2012).

Electrical Conductivity (EC)

The system's electrical conductivity increased from 3.44 to 5.90 mS/cm (tab. 1); however, P5 showed a moderate trend of stabilisation. This suggests that sand filtration helped reduce suspended solids and colloidal ions that cause changes in conductivity. This shows that some ions are being kept, and sediment is settling in the sand filter bed. This is a sign of mineralisation resulting from the decomposition and evaporation of organic matter. (Garcia et al., 2000; Tadesse et al., 2004). In the same way, total dissolved solids increased a little in the treatment units, which means that ions and inorganic salts were accumulated. (Kayombo et al., 2000).

Turbidity

The most significant improvement occurred in turbidity, which decreased from 4.11 NTU at the inlet to 1.69 NTU at P5, with a removal rate of 81.3% (tab. 1). This shows that the sand filter had a good job of getting rid of minute suspended particles, residual organic matter, and microalgal debris that stayed behind after the biological lagoons. The remarkable reduction shows the filter's polishing role and its importance in producing visually and physically clarified effluent. This reduction results from sedimentation of suspended solids and efficient biological flocculation in the facultative and maturation ponds (Mara, 2013; Von Sperling, 2007).

Chemical Pollution Parameters (Nitrogen and Phosphorus)

Table 2. Chemical Pollution Indicators (Ammonium, Nitrite, and Orthophosphate).

Sampling Point	Inlet	1st Settling Pond	Facultative Pond	Maturation Pond	Surface Discharge Lagoon	Sand Filter Lagoon
Ammonium (NH_4^+, mg/L)	4.52 ± 0.14	5.46 ± 0.23	7.22 ± 0.33	7.01 ± 0.25	6.57 ± 0.26	1.07 ± 0.04
Nitrite (NO_2^-, mg/L)	0.24 ± 0.01	0.34 ± 0.02	0.19 ± 0.01	0.24 ± 0.01	0.20 ± 0.01	1.62 ± 0.08
Orthophosphate (PO_4^{3-}, mg/L)	25.52 ± 1.28	14.02 ± 0.66	5.46 ± 0.25	8.62 ± 0.36	3.15 ± 0.14	3.20 ± 0.13

Nitrogen (NH_4^+ and NO_2^-)

The ammonium concentration increased from 4.52 mg/L at the inlet to 7.22 mg/L in the facultative pond. It then reduced to 1.07 mg/L in the sand filter effluent (tab. 2), which means that 83.7% of the ammonium was removed. This pattern shows that the first step is ammonification, then nitrification, and finally volatilisation. (Korkusuz et al., 2004; Luo et al., 2017; Stefanakis & Tsihrintzis, 2009).

The rise in ammonium in the first basins indicates active heterotrophic bacterial degradation of organic nitrogen compounds such as proteins and urea (Tchobanoglous et al., 2003). The subsequent decline is linked to the oxidation of NH_4^+ to NO_2^- and NO_3^- by nitrifying bacteria, mainly Nitrosomonas and Nitrobacter species (Ansa et al., 2012).

Nitrite levels fluctuated between 0.3363 and 0.1897 mg/L throughout the system, with a marked increase (1.62 mg/L) observed in the sand filter outlet, possibly due to incomplete nitrification or reoxidation of ammonium under limited oxygen conditions (Pastich et al., 2016).
Phosphorus (PO_4^{3-})

The concentrations of orthophosphate analysed (tab. 2) showed a significant reduction from 25.524 mg/L at the inlet to 5.464 mg/L in the facultative pond (78.6% removal). However, a lower increase was observed in the maturation pond (8.618 mg/L), followed by stabilisation in the sand filter (3.204 mg/L).

Phosphorus removal in wastewater lagoons occurs mainly through biological uptake, chemical precipitation, and sedimentation (Cooper, 2005; Cooper et al., 1994; Luo et al., 2017). Under anaerobic conditions, polyphosphate-accumulating organisms (PAOs) release phosphate to store carbon as poly-β-hydroxyalkanoates (PHA), while in aerobic phases, they absorb excess phosphate to regenerate their polyphosphate reserves (Nielsen et al., 2012; Oehmen et al., 2007). The alternation of redox conditions in lagoon systems thus favours biological phosphorus removal.

Biodegradability Indices (BOD_5 and COD)

Table 3. Variation of Biodegradability Indices (COD and BOD_5).

Sampling Point	Inlet	1st Settling Pond	Facultative Pond	Maturation Pond	Surface Discharge Lagoon	Sand Filter Lagoon
Chemical Oxygen Demand (COD × 100 mg O_2/L)	288.10 ± 11.52	285.12 ± 10.36	218.59 ± 8.45	142.56 ± 6.23	106.70 ± 4.89	103.84 ± 4.41
Biochemical Oxygen Demand (BOD_5, mg O_2/L)	162.00 ± 7.02	160.00 ± 6.40	105.00 ± 4.41	65.00 ± 2.99	60.00 ± 2.58	25.00 ± 1.25

The chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5) values in Table 3 showed a progressive reduction through the treatment process, from 288.1 mg/L O_2 and 162 mg/L O_2 at the inlet to 103.84 mg/L O_2 and 25 mg/L O_2 at the sand filter outlet, respectively. The overall removal efficiencies were 64.0% for COD and 84.6% for BOD_5, indicating effective degradation of organic matter (tab. 3).
The simultaneous decrease of both indices demonstrates the efficiency of microbial communities in stabilising organic matter under both aerobic and anaerobic conditions (Abdel-Raouf et al., 2012; Ayed et al., 2009; Kayombo et al., 2000; Mara, 2013). BOD_5 removal is mainly attributed to oxidation of biodegradable organic matter by heterotrophic bacteria, while COD reduction includes both biodegradable and non-biodegradable fractions (Abdel-Raouf et al., 2012; Kayombo et al., 2000). The final BOD_5 and COD values in the sand filter effluent meet Algerian wastewater standards (NA 176/2004), indicating that the lagoon treatment system is functioning as intended.

Proposed Improvement and Management Plan
Based on the values obtained from the physicochemical tests and lagoon site prospection, several recommendations were formulated to enhance the performance of the Tidmaine wastewater lagoon system.

Technical Revision
The progressive increase in electrical conductivity recorded in the lagoon ponds suggests that there may be hydraulic interactions between the basins and the underlying aquifer. This remark emphasises the necessity of reviewing the impermeability of the lagoon platforms and, as required, enhancing sealing to avoid infiltration losses and contamination of groundwater resources.

Addition of a Sand Filtration Basin
The water samples collected from point P5 -representing the outlet after the sand filtration unit- demonstrated a significant improvement in the quality of physicochemical parameters compared to other sampling points. This confirms the high efficiency of sand filters in purification. Consequently, it is recommended to install an additional downstream basin -as the figure 01 demonstrated- based on the principle of slow sand filtration, which can further enhance the removal of suspended solids, organic matter, and nutrients.

The significant variation between P5 and upstream points shows the very important polishing function of the sand filtration stage. This unit does more than just mechanically strain. It also:

- physically retains suspended solids and colloids;
- biologically oxidises through microbial biofilms sticking to sand grains;
- Getting nutrients removed through adsorption and assimilation;
- Improved aesthetic and sanitary quality of the treated water.

The sand filter significantly improves the overall efficiency of the Tidmaine lagoon system, making the effluent more suitable for irrigation or industrial use. Its contribution is necessary to meet environmental discharge standards and ensure the sustainability of lagoon-based treatment in arid regions. The impact of sand filters on water treatment has been reported in much recent research. (Hamoda et al., 2004; Verma et al., 2017; Yeszhan et al., 2025; Yu et al., 2025).

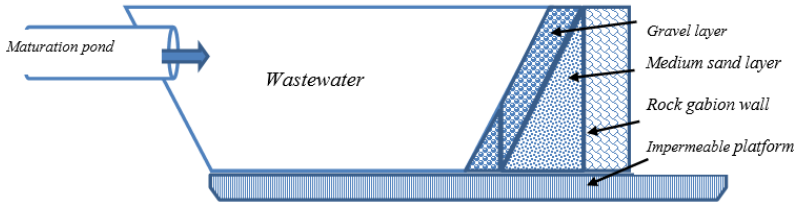

Figure 01. Proposed schematic of a sand filtration basin.

Enhancement of Biological Treatment Mechanisms

The Tidmaine lagoon system would benefit from the integration of biological elements to improve natural purification efficiency, including:

- Macrophytes (e.g., Phragmites spp.) to accelerate the phytoaccumulation of organic pollutants and heavy metals.
- Microphytoplankton and algal biomass to promote natural flocculation and nutrient uptake.
- Activated sludge inoculation to stimulate biodegradation processes, including denitrification and phosphorus removal.

Potential for Reuse of Treated Wastewater

Water resources in the Tidmaine region depend almost exclusively on the deep intercalary aquifer, which is a non-renewable source. Therefore, diversifying water supply through the reuse of treated wastewater represents a suitable, strategic, and sustainable alternative.

When the lagoon system operates efficiently, the effluent quality can meet reuse standards, offering multiple environmental and socioeconomic advantages.

Socioeconomic Impact

Agricultural Reuse

In the studied region (Adrar), agriculture is the most important economic activity. Treated wastewater is rich in nutrients and can be a useful source of water for irrigation, thereby reducing the need for chemical fertilisers. However, due to elevated levels of certain cations associated with salt minerals, it may be necessary to pretreat or dilute with freshwater before irrigation.

Additionally, the stabilised sludge from the lagoons could be used as an organic amendment for composting or improving soil after being analysed for physicochemical properties and made safe for consumers' use.

Industrial Reuse

Treated wastewater can be reused in industrial applications but not for human consumption, such as mining, quarry operations, or petroleum exploration and drilling, thereby conserving high-quality freshwater for domestic use.

Ecological and Environmental Impact

Vegetation Development

The natural growth of herbaceous and shrubby plants and the development of plant-stratum succession around the lagoons have made it easier for birds and small mammals to find suitable habitats and food sources. There have also been reports of predators such as wild cats, jackals, and raptors, which show that this micro-ecosystem has a healthy food web. The presence of predators such as wild cats, jackals, and raptors has also been observed, indicating a balanced trophic structure within this micro-ecosystem.

Habitat and Biodiversity

The Tidmaine lagoon system has developed into a natural habitat for spontaneous flora and fauna, which hosts a wide range of food webs. It is home to many aquatic insect groups (Diptera, Coleoptera, and Hemiptera). It attracts both migratory and resident birds, such as Tadorna casarca, Ciconia ciconia, Himantopus himantopus, Ardea cinerea, Platalea leucorodia, Anas spp., and Fulica atra.

The Adrar Forest Service's annual monitoring reports show that the number of migratory bird species is consistently increasing across wastewater lagoon sites. This shows that these sites are valuable to the environment as artificial wetlands.

Forest Plantation Potential

Purified wastewater can be used to establish protective greenbelts or to support land reforestation programs. In the Tidmaine case, the effluent could cover a 300-hectare forest plantation as belts irrigated through a localised drop system, serving as a windbreak to protect nearby oases from advancing dunes.

As a suggested forest species, Tamarix articulata is well adapted to arid conditions, tolerant of salinity, and capable of developing deep root systems that reach groundwater, making it ideal for ecological restoration in desert environments.

CONCLUSION

- The assessment of the Tidmaine wastewater treatment lagoon indicates that the system efficiently promotes purification under arid climatic conditions, resulting in considerable improvements in key physicochemical and biological parameters. The progressive increase in pH and decrease in turbidity, ammonium, orthophosphate, COD, and BOD_5 indicate the high operating efficiency of the biological stabilisation and physicochemical removal processes. The sand filtration unit is the most important part of the polishing process. It ensures that the effluent is high-quality, meets Algerian discharge standards, and can be safely reused in agricultural and industrial activities. However, the recorded increase in electrical conductivity indicates salt accumulation and the risk of partial infiltration that requires technical interventions, particularly regarding lagoon impermeability and hydraulic management.
- The integration of additional sand filtration ponds and bioremediation based on macrophytes and microbial bioaugmentation would further enhance treatment efficiency and nutrient removal. Beyond its treatment performance, the Tidmaine lagoon contributes to the ecological enrichment of its surroundings, hosting a diversity of animal and plant species adapted to arid ecosystems. The reuse of treated wastewater offers valuable opportunities for agricultural irrigation, industrial applications, and the development of forest tree plantations as protective greenbelts. These findings confirm the combined role of lagoon systems in wastewater management and biodiversity conservation in extreme desert conditions, underscoring their relevance as sustainable, low-cost solutions for arid and semi-arid regions.

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