

## ORIGINAL RESEARCH ARTICLE

# Sustainable wastewater management and risk assessment in Maghnia

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**Abstract:** Located 40 km west of the wilaya of Tlemcen, the Algerian municipality of Maghnia is currently experiencing a severe water shortage that has affected all economic sectors, particularly agriculture. Given that Maghnia is a predominantly agricultural region with 250 hectares of irrigated land, maintaining agricultural productivity under such conditions poses significant challenges. One of the most viable and cost-effective strategies to address this issue is the reuse of non-conventional water sources, specifically the recycling of wastewater treated at the Lagfafe wastewater treatment plant (WWTP). Situated 5 km northwest of the town, the Maghnia WWTP operates using an intensive activated sludge process. This study aims to assess whether the quality of the treated effluent complies with Algerian standards for agricultural reuse. Throughout 2020, wastewater samples were collected and analyzed four times per month at both the inlet and outlet of the treatment plant. The physicochemical parameters examined included temperature, chemical oxygen demand, ortho-phosphates, electrical conductivity, nitrites, nitrates, ammoniacal nitrogen, water potential, dissolved oxygen, suspended solids, and biological oxygen demand. The analytical results indicate that the treated wastewater meets national regulatory standards for agricultural reuse across all evaluated parameters. Consequently, this substantial volume of treated water can be safely used for irrigation, offering a sustainable solution to mitigate the ongoing water crisis affecting the region's agricultural sector.

**Keywords:** Water scarcity; Non-conventional water reuse; Sustainable agriculture; Wastewater treatment; Environmental safety; Maghnia; Algeria

## 1. Introduction

Water is essential for all aspects of human life.<sup>1</sup> The global water crisis, which continues to worsen, is driven by several interrelated factors: rapid population growth,<sup>2</sup> excessive water consumption, degradation of surface and groundwater quality, the impacts of climate change,<sup>3</sup> and decreasing precipitation levels.<sup>4</sup> As a result, this vital resource is becoming increasingly scarce and difficult to manage. While water scarcity

is a global concern, African countries are particularly vulnerable to its effects.

This alarming situation is illustrated by unprecedented droughts affecting rivers and the accelerated melting of glaciers, which compromise water availability for populations, agriculture, and ecosystems.<sup>5</sup> Over the past century, global freshwater use has increased sixfold, with a 1% annual growth rate since the 1980s.<sup>6</sup> According to the World Health Organization (WHO) (2023), over two billion people experienced water stress in 2021 – a

situation worsened by climate change and demographic dynamics. In 2022, 1.7 billion people consumed water contaminated with fecal matter, posing serious risks to public health. Microbial contamination contributes to approximately 505,000 deaths from diarrheal diseases annually, highlighting the critical need for safe drinking water and hygiene.<sup>7</sup>

The increasing demand for water also degrades its quality, as pollution from industrial, agricultural, and urban sources threatens both human health and sustainable development. Globally, 80% of industrial and municipal wastewater is discharged untreated, particularly in developing countries lacking adequate sanitation infrastructure.<sup>8</sup> Pollution from various sectors endangers drinking water sources, disrupts aquatic ecosystems, and threatens biodiversity.<sup>9</sup> Diffuse pollution further contributes to eutrophication, increased water treatment costs, public health hazards, and reduced recreational value of water bodies.<sup>10</sup>

To address global water shortages, several non-conventional water management strategies are being explored. Seawater desalination is a technologically advanced but capital-intensive and logistically complex approach.<sup>11</sup> Advanced wastewater treatment ensures ecological safety before environmental discharge.<sup>12</sup> Strategic reuse of treated wastewater is a cost-effective, simpler, and faster option that enhances water sustainability and local resilience.<sup>13</sup>

Maghnia, a region in northwestern Algeria, is particularly affected by water scarcity. It has an irrigated agricultural area of 250 hectares. The reuse of treated wastewater from the Lagfate wastewater treatment plant (WWTP) presents a promising solution to mitigate agricultural water shortages in the area. The city depends on the Hammam Boughrara dam, which has experienced significant reductions in storage volume due to prolonged drought, severely impacting irrigation. Meanwhile, the treated effluent from the Lagfate WWTP is discharged into the environment without being reused.

This study aims to assess the quality of treated wastewater from the Lagfate WWTP and determine its compliance with Algerian standards for agricultural reuse. By analyzing key physicochemical and microbiological parameters, the study evaluates whether the treated effluent is suitable for safe irrigation. Given the growing water scarcity in Maghnia, this approach offers a sustainable alternative to conventional water sources. The findings aim to support integrated and locally adapted water resource management strategies.

Wastewater reuse involves collecting municipal effluent, treating it at a WWTP, storing it, and distributing it for specific uses.<sup>14</sup> Agricultural reuse of treated wastewater is a widely adopted practice with decades of application across various countries, such as the United States, Mexico, Chile, Peru, Tunisia, Saudi Arabia, Australia, South Africa, China, Italy, and Spain. The volume of reused wastewater is growing annually by more than 30% in Europe and over 40% in the United States and China.<sup>15</sup> Globally, approximately 20% of treated wastewater is currently reused.<sup>16</sup>

The objectives of wastewater reuse include economic efficiency, technical feasibility, and resource conservation. These goals involve the preservation of natural resources by reducing withdrawals from conventional water sources and limiting wastewater discharge;<sup>17</sup> reducing the need for fertilizers due to the nutrient-rich content of treated water, particularly nitrogen and phosphorus; strengthening national capacities in integrated water management; and meeting irrigation demands through reliable water availability.<sup>18</sup>

Depending on the intended use, wastewater reuse can be classified into two main categories. Potable reuse includes both direct reuse (after advanced treatment) and indirect reuse (after environmental buffering, such as aquifer recharge).<sup>19</sup> Non-potable reuse is primarily applied in industrial and agricultural contexts. In industrial settings, recycled water can meet up to 85% of demand, particularly in power generation and paper production, with regulatory frameworks guiding the quality requirements based on the application.<sup>20</sup> In agriculture, which accounts for over 70% of global freshwater consumption, wastewater reuse presents the greatest reuse potential in the short to medium term.<sup>21,22</sup>

To ensure public health and environmental safety, wastewater reuse must be regulated. In response to growing concerns, the WHO, the Food and Agriculture Organization, and various countries have developed guidelines for safe reuse practices.<sup>23</sup> The strategic implementation of wastewater reuse offers multiple benefits.<sup>24</sup> It supports the preservation of high-quality water sources and provides economic advantages for farmers, including lower irrigation costs and reduced fertilizer use due to the nutrient content of treated wastewater. It also ensures year-round water availability, facilitating crop diversification and improved yields. Moreover, it stimulates the agri-food sector, contributing to job creation and improved livelihoods. The development of the agricultural sector, in turn, stimulates growth in the commercial and agro-industrial

sectors, consequently improving the living standards of citizens and creating new employment opportunities.

However, the lack of strict quality control and proper monitoring can result in adverse consequences, including the spread of waterborne diseases and ecosystem degradation. Therefore, strict adherence to reuse standards is essential.<sup>25</sup>

Advanced wastewater treatment plays a crucial role in protecting public health from pathogenic microorganisms, safeguarding aquatic biodiversity, preserving surface and groundwater resources, and creating a reliable, economically viable water source that contributes to community resilience.

As global water quality and availability deteriorate, countries must diversify their water sources. A review of wastewater reuse practices in Morocco, Algeria, and France highlights promising outcomes. In France, the Limagne Noire project irrigates 700 hectares using treated water from the Clermont-Ferrand WWTP. The initiative demonstrates technical reliability, sound institutional coordination, and economic viability – maintaining 60 agricultural jobs and generating €1.66/m<sup>3</sup> in added value.<sup>26,27</sup> In Algeria, the Boumerdès region produces over 400,000 m<sup>3</sup> of treated wastewater annually, with a small portion reused for agriculture. Since 2002, two farmers in Corso have irrigated 71 hectares with treated wastewater, yielding crops of comparable quality to those irrigated with potable water. The initiative is positively assessed by both agricultural and public health authorities.<sup>28,29</sup> In Morocco, a study in Drrarga evaluated the use of treated wastewater for tomato irrigation. While yields doubled and fertilizer use decreased, soil nutrient depletion and potential nitrate contamination of groundwater were noted, emphasizing the need for complementary fertilization and monitoring.<sup>18</sup>

According to the National Economic and Social Council (NESC, 2000), Algeria faces structural water scarcity, with per capita resources below 1,000 m<sup>3</sup>/year.<sup>30,31</sup> The most common form of reuse is agricultural irrigation,<sup>32</sup> with treated wastewater reuse increasing from 17 × 10<sup>6</sup> m<sup>3</sup> in 2011 to 200 × 10<sup>6</sup> m<sup>3</sup> in 2014.<sup>33</sup> However, resource limitations and rising demand continue to intensify water stress. In response, Algeria has promoted wastewater recycling, rural hydraulic projects, and improved irrigation efficiency. Desalination is being adopted in urban centers such as Algiers, Oran, and Arzew, though its cost remains high.<sup>34</sup> Algeria's total renewable water potential is estimated at 18 × 10<sup>9</sup> m<sup>3</sup>/year. Irrigation accounts for 62% of consumption, followed by domestic (35%) and industrial (3%) uses.<sup>35</sup>

In 2016, Algeria reused 14.6 × 10<sup>6</sup> m<sup>3</sup> of treated wastewater to irrigate over 11,000 hectares, particularly in regions such as El Oued, Ouargla, Guelma, and Tlemcen. By 2019, this volume had reached 1.32 × 10<sup>6</sup> m<sup>3</sup> for 11,045 hectares.<sup>36,37</sup> Successful agricultural reuse depends on rigorous treatment and compliance with national standards. Algeria has introduced legislation to ensure public health protection and groundwater safety.<sup>38</sup>

Despite the growing literature on wastewater reuse, most studies are descriptive, small-scale, or urban-centric. There is a lack of robust data on the operational performance of full-scale WWTPs in semi-arid inland regions where water scarcity is most acute. Existing studies often suffer from inconsistent sampling and lack of seasonal analysis, as well as limited data on emerging contaminants (e.g., pharmaceuticals, microplastics), which pose unregulated health risks.

This study adopts a rigorous and original approach. Methodologically, it implements a 1-year sampling campaign with four samples per month. Statistically, it uses paired-sample *t*-tests and 95% confidence intervals (CIs) to assess significant changes between influent and effluent. Technically, it evaluates a full-scale activated sludge WWTP under real semi-arid conditions. Politically, it highlights regulatory gaps and contributes evidence-based recommendations for water reuse policy. By integrating these dimensions, the study provides a transferable contribution to sustainable water management in Global South contexts facing climate stress and structural constraints.

## 2. Methods

### 2.1. Geographical location and population of Maghnia

Maghnia is situated approximately 40 km west of the Tlemcen Province in northwestern Algeria. It is bordered to the east by Remchi,<sup>39</sup> to the north by Fellaoucene, to the west by the Moroccan border, and to the south by Béni Bousaid. The municipality covers a total area of 294 km<sup>2</sup>. The geographical location of the Maghnia district is illustrated in [Figure 1](#). The population of Maghnia grew from approximately 87,400 in 2008 to 150,000 in 2021.

### 2.2. Climate conditions in Maghnia

Climatic data presented in this section were obtained from the climatological station in Maghnia. The analysis focuses on temperature, precipitation, and seasonal variations.

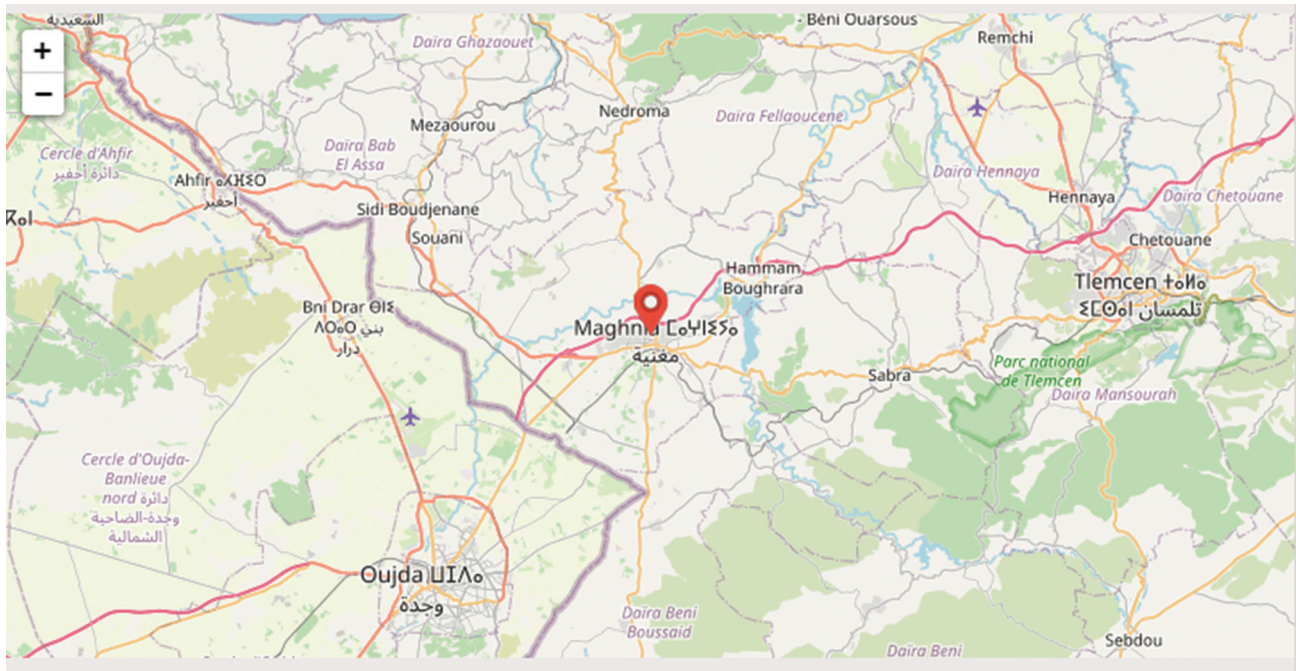


Figure 1. Location of Maghnia

2.2.1. Temperature and rainfall

According to Table 1, the climate of Maghnia is characterized by hot, dry summers. The highest average monthly temperature (27°C) was recorded in August, accompanied by minimal rainfall ranging from 3.4 mm to 6.01 mm. Winters are relatively cool and wet, with temperatures ranging from 10.4°C to 13.5°C.<sup>40</sup> The lowest average temperature (10.4°C) was observed in January. Rainfall during the winter season varies between 34.9 and 40.5 mm. Spring, extending from March to May, is marked by mild temperatures (13.5 – 18.8°C) and is the wettest season, with average monthly precipitation ranging from 31.9 to 41.5 mm. Autumn is also mild, with rainfall levels ranging from 15.4 to 40.8 mm.

2.2.2. Winds

In Maghnia, wind patterns vary by season. During autumn and winter, winds are predominantly from the west and southwest during the day, shifting to the north and southwest at night, often with high intensity. In contrast, during spring and summer, winds are generally weaker and prevail throughout the day and into part of the night.

2.3. Location of the WWTP

Commissioned in 1999, the Lagfate WWTP is currently managed and operated by the National Sanitation Office. It occupies an area of 11.233 hectares and is located 5 km northwest of Maghnia. The plant is bordered to

Table 1. Average monthly rainfall and temperature (1970 – 2019)

Month	Average temperature (°C)	Average monthly rainfall (mm)
September	23.4	15.4
October	19.6	26.3
November	14.6	40.8
December	11.6	34.9
January	10.4	40.5
February	11.3	38.2
March	13.5	41.3
April	15.5	41.5
May	18.8	31.9
June	22.7	8.3
July	26.3	3.4
August	27	6.0

Note: Climatic data were obtained from ref.<sup>41</sup>

the east by the Boughrara Dam, to the west by the town of Maghnia, to the north by Ouled Bendamou, and to the south by Oued Charef. Figure 2 illustrates the geographical location of the Lagfate WWTP.

2.4. Overview of the WWTP layout and functional setup

The Lagfate WWTP treats domestic wastewater from Maghnia and is designed to serve a population equivalent



**Figure 2.** Top view of the Maghnia wastewater treatment plant. The image was obtained from Google Earth in 2022.

of 150,000, with an average daily flow of 30,000 m<sup>3</sup>. The facility covers an area of 11 hectares and has been managed and operated by the National Sanitation Office since 2003. The WWTP fulfills two essential roles: (i) to protect public health and the environment and (ii) to prevent the pollution of the Hammam Boughrara dam by wastewater discharged from urban areas in the Maghnia urban area. The main components of the Lagfate WWTP are designed for storm overflow, pre-treatment, biological treatment, and sludge treatment functions.

#### 2.4.1. Storm overflow

The overflow weir is designed to handle a flow rate of 3,266 m<sup>3</sup>/h.

#### 2.4.2. Pre-treatment

The pre-treatment stage includes several operations: (i) “screening” comprises one manually cleaned coarse screen, one manual bypass screen, and two mechanized fine screens and (ii) “grit and oil removal” is performed using two longitudinal grit chambers with dual compartments.

#### 2.4.3. Biological treatment

For this process, denitrification and aeration basins are installed, consisting of four units combined into a single structural unit. In addition, two secondary clarifiers are used to settle and clarify the effluent after biological treatment. For chlorination, a reinforced concrete tank with a volume of 826.5 m<sup>3</sup> is used; however, this process was not performed in 2020.

#### 2.4.3. Sludge treatment

The sludge is thickened and then directed to drying beds for dewatering.

## 2.5. Analytical methods

To assess the quality of treated wastewater from the Lagfate WWTP and ensure that the water meets agricultural reuse standards (Table 2), we conducted analyses on both inflow and outflow wastewater in 2020. Sampling was performed four times per month, except for September, when no analyses were performed.

Wastewater samples were collected at both the inlet (raw water) and outlet (treated effluent) of the WWTP, before discharge into the natural environment. Samples were carefully taken to ensure they accurately represented the source environment. Sampling was conducted between 11:00 AM and 1:00 PM, during peak activity periods. Standard glass vials were used for physicochemical sample collection. These vials were thoroughly cleaned (washed, rinsed, and dried) and then sterilized before use. The procedure for collecting samples involved holding the sterile container by its base, carefully lowering it beneath the wastewater surface, uncapping it, and filling it to the required depth. After collection, the container was immediately sealed. Proper labeling and storage conditions were maintained, ensuring protection from light and heat. The samples were transported in a cooler, maintaining a temperature of approximately 4°C.

The following physicochemical parameters were analyzed: temperature, chemical oxygen demand (COD), ortho-phosphates (PO<sub>4</sub><sup>3-</sup>), conductivity, nitrite (NO<sub>2</sub><sup>-</sup>), nitrate (NO<sub>3</sub><sup>-</sup>), ammoniacal nitrogen (N-NH<sub>4</sub><sup>+</sup>), water potential, dissolved oxygen (DO), suspended solids, and biological oxygen demand (BOD<sub>5</sub>). COD, PO<sub>4</sub><sup>3-</sup>, NO<sub>2</sub><sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and N-NH<sub>4</sub><sup>+</sup> were measured using a spectrophotometer. Suspended solids were determined by filtration. Water potential, DO, and BOD<sub>5</sub> were

**Table 2. Algerian standards for physical and chemical parameters in wastewater reuse for agriculture**

Parameters	Unit	Limit
Physical		
pH	-	6.5 <pH <8.5
TSS	mg/L	30
Conductivity	dS/m	3
Chemical		
BOD <sub>5</sub>	mg/L	30
COD	mg/L	90
Cl <sup>-</sup>	mEq/L	10
NO <sub>3</sub> <sup>-</sup> -N	mg/L	30
HCO <sub>3</sub> <sup>-</sup>	mEq/L	8.5
Toxic elements <sup>a</sup>		
Al	mg/L	20
As	mg/L	2.0
Be	mg/L	0.5
B	mg/L	2.0
Cd	mg/L	0.05
Cr	mg/L	1.0
Co	mg/L	5.0
Cu	mg/L	5.0
CN <sup>-</sup>	mg/L	0.5
F <sup>-</sup>	mg/L	15
Fe	mg/L	20
Phenols	mg/L	0.002
Pb	mg/L	10.0
Li	mg/L	2.5
Mn	mg/L	10.0
Hg	mg/L	0.01
Mo	mg/L	0.05
N	mg/L	2.0
Se	mg/L	0.02
V	mg/L	1.0
Zn	mg/L	10.0

Note: <sup>a</sup>Toxic to fine-textured, neutral or alkaline soil types. TSS: total suspended solid; BOD: biological oxygen demand; COD: chemical oxygen demand; Cl: chloride; NO<sub>3</sub><sup>-</sup>-N: nitrate-nitrogen; HCO<sub>3</sub><sup>-</sup>: bicarbonate; Al: aluminum; As: arsenic; Be: beryllium; B: boron; Cd: cadmium; Cr: chromium; Co: cobalt; Cu: copper; CN<sup>-</sup>: cyanides; F<sup>-</sup>: fluoride; Fe: iron; Pb: lead; Li: lithium; Mn: manganese; Hg: mercury; Mo: molybdenum; Ni: nickel; Se: selenium; V: vanadium; Zn: zinc.

measured using a pH meter, an oximeter, and a BOD<sub>5</sub> meter, respectively. The analytical methods employed are described below.

#### 2.5.1. pH measurement

pH is a critical parameter for assessing the acidity or alkalinity at each sampling site. This measurement was performed *in situ* by immersing the electrode of a portable pH meter (model: pH 90; WTW, Germany) directly into the sample container. The reading was recorded once the pH value stabilized on the meter's display.

#### 2.5.2. Conductivity measurement

Conductivity measurements were also performed *in situ*, using a portable conductivity meter (WTW, Germany). After calibrating the instrument, the electrode was immersed in the water sample, and the reading was recorded once it stabilized. The conductivity was expressed in  $\mu\text{S}/\text{cm}$ .

#### 2.5.3. Total suspended solid (TSS) concentration measurement

TSSs, comprising both organic and inorganic fractions, were measured by filtration. The TSS concentration was determined gravimetrically after drying the filter paper at 105°C. Before filtration, the filter paper was washed with distilled water and dried in an oven at 120°C for 2 h. After cooling in a desiccator for 24 h, the initial mass of the filter paper ( $M_0$ ) was recorded. The pre-weighed filter paper was then used to filter a 50 mL aliquot of the water sample. The mass of the filter paper containing the retained solids ( $M$ ) was recorded after the same drying and cooling procedure. The TSS concentration was calculated using the following formula:

$$\text{TSS} = \frac{(M - M_0) \times 1000}{V} \quad (I)$$

where  $V$  is the volume of the water sample analyzed (50 mL),  $M$  is the mass of the filtration disc after use (mg), and  $M_0$  is the mass of the filter paper before use (mg).

#### 2.5.4. BOD measurement

The BOD<sub>5</sub> was measured using a BOD<sub>5</sub> meter. The procedure involved filling 250 mL BOD<sub>5</sub> bottles with the water sample, sealing them with the instrument's stopper and agitator, and incubating them for five days. The reading from the BOD<sub>5</sub> meter was then corrected

using an appropriate factor. BOD<sub>5</sub> values (mg/L) are calculated using Equation II.

$$\text{BOD}_5 = \text{Reading} \times \text{Correction factor} \quad (\text{II})$$

#### 2.5.5. COD measurement

COD was measured by heating a diluted water sample with potassium dichromate in a COD reactor at 150°C for 2 h. A blank sample (reagent + distilled water) was prepared similarly. After cooling, the absorbance of both the sample and the blank was measured at 420 nm using a spectrophotometer (DR2000, Germany). The COD value was determined based on the difference in absorbance between the sample and the blank.

#### 2.5.6. Nitrate concentration measurement

Nitrate concentration was determined using a DR/2000 spectrophotometer with a specific program 355 which was set to 500 nm (DR2000, Germany). After dilution and reaction with a NitroVer 5 capsule, the absorbance of the sample was measured at 500 nm, with a blank used for calibration. The final result was adjusted for the dilution factor.

#### 2.5.7. Ammonium (NH<sub>4</sub>) concentration measurement

NH<sub>4</sub> concentration was measured using a DR/2000 spectrophotometer with a specific program (DR2000, Germany) at 425 nm. After dilution and the addition of stabilizing and Nessler reagents, the sample color was measured against a distilled water blank after a 1-min reaction period.

#### 2.5.8. PO<sub>4</sub><sup>3-</sup> concentration measurement

PO<sub>4</sub><sup>3-</sup> concentration was measured using a DR/2000 spectrophotometer with a specific program (DR2000, Germany) at 890 nm. After dilution and reaction with a ChromaVer. 3 reagent capsule, the blue color of the sample was measured against a distilled water blank following a 2-min reaction period.

#### 2.5.9. Temperature measurement

Temperature measurements were performed *in situ* using a digital thermometer integrated into the portable conductivity meter (WTW, Germany). The thermometer probe was immersed directly into the water sample, and the temperature reading was recorded once it stabilized. Temperature was expressed in degrees Celsius (°C).

#### 2.5.10. DO measurement

DO concentrations were measured *in situ* using a portable DO meter (WTW, Germany). The DO probe was immersed directly into the water sample, and

the reading was allowed to stabilize before being recorded. The instrument was calibrated according to the manufacturer's guidelines before use. DO was expressed in mg/L and as a percentage of saturation (%).

#### 2.5.11. Nitrite measurement

Nitrite concentration was determined using a DR/2000 spectrophotometer with a specific program (Program 345) (Hach DR2000, Germany). After sample preparation and reaction with a NitriVer 3 Nitrite Reagent Powder Pillows, the absorbance of the sample was measured at 507 nm with a blank used for zeroing calibration. Nitrite concentration was expressed in mg/L.

### 2.6. Statistical analysis

All statistical analyses were performed using Microsoft Excel. Descriptive statistics, including means, standard deviations, maximum and minimum values, and 95% CI, were calculated for all measured parameters. To assess the statistical significance of the reduction in COD concentrations between the influent and effluent wastewater, a paired samples *t*-test was conducted. The paired *t*-test was chosen due to its suitability for comparing means from two related groups (i.e., measurements taken before and after treatment from the same source). A  $p < 0.05$  was considered statistically significant.

## 3. Results and discussion

### 3.1. Temperature

Temperature was measured using a thermometer for the area and both inflow and outflow wastewater. These measurements are displayed in [Figure 3](#) and [Table 3](#). From [Figure 3](#), we can observe that the temperatures of the inflow and outflow wastewater are relatively similar, with the two curves nearly overlapping. The average temperature of the inflow wastewater is  $20.50 \pm 3.97^\circ\text{C}$ , while the average temperature of the outflow wastewater is  $20.76 \pm 4.26^\circ\text{C}$ . The maximum temperatures for the inflow and outflow wastewater are  $26.75^\circ\text{C}$  and  $27.50^\circ\text{C}$ , respectively. The minimum temperature for the inflow wastewater is  $11^\circ\text{C}$ , while the minimum for the outflow wastewater is  $12^\circ\text{C}$ .

### 3.2. pH

The pH values of the inflow and outflow wastewater were measured, and the results are presented in [Figure 4](#) and [Table 4](#). The results demonstrate that the pH values of both the influent (mean: 7.82, 95% CI: 7.74 – 7.90) and effluent (mean: 7.95, 95%

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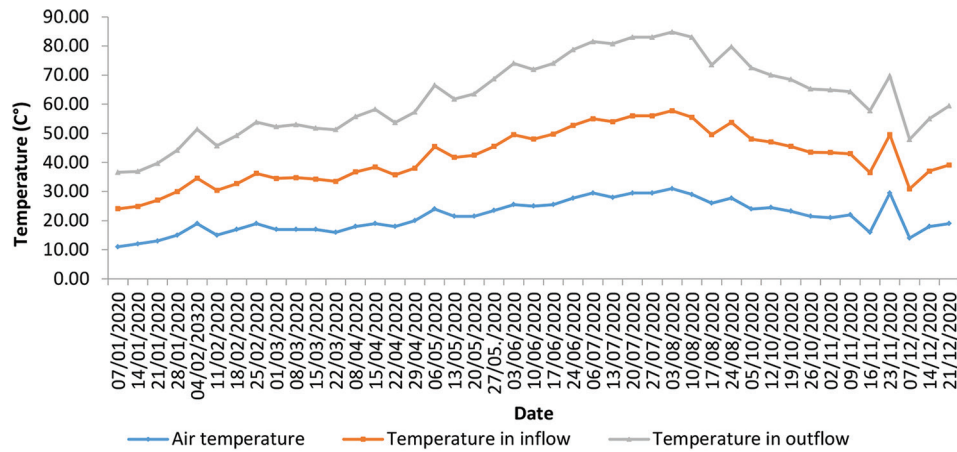


Figure 3. Temperature variations in inflow and outflow wastewater at the Lagfate wastewater treatment plant

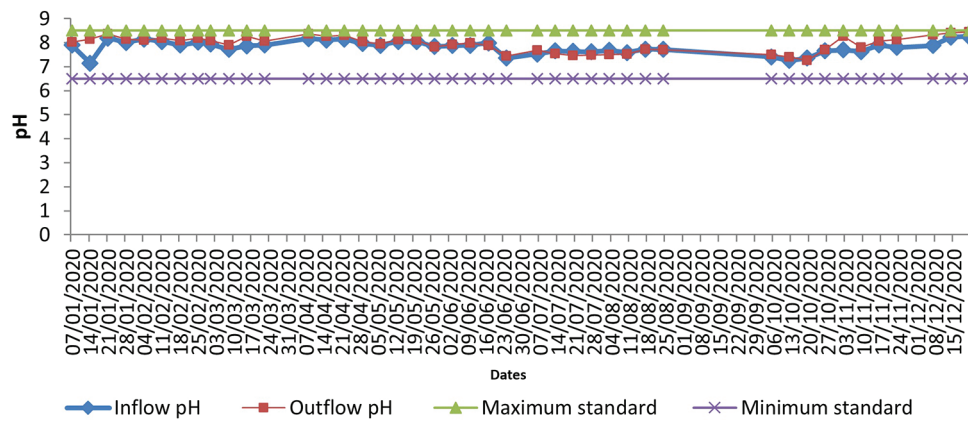


Figure 4. Variations in pH values of wastewater at the Lagfate wastewater treatment plant

Table 3. Temperature of the inflow and outflow wastewater

Wastewater	Temperature (°C)				
	Average	Maximum	Minimum	Median	SD
Inflow	20.50	26.75	11.00	21.50	3.97
Outflow	20.76	27.50	12.00	20.50	4.26

Abbreviation: SD: standard deviation.

Table 4. pH values of the inflow and outflow wastewater

Wastewater	pH					
	Average	Maximum	Minimum	Median	95% CI	SD
Inflow	7.82	8.25	7.14	7.88	7.74 – 7.90	0.26
Outflow	7.49	8.44	7.25	8.04	7.85 – 8.05	0.31

Note: The *p*-value was calculated to be  $1.68 \times 10^{-4}$ .

Abbreviations: CI: confidence interval; SD: standard deviation.

CI: 7.85 – 8.05) wastewater are within the acceptable range established by the agricultural reuse standards. An independent samples *t*-test reveals a statistically significant increase in pH in the effluent compared to the

influent wastewater ( $p = 0.000168$ ), though the increase is marginal. However, both values remain consistently within the regulatory limits. In addition, the low and comparable standard deviation (SD) observed for the

influent (SD = 0.27) and effluent (SD = 0.32) suggests a stable pH throughout the monitoring period.

**3.3. COD**

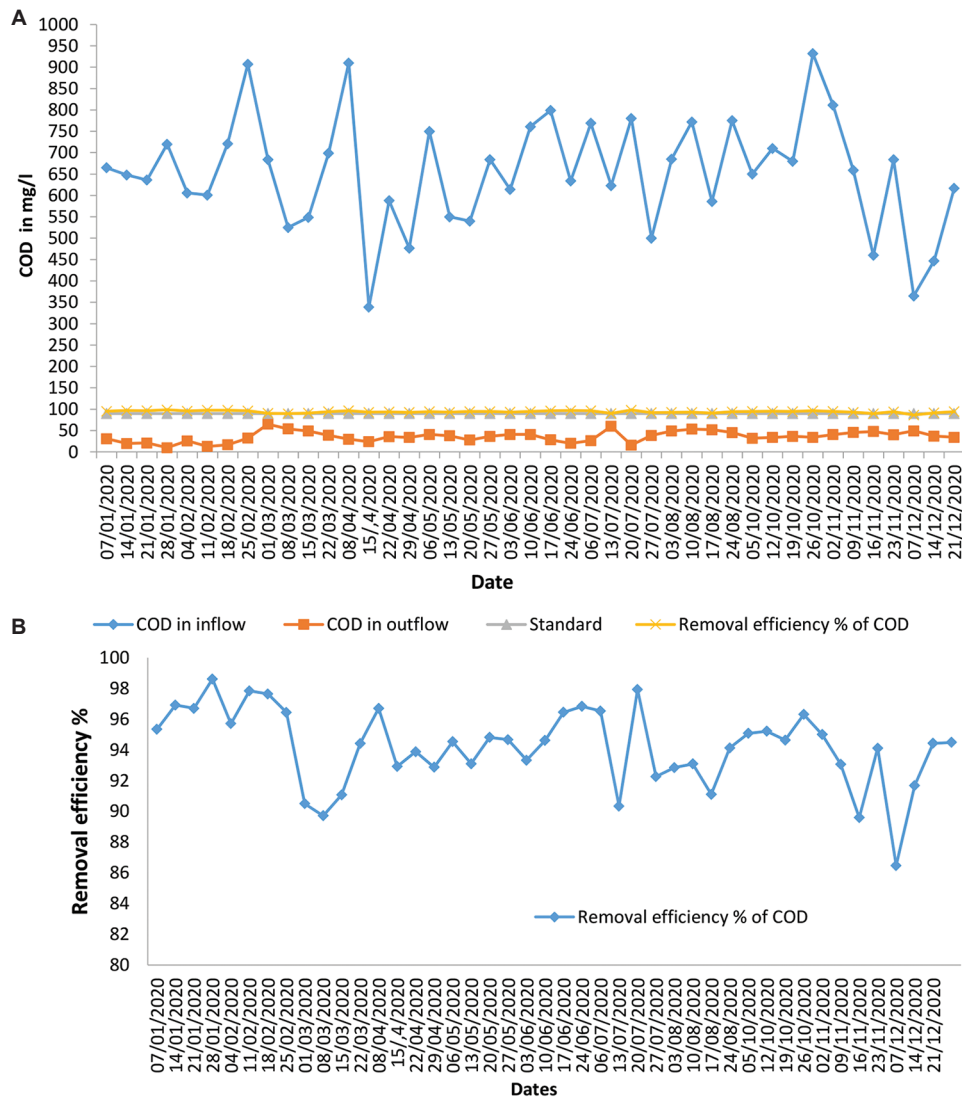
Figure 5A and Table 5 display the measured COD of wastewater. The results indicate a significant organic

load in the influent wastewater, as indicated by high COD (mean: 653.76 ± 132.54 mg/L; maximum: 932 mg/L; minimum: 339 mg/L), likely exacerbated by reduced water consumption during a regional drought. In contrast, effluent COD consistently remained below regulatory thresholds, with a high average removal efficiency of

**Table 5. COD of the inflow and outflow wastewater**

Wastewater	COD (mg/L)					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	653.76	932	339	659	132.54	615.04 – 692.50
Outflow	36.00	65	10	36.5	12.48	32.35 – 39.65

Note: The *p*-value was calculated to be 3.97×10<sup>-47</sup>.  
Abbreviations: CI: confidence interval; SD: standard deviation; COD: chemical oxygen demand.



**Figure 5. (A) Variations in chemical oxygen demand (COD) in inflow and outflow wastewater at the Lagfate wastewater treatment plant. (B) Variations in removal efficiency of COD at the Lagfate wastewater treatment plant.**

94.48% (range: 86.46–98.61%) (Figure 5B). This robust performance is further supported by a highly significant reduction in COD ( $p < 3.97 \times 10^{-47}$ ) from the influent (95% CI: 615.04 – 692.50 mg/L) to the effluent (95% CI: 32.35 – 39.65 mg/L), accompanied by a marked decrease in variability. These findings underscore the remarkable efficacy of the activated sludge process in removing oxidizable organic matter.

### 3.4. BOD

The results of the BOD<sub>5</sub> measurements are displayed in Figure 6A and Table 6. BOD<sub>5</sub> in the influent wastewater was relatively high, with an average value

of  $399.12 \pm 91.33$  mg/L. The maximum concentration of 640 mg/L was recorded in October 2020, while the minimum value of 200 mg/L was observed in November 2020. The significant separation between the influent and effluent curves clearly indicates effective BOD<sub>5</sub> removal.

Throughout the study period, the effluent BOD<sub>5</sub> consistently aligned with the regulatory standard, with no values exceeding the limit of 30 mg/L. This confirms that the treated wastewater complies with the standard for agricultural reuse concerning BOD<sub>5</sub>.

The recorded removal efficiencies were consistently high. The average removal efficiency was 96.96%, with

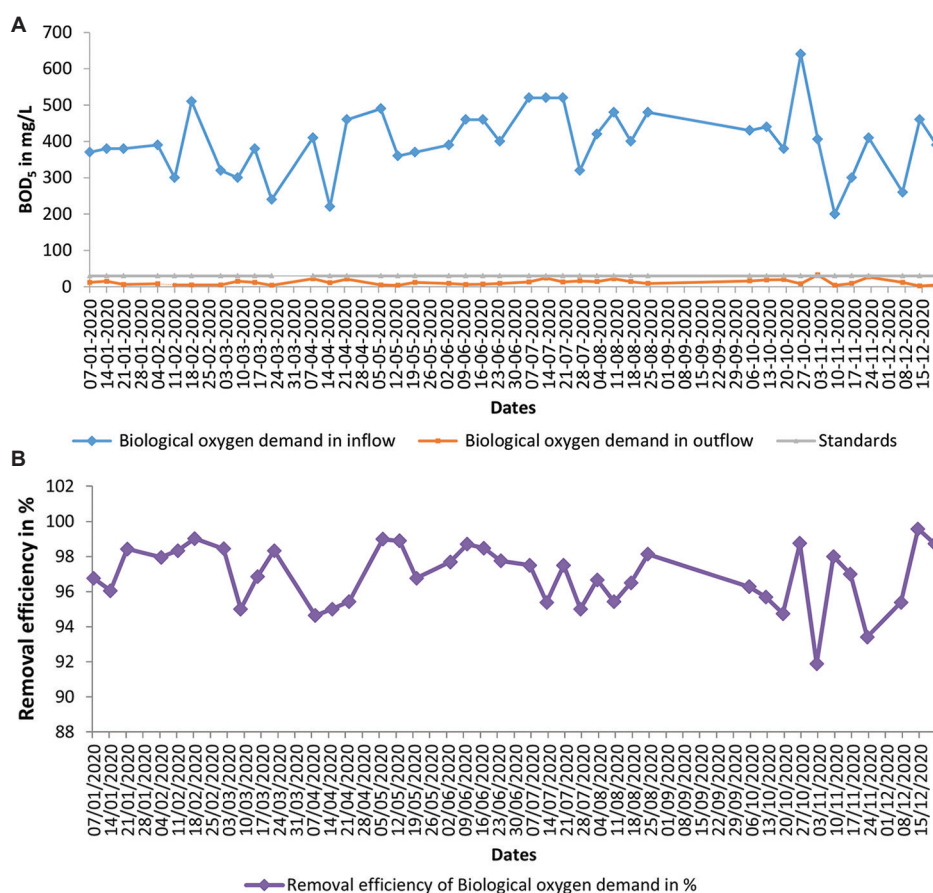


Figure 6. (A) Variations in biological oxygen demand (BOD<sub>5</sub>) in inflow and outflow wastewater at the Lagfafa wastewater treatment plant. (B) Variations in removal efficiency of BOD<sub>5</sub> % at the Lagfafa wastewater treatment plant.

Table 6. BOD<sub>5</sub> of the inflow and outflow wastewater

Wastewater	BOD <sub>5</sub> (mg/L)					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	399.12	640	200	400	91.33	372.44 – 425.82
Outflow	12.12	33	2	12	7.19	10.03 – 14.23

Note: The  $p$ -value was calculated to be  $1.49 \times 10^{-26}$ .

Abbreviations: CI: confidence interval; SD: standard deviation; BOD: biological oxygen demand.

a maximum of 99.56% observed in December 2020 and a minimum of 91.87% in November 2020 (Figure 6B). These results reflect the high performance of the activated sludge process in degrading organic matter.

An independent samples *t*-test yielded a highly significant *p*-value ( $p < 1.49 \times 10^{-26}$ ), rejecting the null hypothesis and confirming a statistically significant difference in mean BOD<sub>5</sub> concentrations between influent and effluent samples. The 95% CI for the

influent BOD<sub>5</sub> mean ranged at 372.44 – 425.82 mg/L, while the effluent BOD<sub>5</sub> mean was 10.03 – 14.23 mg/L. These non-overlapping intervals further support the conclusion of a substantial and statistically significant reduction in BOD<sub>5</sub> levels due to the treatment process.

### 3.5. TSSs

The concentration of TSS in inflow and outflow wastewater is displayed in Figure 7A and Table 7.

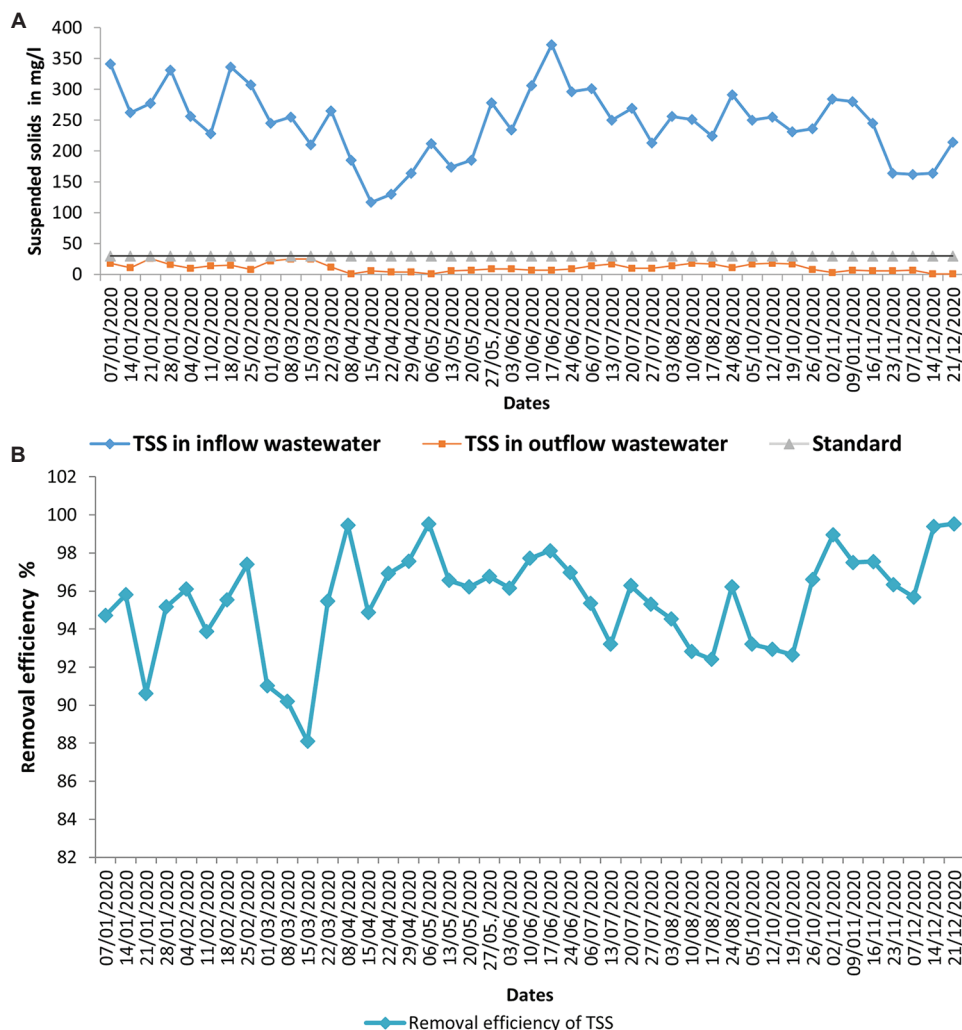


Figure 7. (A) Variations in total suspended solids (TSS) concentrations in inflow and outflow wastewater at the Lagfafa wastewater treatment plant. (B) Variations in removal efficiency % of TSS at the Lagfafa wastewater treatment plant.

Table 7. TSS concentration in the inflow and outflow wastewater

Wastewater	TSS (mg/L)					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	244.32	372	117	250	57.09	227.65 – 261.01
Outflow	11.02	26	1	10	6.67	9.07 – 12.97

Note: The *p*-value was calculated to be  $6.01 \times 10^{-29}$ .

Abbreviations: CI: confidence interval; SD: standard deviation; TSS: total suspended solids.

The results revealed that the TSS concentration in the effluent is significantly lower than that of the influent, indicating highly effective removal of suspended matter during the treatment process.

Statistical analysis confirms a highly significant reduction ( $p < 6.01 \times 10^{-29}$ ) in TSS concentrations between the influent (mean: 244.33 mg/L; 95% CI: 227.65 – 261.01 mg/L) and the effluent (mean: 11.02 mg/L; 95% CI: 9.07 – 12.97 mg/L). This sharp decrease is accompanied by a considerable reduction in variability, as reflected by the SD of 6.68 mg/L in the effluent compared to 57.10 mg/L in the influent. These results underscore the high performance of the treatment process in removing suspended solids.

The extremely low  $p$ -value from the independent samples  $t$ -test confirms the statistical significance of this reduction, and the non-overlapping CIs further validate this conclusion.

The removal efficiency was consistently high throughout the monitoring period, with an average of 95.48%, a maximum of 99.53%, and a minimum of 88.09% (Figure 7B). All effluent TSS concentrations were well below the regulatory limit, confirming compliance with the agricultural reuse standard.

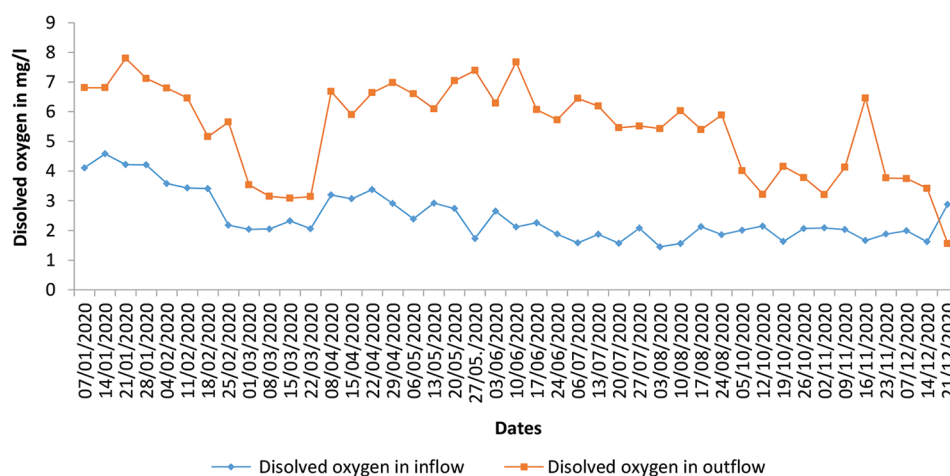
### 3.6. DO

The concentrations of DO in inflow and outflow wastewater are displayed in Figure 8 and Table 8. The concentration of DO in the effluent is consistently higher than that of the influent, indicating an increase in DO concentrations following treatment. This improvement is primarily attributed to the aeration phase within the activated sludge process.

An independent samples  $t$ -test revealed a highly significant increase in DO levels ( $p = 2.65 \times 10^{-17}$ ). The 95% CI for the mean DO concentration in the influent ranged at 2.21 – 2.69 mg/L, while that of the effluent ranged at 4.95 – 5.85 mg/L. The non-overlapping CIs further substantiate the statistical significance of this increase.

Interestingly, the SD of DO concentrations in the effluent (1.54 mg/L) is higher than that in the influent (0.82 mg/L), suggesting greater variability in DO levels post-treatment. This may reflect operational variations or fluctuations in microbial activity during aeration.

In conclusion, the treatment process demonstrates a statistically significant and operationally relevant increase in DO concentrations, enhancing the quality of the treated effluent for potential reuse, despite the observed increase in variability.



**Figure 8. Variations in dissolved oxygen concentrations in inflow and outflow wastewater at the Lagfate wastewater treatment plant**

**Table 8. Dissolved oxygen concentration in the inflow and outflow wastewater**

Wastewater	Dissolved oxygen (mg/L)					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	2.45	4.58	1.45	2.12	0.82	2.2 – 2.69
Outflow	5.40	7.80	1.56	5.89	1.54	4.95 – 5.85

Note: The  $p$ -value was calculated to be  $2.65 \times 10^{-17}$ .  
Abbreviations: CI: confidence interval; SD: standard deviation.

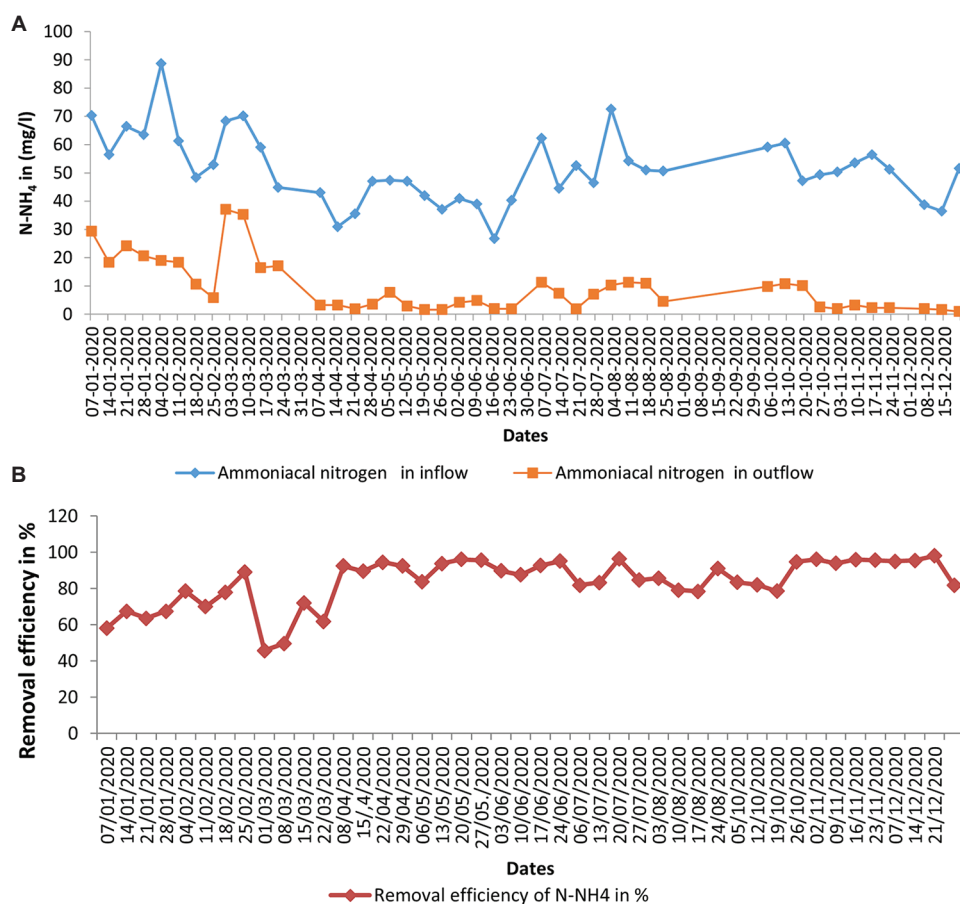
### 3.7. NH<sub>4</sub>

The measured concentrations of NH<sub>4</sub> in inflow and outflow wastewater are displayed in Figure 9A and Table 9. The results demonstrate the effective removal of N-NH<sub>4</sub><sup>+</sup> through the treatment process. Statistical analysis reveals a highly significant reduction in N-NH<sub>4</sub><sup>+</sup> concentrations between the influent (mean: 51.53 mg N/L; 95% CI: 47.95 – 55.11 mg N/L) and the effluent (mean: 9.37 mg N/L; 95% CI: 6.67 – 12.07 mg N/L). The independent samples *t*-test

yielded an extremely low *p*-value ( $p = 2.46 \times 10^{-31}$ ), confirming the statistical significance of this reduction.

Moreover, the lower SD in the effluent (3.23 mg N/L), compared to the influent (12.24 mg N/L), indicates improved consistency in nitrogen concentrations after treatment. The median values of 50.63 mg N/L for the influent and 5.80 mg N/L for the effluent are consistent with the respective means, further supporting the conclusion of substantial nitrogen removal.

The N-NH<sub>4</sub><sup>+</sup> removal efficiencies varied over the



**Figure 9. (A) Variations in ammoniacal nitrogen (N-NH<sub>4</sub>) concentrations in inflow and outflow wastewater at the Lagfafe wastewater treatment plant. (B) Variations in N-NH<sub>4</sub> concentrations in inflow and at the Lagfafe wastewater treatment plant.**

**Table 9. N-NH<sub>4</sub> concentration in the inflow and outflow wastewater**

Wastewater	N-NH <sub>4</sub> (mg N/L)					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	51.53	88.68	26.76	50.63	12.24	47.95 – 55.11
Outflow	9.37	37.09	0.97	5.80	3.23	6.67 – 12.07

Note: The *p*-value was calculated to be  $2.46 \times 10^{-31}$ .

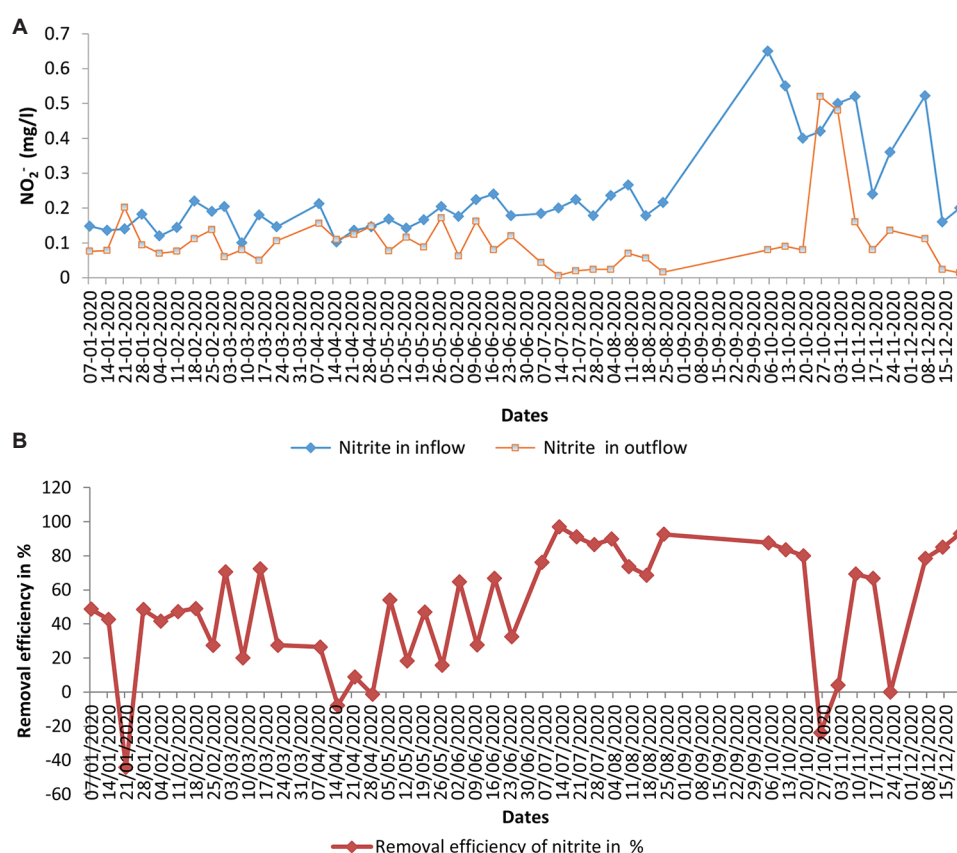
Abbreviations: CI: confidence interval; SD: standard deviation; N-NH<sub>4</sub>: ammoniacal nitrogen.

monitoring period, with an average efficiency of 81.80%, a maximum of 98.12 % recorded in December 2020, and a minimum of 45.75% observed in March 2020 (Figure 9B). These results highlight both the high performance and operational variability of the activated sludge process in reducing N-NH<sub>4</sub><sup>+</sup> levels.

According to Algerian regulations, no maximum limit is specified for N-NH<sub>4</sub><sup>+</sup> concentrations in treated wastewater intended for agricultural reuse, as it is regarded as a beneficial nutrient. Its presence can enhance soil fertility and support crop growth.

### 3.8. NO<sub>2</sub><sup>-</sup>

The measured NO<sub>2</sub><sup>-</sup> concentrations in inflow and outflow wastewater are displayed in Figure 10A and Table 10. The results indicate that the degradation of NO<sub>2</sub><sup>-</sup> is generally effective. The average NO<sub>2</sub><sup>-</sup> concentration in the influent wastewater is 0.23 ± 0.13 mg N/L, while that of the effluent is 0.10 ± 0.09 mg N/L. The maximum values recorded for the influent and effluent are 0.65 and 0.52 mg N/L, respectively, whereas the minimum concentrations are 0.10 mg N/L for the influent



**Figure 10.** Variations in nitrite (NO<sub>2</sub><sup>-</sup>) concentrations in inflow and outflow wastewater at the Lagfate wastewater treatment plant. (B) Variations in removal efficiency of NO<sub>2</sub><sup>-</sup> at the Lagfate wastewater treatment plant.

**Table 10.** NO<sub>2</sub><sup>-</sup> concentration in the inflow and outflow wastewater

Wastewater	NO <sub>2</sub> <sup>-</sup> (mg N/L)					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	0.23	0.65	0.10	0.19	0.13	0.191 – 0.269
Outflow	0.10	0.52	0.006	0.08	0.09	0.071 – 0.129

Note: The *p*-value was calculated to be 5.14×10<sup>-8</sup>.

Abbreviations: CI: confidence interval; SD: standard deviation; NO<sub>2</sub><sup>-</sup>: nitrite.

and 0.006 mg N/L for the effluent. The average  $\text{NO}_2^-$  removal efficiency was 42.44% (Figure 10B). However, removal efficiency was occasionally reduced, likely due to elevated concentrations resulting from the denitrification of  $\text{NO}_3^-$ .

Statistical analysis confirms a significant reduction in  $\text{NO}_2^-$  concentrations between the influent (mean: 0.23 mg N/L; 95% CI: 0.191 – 0.269 mg N/L) and the effluent (mean: 0.10 mg N/L; 95% CI: 0.071 – 0.129 mg N/L). The independent samples *t*-test yielded a highly significant *p*-value ( $p = 5.14 \times 10^{-8}$ ), indicating that this decrease is unlikely due to random variation. Furthermore, the SD in the effluent (0.09 mg N/L) is slightly lower than that in the influent (0.13 mg N/L), suggesting a modest improvement in the stability of  $\text{NO}_2^-$  concentrations post-treatment.

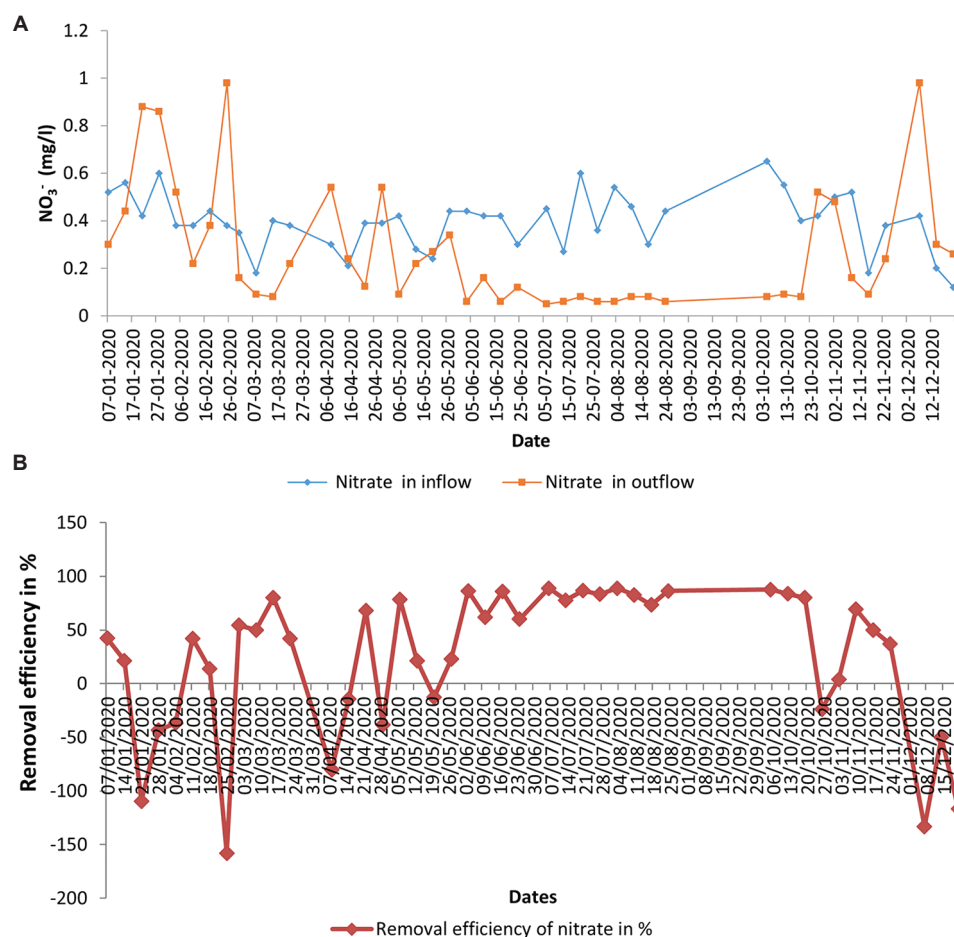
In summary, the wastewater treatment process effectively reduces average  $\text{NO}_2^-$  concentrations, though the efficiency may be impacted by  $\text{NO}_3^-$  reduction

dynamics. The process also contributes to a slight decrease in concentration variability in the treated effluent.

### 3.9. $\text{NO}_3^-$

The measured  $\text{NO}_3^-$  concentrations in inflow and outflow wastewater are displayed in Figure 11A and Table 11. The results indicate that the influent and effluent  $\text{NO}_3^-$  concentration curves are nearly superimposed, suggesting that the values are close to each other. Concentrations in both wastewater sources remain well below the standard threshold. It is important to note that Algerian regulations on the reuse of treated wastewater for agricultural purposes do not define a limit for  $\text{NO}_3^-$ , as it is considered a beneficial nutrient for crops.

The independent samples *t*-test yielded a statistically significant *p*-value ( $p = 0.0028$ ,  $\alpha = 0.05$ ), confirming a significant reduction in  $\text{NO}_3^-$  concentrations following treatment. The 95% CI for the influent



**Figure 11. (A) Variations in nitrate ( $\text{NO}_3^-$ ) concentrations in inflow and outflow wastewater at the Lagfate wastewater treatment plant. (B) Variations in removal efficiency of  $\text{NO}_3^-$  wastewater at the Lagfate wastewater treatment plant.**

NO<sub>3</sub><sup>-</sup> concentration is estimated to be 0.355 – 0.425 mg N/L, while that of the effluent is 0.194 – 0.346 mg N/L. The non-overlapping nature of the CIs reinforces the statistical significance of the observed reduction. However, the effluent exhibits greater variability (SD: 0.26 mg N/L) than the influent (SD: 0.12 mg N/L), indicating increased fluctuation in NO<sub>3</sub><sup>-</sup> levels after treatment.

The average nitrate removal efficiency was 56.58%, (Figure 11B) indicating moderate denitrification performance. Nevertheless, the treated water from the Lagfate WWTP remains suitable for agricultural reuse, given the absence of regulatory restrictions on NO<sub>3</sub><sup>-</sup> concentrations and its agronomic value.

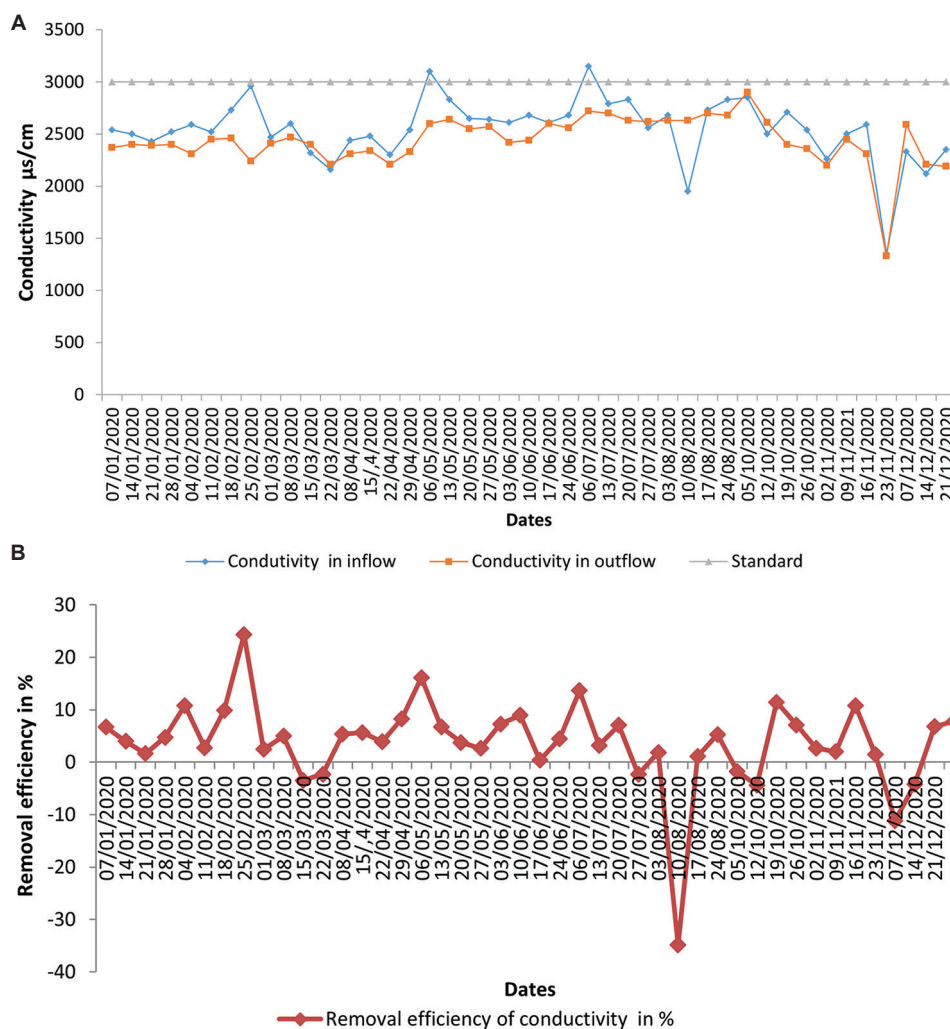
### 3.10. Conductivity

**Table 11. NO<sub>3</sub><sup>-</sup> concentration in the inflow and outflow wastewater**

Wastewater	NO <sub>3</sub> <sup>-</sup> (mg N/L)					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	0.39	0.65	0.27	0.40	0.12	0.355 – 0.425
Outflow	0.27	0.98	0.05	0.16	0.26	0.194 – 0.346

Note: The *p*-value was calculated to be 0.0028.

Abbreviations: CI: confidence interval; SD: standard deviation; NO<sub>3</sub><sup>-</sup>: nitrate.



**Figure 12. (A) Variations in the conductivity of inflow and outflow wastewater at the Lagfate wastewater treatment plant. (B) Variations in removal efficiency % of conductivity at the Lagfate wastewater treatment plant.**

**Table 12. Conductivity of the inflow and outflow wastewater**

Wastewater	Conductivity ( $\mu\text{S}/\text{cm}$ )					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	2546.97	3150	1350	2560	303.06	2458.42 – 2635.52
Outflow	2440.46	2900	1330	2440	241.82	2369.81 – 2511.12

Note: The  $p$ -value was calculated to be 0.00085.

Abbreviations: CI: confidence interval; SD: standard deviation.

Electrical conductivity measurements are presented in [Figure 12A](#) and [Table 12](#). The results indicate that the conductivity of both influent and effluent remains below the threshold established by the agricultural reuse standard, indicating compliance for this parameter.

Statistical analysis using an independent samples  $t$ -test revealed a statistically significant reduction in electrical conductivity after treatment ( $p = 0.00085$ ,  $\alpha = 0.05$ ). The mean conductivity for the influent is  $2546.97 \mu\text{S}/\text{cm}$ , with a 95% CI of  $2458.42 - 2635.52 \mu\text{S}/\text{cm}$ , while the mean conductivity for the effluent is  $2440.46 \mu\text{S}/\text{cm}$ , with a 95% CI of  $2369.80 - 2511.12 \mu\text{S}/\text{cm}$ . The partial non-overlap between these intervals supports the conclusion that the observed difference is statistically significant and unlikely due to random variation.

Moreover, the effluent reports a slightly lower SD ( $241.82 \mu\text{S}/\text{cm}$ ) compared to the influent ( $303.06 \mu\text{S}/\text{cm}$ ), suggesting a modest reduction in variability, likely attributable to the removal of some dissolved salts during the treatment process.

The average removal efficiency for conductivity was 7.80%, with recorded values ranging from a maximum of 24.32% to a minimum of -34.87% ([Figure 12B](#)). These fluctuations reflect the limited capacity of the activated sludge process to reduce conductivity, as this parameter is primarily influenced by the concentration of dissolved ions rather than biodegradable matter. Nonetheless, all effluent values remained within the acceptable range for agricultural reuse.

### 3.11. Phosphorus

Variations in  $\text{PO}_4$  concentrations (in mg P/L) over the study period are displayed in [Figure 13A](#) and [Table 13](#). The results illustrate a clear reduction in  $\text{PO}_4$  concentrations, indicating effective removal through the treatment process. The average, maximum, and minimum removal efficiencies were 78.75%, 95.00%, and 28.90%, respectively ([Figure 13B](#)).

The independent samples  $t$ -test yielded a statistically significant  $p$ -value ( $p = 9.80 \times 10^{-6}$ ,  $\alpha = 0.05$ ), confirming

a significant decrease in  $\text{PO}_4^{3-}$  concentration post-treatment. The mean influent concentration is 13.59 mg P/L (95% CI: 12.39 – 14.79 mg P/L), while the effluent concentration averaged 9.41 mg P/L (95% CI: 7.91 – 10.91 mg P/L). The non-overlapping CIs substantiate the statistical significance of this reduction.

Notably, the SD increased in the effluent (5.14 mg P/L) compared to the influent (4.10 mg P/L), suggesting greater variability in  $\text{PO}_4^{3-}$  concentrations after treatment. This could be attributed to seasonal fluctuations or operational inconsistencies in the  $\text{PO}_4^{3-}$  removal process. Despite this variability, the system achieved a substantial reduction, albeit less consistent than those observed for other parameters such as  $\text{BOD}_5$  or TSS.

Algerian regulations for agricultural reuse of treated wastewater do not specify a limit for phosphorus (or  $\text{PO}_4^{3-}$ ), given its beneficial role as a nutrient for crop fertilization. However, for discharge into the natural environment, a maximum allowable concentration of 2 mg P/L is imposed to mitigate eutrophication risks. Since the effluent concentrations in this study exceed this threshold, direct discharge into surface water bodies, such as the Hammam Bouhrara Dam, could pose ecological risks if not managed appropriately.

While the treatment process effectively reduces  $\text{PO}_4^{3-}$  concentrations, the residual levels remain above environmental discharge limits. Therefore, reusing this phosphorus-rich effluent in agriculture offers a sustainable solution by supporting crop growth and simultaneously protecting the receiving water bodies from nutrient over-enrichment.

### 3.12. Strengths and limitations

This study offers valuable insights into the quality of treated wastewater from the Lagfafa WWTP and its potential for agricultural reuse. To ensure a comprehensive and representative evaluation, wastewater samples were collected four times per month throughout the year 2020. This sampling strategy captured all four seasons, accounting for the influence of seasonal variability, which is an important factor affecting treatment performance and effluent quality

### Maghnia wastewater and risk assessment



**Figure 13. (A) Variations in phosphate ( $\text{PO}_4^{3-}$ ) concentrations in inflow and outflow wastewater at the Lagfate wastewater treatment plant. (B) Variations in removal efficiency % of  $\text{PO}_4^{3-}$  at the Lagfate wastewater treatment plant, the positive cells were observed.**

**Table 13.  $\text{PO}_4^{3-}$  concentration in the inflow and outflow wastewater**

Wastewater	$\text{PO}_4^{3-}$ (mg P/L)					
	Average	Maximum	Minimum	Median	SD	95% CI
Inflow	13.59	22.8	8.0	12.3	4.10	12.39 – 14.79
Outflow	9.41	20.0	0.4	9.6	5.14	7.91 – 10.91

Note: The  $p$ -value was calculated to be  $9.80 \times 10^{-6}$ .

Abbreviations: CI: confidence interval; SD: standard deviation;  $\text{PO}_4^{3-}$ : phosphate.

due to changes in temperature, precipitation, organic load, and hydraulic flow.

A major strength of the study lies in its year-round monitoring framework. The results indicate that the treatment process maintained consistent performance across different seasons, with significant reductions observed in key pollution indicators, such as COD,  $\text{BOD}_5$ , and TSS. These findings suggest that, within the local context, seasonal variability did not substantially compromise the effectiveness of the treatment system.

However, several limitations should be

acknowledged. Although the sampling frequency was relatively high, short-term fluctuations or pollution peaks may have gone undetected. Such events could impact the suitability of treated wastewater for irrigation, especially in sensitive cropping systems. Moreover, the one-year duration of the study may not fully capture long-term trends in effluent quality, which are essential for evaluating the sustainability of reuse practices.

Another significant limitation is the absence of data on emerging contaminants, including pharmaceutical residues, hormones, endocrine-disrupting compounds,

and microplastics. Although typically present at trace levels, these micropollutants can persist in treated effluent and pose environmental and health risks, particularly when the water is reused for agriculture. Monitoring these substances requires advanced analytical techniques, which were beyond the scope of this study. Future research should prioritize the detection and quantification of such contaminants to provide a more comprehensive assessment of the safety and long-term feasibility of treated wastewater reuse.

#### 4. Conclusion

This study presents a comprehensive, year-long evaluation of the Lagfate WWTP to assess the feasibility of treated effluent reuse for agricultural purposes in the Maghnia region. Through systematic monitoring and rigorous statistical analysis, the research demonstrated consistent and significant reductions in key pollutants, namely COD, BOD<sub>5</sub>, and TSS, with treated effluent concentrations generally complying with both national and international irrigation standards. These outcomes confirm the technical viability of wastewater reuse in semi-arid areas affected by chronic water scarcity.

From an operational standpoint, the Lagfate WWTP treats an average of 29,400 m<sup>3</sup> wastewater per day, producing approximately  $10.73 \times 10^6$  m<sup>3</sup> of reusable treated water annually. This substantial volume represents a promising alternative water source that could help alleviate the agricultural water crisis currently facing the Maghnia region. In addition, the nutrient-rich composition of the treated effluent provides agronomic benefits by improving soil fertility and reducing dependence on synthetic fertilizers. Harnessing this underutilized resource could foster more sustainable agricultural practices, enhance food security, and reduce pressure on conventional freshwater supplies. Conversely, the continued discharge of treated effluent into natural waterways particularly toward the Hammam Boughrara dam poses ecological risks, including eutrophication caused by nutrient accumulation.

This study distinguishes itself from much of the existing literature through its methodological rigor and seasonal comprehensiveness. In contrast to previous research often limited to short-term or descriptive analyses, this study employed inferential statistical methods, specifically paired *t*-tests and 95% CIs, to robustly assess treatment performance. This approach strengthens the scientific validity and interpretability of the results.

Furthermore, by spanning all four seasons, the study provides valuable insights into the temporal variability

of treatment efficiency, a dimension often overlooked in similar investigations. Rather than focusing solely on agronomic benefits or environmental impacts, this research adopts a balanced perspective, evaluating both the nutrient potential of treated effluents for irrigation and the ecological implications of residual pollutants.

To reiterate, the findings affirm not only the technical and environmental feasibility of wastewater reuse but also its strategic importance in integrated water resource management for semi-arid regions. The study offers concrete guidance to policymakers, local authorities, and farmers, advocating for the sustainable use of non-conventional water resources to bolster agricultural productivity and strengthen environmental resilience.

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#### Author contributions

This is a single-authored article.

#### Conflict of interest

The author declares there are no conflicts of interest with any institute or organization.

#### Availability of data

Not applicable.

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