Spatial Evaluation of Wastewater Treatment Efficacy in Five Egyptian Regions: Implications for Water Scarcity

Aya G. Atalla[1], Eman M. Ismail[2], Islam M. Tork[3], and Shaymaa Abdelmalek[4*]

1. Central Laboratories, Greater Cairo Sanitary Drainage Company, Cairo, Egypt.
2. Department of Veterinary Hygiene and Management, Faculty of Veterinary Medicine, Cairo University, Egypt.
3. Regional Center for Food and Feed (RCFF), Agricultural Research Center (ARC), Egypt.
4. Department of Microbiology, Faculty of Veterinary Medicine, Cairo University.

* Corresponding author: Shaymaa Abdelmalek, e-mail address: shaymaa_malek@cu.edu.eg

1. Abstract

Water scarcity is a critical challenge in the 21st century, driven by increasing anthropogenic activities and rising demand for clean water. Safe reuse of treated wastewater provides a sustainable solution, but treatment levels vary worldwide. Egypt is predicted to face limited access to potable water, making effective wastewater treatment essential. Spatial distribution and diverse human activities significantly impact treatment efficacy. This cross-sectional observational study evaluates the performance of treatment processes and wastewater quality at five geographically distributed WWTPs. Samples were collected and analyzed for 19 physicochemical parameters. Data analysis was conducted using R software and R Studio for descriptive statistics, data distribution normality, and inferential statistics based on differences in pre- and post-treatment values. Significant differences ($p < 0.05$) were identified in most parameters, showing that removal efficacy depends on geographic location. Conversely, no significant differences were observed for EC, CN, TP, DO, Zn, or Hg ($p > 0.05$), indicating that the removal efficiency of these specific parameters was not affected by location. An overall removal efficiency comparison among the studied WWTPs identified that Plant 3 shows the highest removal efficacy percentage for organic and aggregate, approximately 60%. However, plant 4 reports the lowest at 53.6%. Additionally, plant 1 has the highest removal efficacy percentage for TP, TN, and heavy metals, around 86%. However, plant 4 records the lowest at about 75%. This study sheds light on the importance of continuous evaluation and geographically sensitive approaches to improve wastewater treatment performance and support water-safe reuse efforts amid Egypt's growing water scarcity.

Key words: Water reuse; Spatial analysis; Treatment assessment; Removal efficacy; WWTPs.

2. Introduction

Water scarcity stands as one of the most critical global challenges of this century. The increasing demand for clean water resources is caused by rapid population growth, urbanization, and climate change [1]. In recent years, severe weather events have occurred, including extended heat waves in some countries and floods in others, disrupting the natural water circulation [2]. According to the UN reports, around three out of four people could be affected by drought

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

Open QR reader and scan code to access this article online

impacts by 2025 [3]. This creates an urgent need to consider new regulations.

In addition to this, wastewater is produced due to various anthropogenic activities, such as domestic, industrial, and farming processes [4]. It contains a wide range of pollutants, including organic and inorganic compounds, toxic heavy metals, and pathogenic microorganisms [5]. Around 80% of wastewater is discharged untreated into freshwater bodies [6]. This may lead to eutrophication of aquatic environments [7], causing serious health implications, and resulting in the accumulation of toxic elements in crops irrigated with this effluent [8].

Sustainable treatment and reuse of wastewater effluent represent a vital alternative water source that can alleviate water scarcity. However, wastewater treatment implementation remains a challenge in low-income countries [9]. In some developed countries, 74% of wastewater is treated, while in other developing countries, only around 4% of collected wastewater undergoes treatment processes [10]. Developed countries have the infrastructure and advanced technologies required for effective treatment. Developing countries are exposed to untreated wastewater with limited access to clean potable water [6]. Therefore, global actions should be undertaken to increase the quality and percentage of recycled water [9].

In Egypt, the share of Nile water is declining per capita. It dropped from around 850 m^3/year to 670 m^3 by 2017 and is expected to reach 536 m^3 in 2025 [11]. This growing water scarcity has driven the government to seek alternative water resources. According to the CAPMAS reports, treated wastewater effluent represents roughly 87.8% of total collected sewage across Egypt [12]. Safe reusage of this water is vital to support Egypt's water security strategies and sustainability.

Many studies assess wastewater removal efficacy by comparing influent and effluent qualities of Wastewater Treatment Plants (WWTPs). Other studies evaluate only treated effluents against Egyptian regulatory standards. Few research efforts considered geographical and socio-cultural variations. The influence of human activities, such as domestic and agricultural practices, on wastewater treatment in urban, rural, and coastal environments remains an unexplored area of study. This study aims to compare five WWTPs considering their geographical distributions across Egypt. Stages of treatment and type of biological treatment are the same in the selected five WWTPs. The goal is to determine whether ecological variety influences wastewater treatment, providing insights into more specific wastewater management strategies.

3. Materials and Methods

3. 1. Study design and duration

A cross-sectional observational study aimed to assess the treatment operations and wastewater quality in five WWTPs located in different geographies in Egypt (Fig. 1), each representing distinct populations and environmental activities across five major governorates in Egypt. Ten influent and effluent wastewater samples were collected from October to November 2024. For each WWTP, a checklist was adopted, covering the topographical findings, plant design, treatment procedures, and design and operational capacity.

3. 2. Topographical assessment

A topographical assessment of each plant was performed to determine the main receiving drain for the effluent

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

discharge and the environmental context associated with the served area (Table 1).

3.3. Description of the treatment process

The wastewater treatment processes implemented at the five WWTPs follow the protocols established by the Holding Company for Water and Wastewater [11]**.** The treatment sequence begins with bar screening, which involves the use of mechanical or manual screens to remove large floating or suspended solids, such as plastics, from the influent stream. Followed by grit and oil removal, where the wastewater passes through specially designed channels equipped with grit chambers that allow inorganic particles larger than 0.2 mm in diameter and with a specific gravity exceeding 2.65 to settle out. Concurrently, oils and greases that accumulate at the surface are removed via surface skimming mechanisms. Subsequently, the flow enters the primary settling tanks, where a substantial portion of settleable organic and inorganic suspended solids is removed by sedimentation, along with the separation of floating materials. The biological treatment occurs in aeration tanks, where aerobic bacteria digest dissolved organic matter under optimal conditions of oxygenation and mixing; all studied WWTPs use the conventional activated sludge system except WWTP3 (Nahtai), which employs a mixed system of Moving Bed Biofilm Reactor (MBBR) and conventional activated sludge system. The resulting biomass is separated in secondary settling tanks, reducing the levels of suspended and organic matter. Finally, chlorine contact tanks disinfect the treated effluent by adding free chlorine to reduce microbial load before discharge into the drainage system.

3.4. Sample collection and ethical approval

Signed consents are obtained from the governmental companies responsible for the WWTPs included in the scope of study. Sample collection and transportation were performed following the standard procedures of the American Public Health Association [13]**.** Ten wastewater samples were collected from the five investigated WWTPs, where two influent and effluent samples were collected from each plant. An influent sample was collected from the general inlet of the plant before entering any treatment process, and the other is an effluent sample collected at the discharge point after chlorination. 2-liter grab samples were collected using a prepared plastic fetcher attached to a rope from the sampling points into sterilized bottles. At every sampling point, the fetcher is rinsed three times with the intended wastewater sample before sample collection. The collected wastewater samples were transported in an icebox to Al-Dayora Central Laboratory, Greater Cairo Sanitary Drainage Company, for instant physical and chemical water quality analysis, and to the Regional Center for Food and Feed, the Agricultural Research Center, for heavy metals analysis

3.5. Physicochemical wastewater quality assessment:

Physicochemical water quality was analyzed according to APHA (13), where the determination of organic and inorganic constituents of collected wastewater samples, besides heavy metals assessment, was performed. In situ measurements of temperature (ºC) and pH were performed using a portable meter (PHOENIX Instrument®, Model: EC-26 pH, Italy). Dissolved Oxygen (DO) (mg/L) was measured using a portable meter (HACK®, Model: HQ1130 DO/1 Channel, USA). Turbidity

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

(NTU) was measured using a portable turbidimeter (VELP SCIENTIFICA®, Model: tb1 r109b12150, Singapore). Organic constituents include biochemical Oxygen Demand (BOD5) (mg/L), which was determined using a bench-top multimeter (HACK®, Model: HQ440D, USA). A UV VIS Spectrophotometer (HACK®, Model: DR6000, Germany) was used to quantify Chemical Oxygen Demand (COD) (mg/L). Total Organic Carbon (TOC) (mg/L) was detected using (ANALYTIC Jena GmbH®, Type: multi N/C 3100, Germany). Inorganic constituents, including total Dissolved Solids (TDS) (mg/L) and Electrical Conductivity (EC) (µS/cm), were determined using a bench-top multiparameter meter (HACK®, Model: HQ440D, USA). A UV VIS Spectrophotometer (HACK®, Model: DR6000, Germany) was used to measure Cyanide (CN) (mg/L), and Total Phosphorus (TP) (mg/L). Total Nitrogen (TN) (mg/L) was detected using (ANALYTIC Jena GmbH®, Type: multi N/C 3100, Germany).

3.6. Heavy metals assessment:

10 mL of each wastewater sample was digested with 7 mL of nitric acid and 2 mL of hydrogen peroxide using a heat block. The temperature was increased gradually, starting from 80 °C and rising to 140 °C. After cooling, the digested mixture was transferred into polypropylene tubes and diluted to a final volume of 50 mL using deionized water [14]**.** Blank samples were processed using the same procedure to assess potential cross-contamination. Digested wastewater samples underwent a filtration process to eliminate suspended particles and potential contaminants using a 0.45 µm membrane filter to ensure the removal of particulate matter while preserving dissolved elements. All samples, including blanks and standard solutions, were analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy ICP-OES (PerKinElmer®, model: Avio 220 Max ICP-OES, USA). Target metals included Lead (Pb), Nickel (Ni), Cadmium (Cd), Copper (Cu), Iron (Fe), Zinc (Zn), Mercury (Hg), Arsenic (As), with results reported in mg/L.

3.7. Statistical and data analysis

The data were analyzed using R (version 4.5.1) and RStudio. The data were collected in a CSV format, where measurements for each water quality parameter before and after treatment, and the calculated differences were included. Effluent wastewater quality was evaluated for compliance using a combination of national and international standards relevant to wastewater discharge and reuse. Regulatory benchmarks included the Egyptian law [15] which is used to compare these parameters: pH, DO, CN, and Fe, along with guidelines from Wastewater Engineering: Treatment and Resource Recovery [16], which is used to compare these parameters: Turbidity, BOD5, COD, TOC, TDS, Pb, Ni, Cd, Cu, Zn, Hg, As, the EU Council Directive 91/271/EEC concerning urban wastewater treatment [17], which is used to evaluate TP and TN, and the FAO limits [18], which is used to evaluate EC. The alternative hypothesis tests the relationship between wastewater removal efficacy and the geographical distribution of the study scope WWTPs.

R is used for descriptive analysis, distribution of data, and inferential analysis using Student's t-test for normally distributed data and the Wilcoxon Signed-Rank Test for skewed distributions. Pearson's correlation coefficient test assesses the correlation between the difference before and after treatment (difference of all variables

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

(diff.), and the paired correlations between (diff.) BOD5/ (diff.) COD, (diff.) BOD/ (diff.) TOC, (diff.) TOC/ (diff.) COD, (diff.) COD/ (diff.) TN, (diff.) TP/ (diff.) TN, (diff.) Turbidity/ (diff.) COD, (diff.) Turbidity/ (diff.) BOD5, and (diff.) Turbidity/ (diff.) TOC. Removal Efficacy% is calculated for each parameter. Overall removal efficacy% is calculated for organic and aggregate parameters, TP, TN, and heavy metals

4. Results

Two samples, one influent sample and one effluent sample, are collected from each of the five WWTPs. Physicochemical parameters such as temperature, pH, DO, Turbidity, BOD5, COD, TOC, TDS, EC, CN, TP, and TN were measured. Heavy metals such as Pb, Ni, Cd, Cu, Fe, Zn, Hg, and As were measured as well (Table 2).

4.1. Data description and statistical analysis

The data were collected in a CSV file, including readings of each parameter, before treatment, after treatment, and the difference between the two readings. Descriptive analysis was performed to examine data distribution, and normality of the differences was assessed using the Shapiro–Wilk test. Data distribution was visualized using boxplots for the values before treatment, after treatment, and their differences (Fig. 2). The figure displays a series of boxplots comparing the distributions of measured values for 19 wastewater quality parameters before and after treatment. Each panel represents a different parameter, including organic (BOD5, COD, TOC), aggregate (TDS, TN, TP), physicochemical (pH, DO, Turbidity, EC), and heavy metals (Pb, Ni, Cd, Cu, Fe, Zn, Hg, As). For each parameter, the box plots illustrate the shift in values resulting from treatment, with "Before" and "After" shown side by side, and the "Diff" (difference) depicted to highlight the magnitude of removal.

The results show substantial reductions in the median and interquartile range for most parameters after treatment, particularly for organic contaminants, aggregates, and heavy metals, demonstrating the high efficacy of the treatment plants in lowering pollutant concentrations. Some parameters, such as pH and DO, display more moderate changes, reflecting expected operational stability. The spread of values ("whiskers" and outliers) reveals both the central tendency and variability in removal performance across samples. This comprehensive comparison underscores the effectiveness and consistency of the treatment process in improving water quality.

Histograms were used to describe the distribution of the differences between pre- and post-treatment values (Fig. 3). The histograms illustrate that, for most parameters (such as BOD5, COD, TOC, heavy metals, and aggregates), the majority of the difference values are positive, reflecting a reduction in contaminant concentration following treatment. These distributions are often right-skewed or show clear mass around positive difference values, confirming consistent removal across samples. Some parameters (notably pH and DO) display narrower spreads and, in a few cases, differences centered closer to zero, indicating lesser or more stable shifts due to treatment. For certain metals (like Cd, As, Zn), differences are small and distributions are tightly clustered around the lower end, matching their typically lower initial concentrations. Subplots for each parameter allow visual recognition of both the extent of removal (with broader, more positive distributions reflecting greater efficacy) and the degree

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053
Open QR reader and scan code to access this article online

of variability or occurrence of outliers in treatment performance.

The Shapiro Wilk test revealed that all parameters except DO, Zn, and Hg exhibited p-values greater than 0.05, consistent with a normal distribution. In contrast, DO, Zn, and Hg deviated from normality, as indicated by Shapiro–Wilk p-values below 0.05. Statistical analysis was performed to determine whether geographical distribution influences the removal efficacy of the WWTPs. Parametric data were evaluated using Student's t-test, while non-parametric data (DO, Zn, and Hg, as indicated by the Shapiro–Wilk test) were analyzed using the Wilcoxon Signed-Rank Test. The resulting p-values for each parameter are summarized in Table 3. Significant differences ($p < 0.05$) were observed for most parameters, indicating that treatment efficacy varied with geographical distribution. However, no significant difference was detected for EC, CN, TP, DO, Zn, or Hg (all $p > 0.05$), suggesting that for these specific parameters, removal efficacy was not markedly influenced by location.

4.2. Overall correlations between all variables

Pearson's correlation coefficient test is used to assess the correlation between all variables, and the results were visualized using a heat map (Fig. 4). The figure presents the correlation matrix for 19 water quality parameters, illustrating the strength and direction of pairwise relationships among physicochemical variables, nutrients, and heavy metals measured in wastewater samples. The heatmap displays correlation coefficients ranging from -1 (strong negative correlation, shown in red) to +1 (strong positive correlation, shown in dark blue), with numerical values inside each cell. Notably, strong positive correlations are observed between several heavy metals, such as Ni and Cd (r = 0.89), and between different nitrogen-related parameters. In contrast, strong negative correlations are evident between pH and CN (r = -0.7), as well as among certain organic and inorganic parameters. The matrix highlights distinct clusters where parameters tend to increase or decrease together, underscoring potential common sources or coupled removal mechanisms in the treatment process. Conversely, some parameters, such as DO and BOD5, show weak or negligible pairwise associations, indicating independent behavior across samples. This comprehensive correlation analysis provides insights into how different contaminants and water quality indicators co-vary, informing interpretation of treatment performance and optimization strategies.

4.3. Significant correlations between paired parameters

Pearson's correlation coefficient test is used to assess significant paired correlation as well. The figure 5 reveals several strong associations. Notably, TP and TN exhibit a very strong negative correlation (r = -0.94), indicating that as the reduction of TP increases, the reduction of TN also becomes more pronounced in the opposite direction. COD and TN are similarly strongly and inversely correlated (r = -0.85), while COD and turbidity also show a high negative relationship (r = -0.84). In contrast, moderate positive correlations are observed between pairs such as BOD5 and TOC (r = 0.54), as well as BOD5 and turbidity (r = 0.56), suggesting that greater removal of one is moderately associated with greater removal of the other. Other parameter pairs, like BOD5 versus COD or TOC versus COD, exhibit weaker associations, reflecting more independent behaviour in their treatment responses.

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

In summary, this comprehensive correlation matrix highlights both the interconnectedness and distinct removal patterns among nutrients, organics, and aggregate indicators. Strong correlations point to possible shared removal mechanisms or operational dependencies, while weaker or opposing trends reveal parameters that are governed by separate processes or are more variably influenced by treatment.

Overall, this matrix of bivariate scatterplots and correlation coefficients provides insight into how changes in one parameter are linked to changes in others during treatment, revealing underlying relationships and hinting at shared removal mechanisms or interconnected processes among both nutrient and contaminant indicators.

4.4. Wastewater removal efficacy

Wastewater removal efficacy was calculated for each parameter using the difference between pre- and post-treatment (Table 4). Removal efficacy was calculated for organic and aggregate values, as well as TP, TN, and heavy metals parameters, depending on values resulting from (Table 4) (Fig. 6) (Fig. 7). Overall, plant 3 shows the highest treatment efficacy percentage for organic and aggregate, which is about 60%. However, plant 4 hits the lowest treatment efficacy percentage for organic and aggregate, which represents 53.6%. Additionally, plant 1 has the highest removal efficacy percentage for TP, TN, and heavy metals, which is around 86%. However, plant 4 hits the lowest treatment efficacy percentage for TP, TN, and heavy metals, which is about 75% (Table 5).

The combined charts provide a comprehensive visual assessment of removal (or reduction) efficiency for a wide range of wastewater quality parameters across multiple treatment plants. Presented side by side, the first chart displays the mean reduction and variability for key nutrients and heavy metals (TP, Ni, Cu, Fe), while the second chart focuses on cyanide (CN) and additional heavy metals (Pb, Cd, Zn, Hg, As). Each grouped bar represents the average decrease in contaminant concentration from influent to effluent for a given parameter and plant, with error bars denoting the standard deviation. Together, the charts reveal robust removal performance for most parameters, particularly for metals (such as Ni, Cu, Fe, Pb, Zn) and nutrients (TP), where high mean reductions are consistently observed. The error bars highlight the degree of variability in removal efficiency among the different plants or samples, with some parameters (e.g., Cd, Hg, As) showing more variation, likely due to differences in treatment process effectiveness or influent composition. Parameters show substantial decreases, underscoring the effectiveness of the treatment plants in contaminant removal. (Fig. 6). Figure 7 displays a grouped bar chart illustrating the removal efficiency for key organic and aggregate parameters—Turbidity, BOD5, COD, TOC, TDS, EC, and TN—across several WWTPs. Each bar represents the mean reduction achieved for a parameter at each plant, while the accompanying error bars denote the standard deviation, reflecting variability among samples. All the previous data collected together in a raincloud figure (Fig. 8).

Table 4 presents the removal efficacy percentages for 17 wastewater quality parameters, evaluated across five treatment plants. The results reveal pronounced removal efficiencies above 90% for most organic parameters (BOD5, COD, TOC), turbidity, and heavy metals such as Pb, Ni, Cd, Cu, Fe, and Zn, with

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

several plants achieving near-complete removal (values close to 100%). In contrast, removal for aggregates (TDS, EC) and some nutrients (TN, TP) is typically lower or more variable, with some negative or modest values indicating greater process challenges or measurement variability, particularly for DO and CN.

Table 5 summarizes the overall removal efficacy percentages for organic and aggregate parameters, as well as for TP, TN, and heavy metals, across five WWTPs. The data indicate that all plants achieve moderate to high removal efficiencies, with organic and aggregate removal ranging from 53.63% to 59.90%, and TP, TN, and heavy metals removal ranging from 75.15% to 86.26%. Plant 3 exhibits the highest removal efficacy for organic and aggregate parameters (59.90%), while Plant 1 leads in TP, TN, and heavy metals removal (86.26%). The consistently high values across all plants reflect effective contaminant reduction performance and robust treatment processes. The differences among plants also highlight operational variations or site-specific influences on removal efficiency.

5. Discussion

This study aimed to assess the treatment performance in five WWTPs distributed across different geographical locations in Egypt. Both descriptive (Fig. 2) and inferential (Table 3) statistical analysis were conducted. Correlations between the differences in pre- and post-treatment of all variables are calculated (Fig. 4). Paired correlations for significant parameters are calculated as well (Fig. 5). The removal efficacy% for each parameter is estimated (Table 4). Overall removal efficacy percentages for organic and aggregate, as well as TP, TN, and heavy metals, are also evaluated (Table 5).

The results concluded that most of the measured parameters are significantly associated with the spatial distribution of the WWTPs, including Turbidity, BOD5, COD, TOC, TDS, TN, Pb, Cd, Cu, and As. However, other parameters, such as DO, EC, CN, TP, Zn, and Hg, show no significant association and appear to be more affected by the specific treatment processes at each plant (Table 3).

Strong positive correlations were observed among the measured parameters, such as between DO and TOC, DO and As, Turbidity and Ni, Turbidity and Cd, Turbidity and Fe, COD and TP, COD and As, TDS and EC, TDS and TN, TDS and Ni, TDS and Cu, EC and TN, EC and Ni, EC and Cu, CN and TN, TP and Zn, TP and Hg, TN and Ni, TN and Cd, TN and Cu, Ni and Cd, Ni and Cu, Cd and Cu, Hg and As, Zn and As, Zn and Hg as well (Fig. 4). These correlations suggest that an increase in one parameter is likely to be accompanied by an increase in the other, which can be advantageous for treatment monitoring and control.

In contrast, strong negative correlations were also detected, for example, between pH and CN, pH and Fe, DO and CN, Turbidity and Pb, BOD5 and Pb, COD and TDS, COD and EC, COD and CN, COD and TN, COD and Ni, COD and Cd, COD and Cu, TDS and TP, EC and TP, CN and Zn, CN and Hg, CN and AS, TP and TN, TP and Ni, TP and Cu, TN and As, Pb and Ni, Pb and Cu as well (Fig. 4). This indicates that an increase in one parameter tends to correspond with a decrease in the other. These relationships may allow for the prediction of one parameter based on another, which can enhance monitoring and process control in WWTPs.

The study also evaluated the most significant paired correlations, focusing on differences between pre-treatment and

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

post-treatment values for key water quality parameters. The following findings were highlighted as they are critical indicators in the field: A strong negative correlation was observed between TP and TN, COD and TN, as well as between COD and Turbidity. In addition, there were weak negative correlations between BOD5 and COD, and between COD and TOC, highlighting that these organic pollution indicators do not always decrease or increase proportionally. On the other hand, moderate positive correlations were found between BOD5 and TOC, and between BOD5 and Turbidity (Fig. 5).

Removal efficacy percentage for each parameter was calculated (Table 4). CN removal varied among plants: plant 2 recorded the highest removal rate of about 95%, plant 3 around 82%, plant 5 roughly 55%, while plant 4 showed a doubling increase in the CN concentration in the effluent. CN is not significantly related to geographic distribution, but it is a useful indicator of the treatment performance within each WWTP.

TP concentration increased by approximately 21% in the effluent of plant 3 (Table 4). The other WWTPs showed low removal efficacy. TP is not significantly linked to spatial distribution, and all studied plants depend on secondary treatment; and advanced tertiary treatment is necessary to reduce phosphorus concentration in the discharged effluent into the environment.

TN removal efficiency percentage ranged from 60.9% in plant 3 to 41% in plant (Table 4). TN is significantly associated with geographical distribution; however, the studied plants require advanced treatment stages, as mentioned before, to decrease N release into the environment.

All WWTPs effectively removed Cd except plant 4 (Table 4). Although Cd is significantly associated with geographic distribution, the current treatment procedures implemented in plant 4 are insufficient to remove Cd and discharge it to the environment again.

Similarly, all WWTPs except plant 2 successfully removed Zn, plant 2 achieved only about 3% (Table 4). Zn is not significantly linked to location distribution. Therefore, plant 2 should find treatment solutions to reduce Zn concentrations in the discharged effluent.

Variations in removal efficacy among the plants are evident, demonstrating different levels of treatment performance and highlighting both the strengths and operational differences across the facilities. Overall, the table provides a detailed quantitative overview of contaminant removal for each parameter and plant, illustrating the robust performance and areas for potential optimization in the treatment processes.

The results indicate consistently high removal efficiency for organic pollutants, particularly BOD5, COD, and TOC, as evidenced by the substantial differences between influent and effluent concentrations across most plants. Turbidity and TDS also show notable reductions, underscoring the effectiveness of the treatment processes for aggregate and particulate contaminants. In contrast, parameters such as EC and TN demonstrate more moderate reductions, consistent with their known resistance to removal in conventional treatment systems. The displayed error bars reveal variability in removal efficacy, suggesting differences in process performance among plants or sampling periods. Overall, the figure provides clear evidence that the treatment plants achieve robust removal of a wide

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

range of organic and aggregate pollutants (Fig. 6), while highlighting the relative performance and consistency for each parameter across sites.

Overall wastewater removal efficacy (Table 5) concluded that plant 3 performs best in removing organic and aggregated pollutants, whereas plant 4 needs to improve its treatment strategies to enhance removal rates. Regarding TP, TN, and heavy metals removal, plant 1 is the most effective, as it successfully removed around 86% indicating an application of effective treatment procedures. In contrast, plant 4 achieved the lowest removal efficiencies for TP, TN, and heavy metals, highlighting the need for implementation of enhanced treatment strategies to reduce their discharge into the environment.

Some studies agree with the findings of this research regarding spatial variation and efficacy correlation. A study conducted in China analyzed wastewater treatment efficacy across 31 regions and concluded that geographic and economic differences, such as higher population density and urbanization, contributed to significant variations in treatment outcomes [19]. Similarly, a study in Egypt evaluated the effectiveness of natural wastewater treatment methods in various regions, including Upper and Lower Egypt. They revealed that spatial variation in the selected WWTPs influenced water quality parameters [20]. Additionally, other research aligns with this study in the evaluation of Balaq's WWTP (plant 1), showing removal efficacies of BOD5 and COD above 90%, aligned with the present findings [21].

While this study identified a weak negative correlation between pre- and post-treatment values of BOD5 and COD, some other studies reported contrasting results. Those studies focused only on effluent values and found a strong positive correlation between BOD5 and COD [22]. BOD5 and COD are crucial indicators for assessing the quality of wastewater treatment, reflecting the organic matter load before and after treatment.

This study has strengths, including the collection of samples from five geographically distributed WWTPs across Greater Cairo, the Middle Nile Delta, and the East Nile Delta regions. It measures 19 water quality parameters in each plant. In addition, this study used R software to analyze data, including data description, statistical analysis, correlations between all parameters by comparing differences between pre- and post-treatment values, significant correlations evaluation, and removal efficacy calculations, indicating treatment performance in each plant. However, this study has some limitations as it does not include samples collected on a seasonal basis to evaluate temporal variation and multivariate factors. Additionally, collecting samples from more distant plants would enhance the spatial coverage.

Further studies should focus on including more seasonally collected samples from a greater number of geographically distributed WWTPs. These studies should also evaluate the biological variation in the wastewater microbiome in both influent and effluent water to understand the associated biohazards and public health significance.

6. Conclusions

At the field level, before implementing any improvements to treatment procedures, samples of soil, potable water, and wastewater should be analyzed chemically and biologically. This analysis will identify significantly

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

affected parameters, find solutions to reduce pollutants in effluent, and clarify the suitable reuse goals for the treated water. In addition, the surrounding environment and related human activities should be considered to ensure the safe reuse of wastewater.

Conflict of interest: Nothing to declare
Acknowledgement: The authors would like to thank Greater Cairo Sanitary Drainage Company, Drinking Water and Wastewater Company in Gharbia, Drinking Water and Wastewater Company in Giza, Alexandria Sanitary Drainage Company, and Al-Dayora Central Lab, GCSDC

7. References

1. Huggins X, Gleeson T, Kummu M, Zipper SC, Wada Y, Troy TJ, et al. Hotspots for social and ecological impacts from freshwater stress and storage loss. Nat Commun. 2022. 21;13 (1): 439.
2. Schumacher DL, Keune J, van Heerwaarden CC, Vilà-Guerau de Arellano J, Teuling AJ, Miralles DG. Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. Nat Geosci. 2019. 19; 12 (9): 712–7.
3. United Nations University Institute for Water, Environment and Health. Invest in nature to cut billion-dollar costs of droughts [Internet]. 2024 [cited 2025 Sep 16]. Available from: https://unu.edu/inweh/news/un-invest-nature-cut-billion-dollar-costs-droughts
4. Nassiri Koopaei N, Abdollahi M. Health risks associated with the pharmaceuticals in wastewater. DARU J Pharm Sci. 2017. 12; 25 (1): 9.
5. Rana RS, Singh P, Kandari V, Singh R, Dobhal R, Gupta S. A review on characterization and bioremediation of pharmaceutical industries' wastewater: an Indian perspective. Appl Water Sci. 2017. 7 (1): 1–12.
6. United Nations Environment Programme (UNEP). 2017 UN world water development report: wastewater the untapped resource [Internet]. 2017 [cited 2025 Sep 16]. Available from: https://www.unep.org/resources/publication/2017-un-world-water-development-report-wastewater-untapped-resource
7. Qadir M, Drechsel P, Jiménez Cisneros B, Kim Y, Pramanik A, Mehta P, et al. Global and regional potential of wastewater as a water, nutrient and energy source. Nat Resour Forum. 2020. 27; 44 (1): 40 – 51.
8. Christou A, Beretsou VG, Iakovides IC, Karaolia P, Michael C, Benmarhnia T, et al. Sustainable wastewater reuse for agriculture. Nat Rev Earth Environ. 2024. 5 (7): 504 – 21.
9. Kato S, Kansha Y. Comprehensive review of industrial wastewater treatment techniques. Environ Sci Pollut Res. 2024. 31 (39): 51064 – 97.
10. Jones ER, van Vliet MTH, Qadir M, Bierkens MFP. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth Syst Sci Data. 2021. 8; 13 (2): 237 – 54.
11. Holding Company for Water and Wastewater (HCWW). Holding Company for Water and Wastewater (HCWW) [Internet]. 2025 [cited 2025 Sep 16]. Available from: https://www.hcww.com.eg/%d9%85%d8%b9%d8%a7%d9%84%d8%ac%d8%a9-%d9%85%d9%8a%d8%a7%d9%87-

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053
Open QR reader and scan code to access this article online

%d8%a7%d9%84%d8%b5%d8%b1%d9%81-%d8%a7%d9%84%d8%b5%d8%ad%d9%8a/

12. Central Agency for Public Mobilization and Statistics (CAPMAS). Annual bulletin for water purification and sanitation statistics year [Internet]. Cairo (Egypt): CAPMAS; 2024 [cited 2025 Sep 16]. Available from: https://www.capmas.gov.eg/Pages/Publications.aspx?page_id=5104&Year=23478

13. American Public Health Association, American Water Works Association, Water Environment Federation. Standard methods for the examination of water and wastewater. 24th ed. Lipps WC, Braun-Howland EB, Baxter TE, editors. Washington (DC): APHA Press; 2023.

14. Association of Official Analytical Chemists (AOAC). Official methods of analysis. 19th ed. George WL, editor. Rockville (MD): AOAC International; 2012. p. 974.27–984.27.

15. Egypt. Law No. 48 of 1982 concerning the protection of the Nile River and waterways from pollution and its Executive Regulations No. 92 of 2013 (Article 52) [Internet]. Cairo: Official Gazette; 2013 [cited 2025 Sep 16]. Available from: https://leap.unep.org/en/countries/eg/national-legislation/ministerial-decree-no-92-2013-amending-ministerial-decree-no-8

16. Metcalf & Eddy Inc. Wastewater engineering: treatment and resource recovery. 5th ed. New York: McGraw Hill Education; 2013.

17. Council of the European Communities. Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment. Off J Eur Communities. 1991. 21; 135: 40 – 52.

18. Food and Agriculture Organization of the United Nations (FAO). Wastewater treatment and use in agriculture. Rome: FAO; 1992.

19. An M, He W, Degefu DM, Liao Z, Zhang Z, Yuan L. Spatial patterns of urban wastewater discharge and treatment plants efficiency in China. Int J Environ Res Public Health. 2018. 31; 15 (9): 1892.

20. Gad M, Abdo SM, Hu A, El-Liethy MA, Hellal MS, Doma HS, et al. Performance assessment of natural wastewater treatment plants by multivariate statistical models: a case study. Sustainability. 2022. 23; 14 (13): 7658.

21. Hegazy MH, Gawad MA. Measuring and evaluating the performance of a wastewater treatment plant. In: Proceedings of the World Congress on Civil, Structural, and Environmental Engineering; 2016 Apr 4–6; Prague, Czech Republic. Ottawa (Canada): Avestia Publishing; 2016. Paper No. AWSPT 111.

22. Ayoub M, El-Morsy A. Applying the wastewater quality index for assessing the effluent quality of recently upgraded Meet Abo El-koum wastewater treatment plant. J Ecol Eng. 2021; 22 (2): 128 – 33.

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

Table (1): General overview and topographical findings of the selected WWTPs.

Overview and topographical data	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
Name and geography	Balaq's WWTP, Al-Qalyobia Governorate	Al-Berka WWTP, Cairo Governorate	Nahtai WWTP, Al-Gharbia Governorate, Middle of the Nile Delta region	Zenine WWTP, Giza governorate	Al-Tanqya Al-Sharqya WWTP, Alexandria governorate, East of the Nile Delta region
Location	Latitudes: N 30°09'36.1" Longitudes: E 31°17'57.2"	Latitudes: N 30°11'02.9" Longitudes E 31°24'56.0"	Latitudes: N 30°42'20.1" Longitudes: E 31°11'48.2"	Latitudes: N 30°01'59.3" Longitudes: E 31°10'57.8"	Latitudes: N 31°12'05.7" Longitudes: E 29°57'42.4"
Design Capacity	600.000 m^3/d	600.000 m^3/d	10.000 m^3/d	400.000 m^3/d	800.000 m^3/d
Operational Capacity	400.000 m^3/d	400.000 m^3/d	9000 m^3/d	330.000 m^3/d	700.000 m^3/d
Type of biological treatment	Conventional Activated Sludge System	Conventional Activated Sludge System	Mixed (Moving Bed Biofilm Reactor (MBBR) System + Conventional activated Sludge System)	Conventional Activated Sludge System	Conventional Activated Sludge System
Main receiving drain	Shebeen El-Qanater drain	Al-Gabal Al-Asfar drain	Al-Atf drain	Al-Moheet drain	Dayer Al-Matar drain
Environmental context	- Mainly an urban area - domestic, commercial, and industrial activities	- Mainly an urban area - domestic, commercial, and industrial activities	- Mainly a rural area - domestic and light industrial activities	- Mainly an urban area - domestic, commercial, and industrial activities	- Mainly a coastal area - domestic, commercial, and industrial activities

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

Table (2): Physicochemical parameters and heavy metal concentrations for influent and effluent samples collected from the study scope WWTPs

Parameter	Sample Type	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Control
Temperature	Input	24.6	27.1	25.8	24.4	21.7	--
	Output	25.3	25.7	25.5	25.5	23.5	--
pH	Input	7.18	7.32	7.41	7.54	7.58	--
	Output	6.96	7.27	7.31	7.15	7.1	7.5[a]
Do	Input	1.24	1.08	1.92	2.3	2.97	--
	Output	6.96	7.11	7.52	5.01	8.83	4[a]
Turbidity	Input	100	99.1	179	42	92.1	--
	Output	1.74	3.17	3.01	6.46	3.9	2[b]
BOD5	Input	200	81	173	101	155	--
	Output	11	6	1	2	32	20[b]
COD	Input	388	363	312	461	342	--
	Output	21	5	28	34	37	60[b]
TOC	Input	50.66	40.57	75.95	59.17	47.34	--
	Output	13.18	12.81	16.82	15.12	8.58	30[b]
TDS	Input	404	414	693	390	1452	--
	Output	375	370	579	385	1335	600[b]
EC	Input	776	748	1076	618	2096	--
	Output	719	690	917	607	1766	1850[d]
CN	Input	0.015	0.046	0.045	0.003	0.016	--
	Output	0.009	0.002	0.008	0.006	0.006	0.1[a]
TP	Input	5.52	5.07	4.68	3.8	5.4	--
	Output	3.8	4.18	5.7	2.59	4.95	1[c]
TN	Input	27.67	29.93	65.92	31.17	41.58	--
	Output	10.99	13.21	25.75	18.38	18.83	12.5[c]
Pb	Input	0.089	0.121	0.073	0.094	0.09	--
	Output	0.004	0.006	0.003	0.005	0.004	0.0056[b]
Ni	Input	1.407	1.39	1.531	1.341	1.482	--
	Output	0.006	0.004	0.005	0.003	0.003	0.0071[b]
Cd	Input	0.001	0.001	0.002	0.001	0.001	--
	Output	0	0	0	0.001	0	0.0011[b]
Cu	Input	0.68	0.343	1.399	0.205	1.271	--
	Output	0	0	0	0	0	0.0049[b]
Fe	Input	14.24	13.5	20.07	12.7	11.93	--
	Output	0	0	0	0	0	3.5[a]
Zn	Input	0.226	0.101	0.013	0.032	0.024	--
	Output	0	0.098	0	0	0	0.058[b]
Hg	Input	0.148	0.122	0.123	0.127	0.128	--
	Output	0.012	0.014	0.013	0.013	0.015	0.0021[b]
As	Input	0.019	0.001	0.005	0.018	0.013	--
	Output	0.003	0	0.002	0.001	0	0.02[b]

(a) Limits of the Egyptian Law 48/1992

(b) Wastewater Engineering: Treatment and Resource Recovery Guidelines

(c) Limits of the EU Council Directive 91/271/EEC

(d) Limits of the FAO 1992

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

Table (3): Statistical comparison of influent and effluent values for each water quality parameter using paired t-tests or the Wilcoxon Signed-Rank Test, as appropriate. The test applied is indicated for each parameter. *p-values* indicate whether differences between before and after treatment are statistically significant ($p < 0.05$). Parameters demonstrated a range of responses, with significant treatment effects found for most, except EC, CN, TP, DO, Zn, and Hg, where no significant difference was observed

Parameter	Method	*p_value*
pH	Student's *t*-test	0.039
DO	Wilcoxon Signed-Rank Test	0.062
Turbidity	Student's *t*-test	0.011
BOD5	Student's *t*-test	0.003
COD	Student's *t*-test	0.0001
TOC	Student's *t*-test	0.0012
TDS	Student's *t*-test	0.053
EC	Student's *t*-test	0.097
CN	Student's *t*-test	0.109
TP	Student's *t*-test	0.235
TN	Student's *t*-test	0.01
Pb	Student's *t*-test	0.0002
Ni	Student's *t*-test	1.88
Cd	Student's *t*-test	0.034
Cu	Student's *t*-test	0.031
Fe	Student's *t*-test	0.0005
Zn	Wilcoxon Signed-Rank Test	0.062
Hg	Wilcoxon Signed-Rank Test	0.062
As	Student's *t*-test	0.040

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

Table (4): Removal efficiency (%) for 17 wastewater quality parameters across five treatment plants. Values indicate the percentage reduction from influent to effluent for each parameter and plant, summarizing overall treatment performance for physicochemical, organic, aggregate, and heavy metal indicators

Sample	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
Turbidity_eff	98.26	96.8	98.32	84.62	95.77
BOD5_eff	94.5	92.59	99.42	98.02	79.35
COD_eff	94.59	98.62	91.03	92.62	89.18
TOC_eff	73.98	68.42	77.85	74.45	81.88
TDS_eff	7.18	10.63	16.45	1.28	8.06
EC_eff	7.35	7.75	14.78	1.78	15.74
CN_eff	40	95.65	82.22	-100	62.5
TP_eff	31.16	17.55	-21.79	31.84	8.33
TN_eff	60.28	55.86	60.94	41.03	54.71
Pb_eff	95.51	95.04	95.89	94.68	95.56
Ni_eff	99.57	99.71	99.67	99.78	99.8
Cd_eff	100	100	100	0	100
Cu_eff	100	100	100	100	100
Fe_eff	100	100	100	100	100
Zn_eff	100	2.97	100	100	100
Hg_eff	91.89	88.52	89.43	89.76	88.28
As_eff	84.21	100	60	94.44	100

Table (5): Overall removal efficacy (%) of organic/aggregate parameters and the combined group of TP, TN, and heavy metals for five WWTps. Values are calculated as percentage reduction from influent to effluent, demonstrating the plants' effectiveness in improving water quality across major contaminant categories

Plant	Organic and Aggregate Treatment Efficacy	TP, TN, and Heavy Metals Treatment Efficacy
Plant 1	55.51%	86.26%
Plant 2	55.60%	75.96%
Plant 3	59.90%	78.41%
Plant 4	53.63%	75.15%
Plant 5	54.84%	84.66%

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

Fig. 1: Spatial distribution of the study scope WWTPs

(1) Balaq's WWTP, Al-Qalyobia Governorate
(2) Al-Berka WWTP, Cairo Governorate
(3) Nahtai WWTP, Al-Gharbia Governorate, Middle of the Nile Delta region
(4) Zenine WWTP, Giza governorate
(5) Al-Tanqya Al-Sharqya WWTP, Alexandria governorate, East of the Nile Delta region

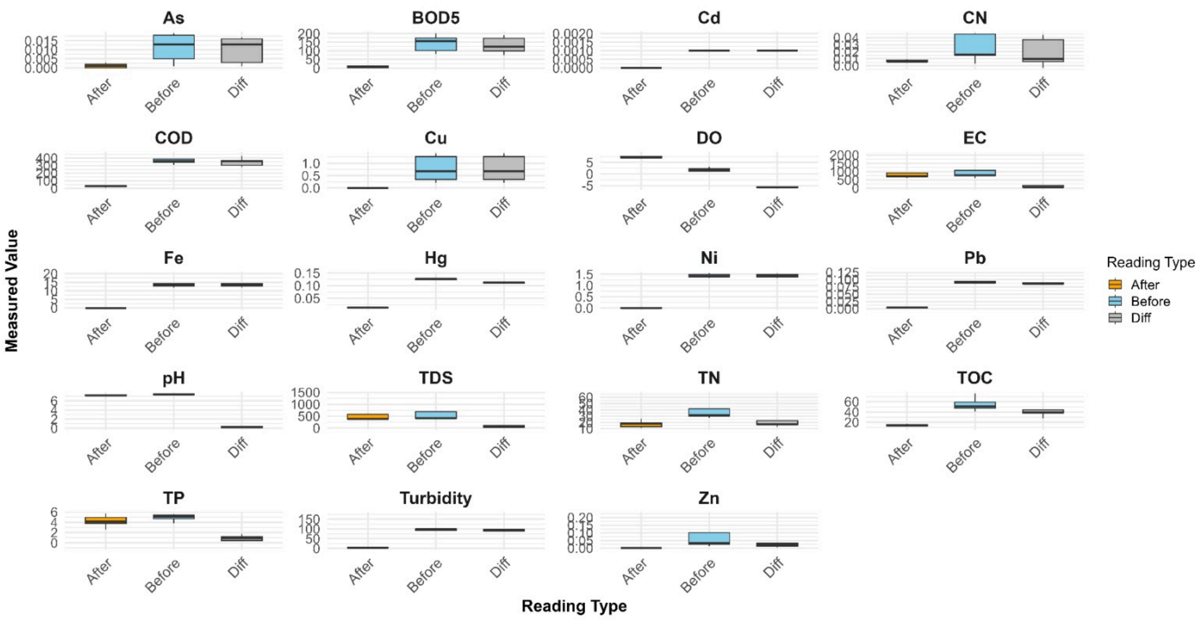

Fig 2: Boxplots comparing distributions of 19 wastewater quality parameters before and after treatment, with difference (Diff) shown for each. The figure highlights substantial reductions in contaminant concentrations across physicochemical, organic, aggregate, and heavy metal parameters, illustrating robust removal efficacy and performance consistency among samples

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

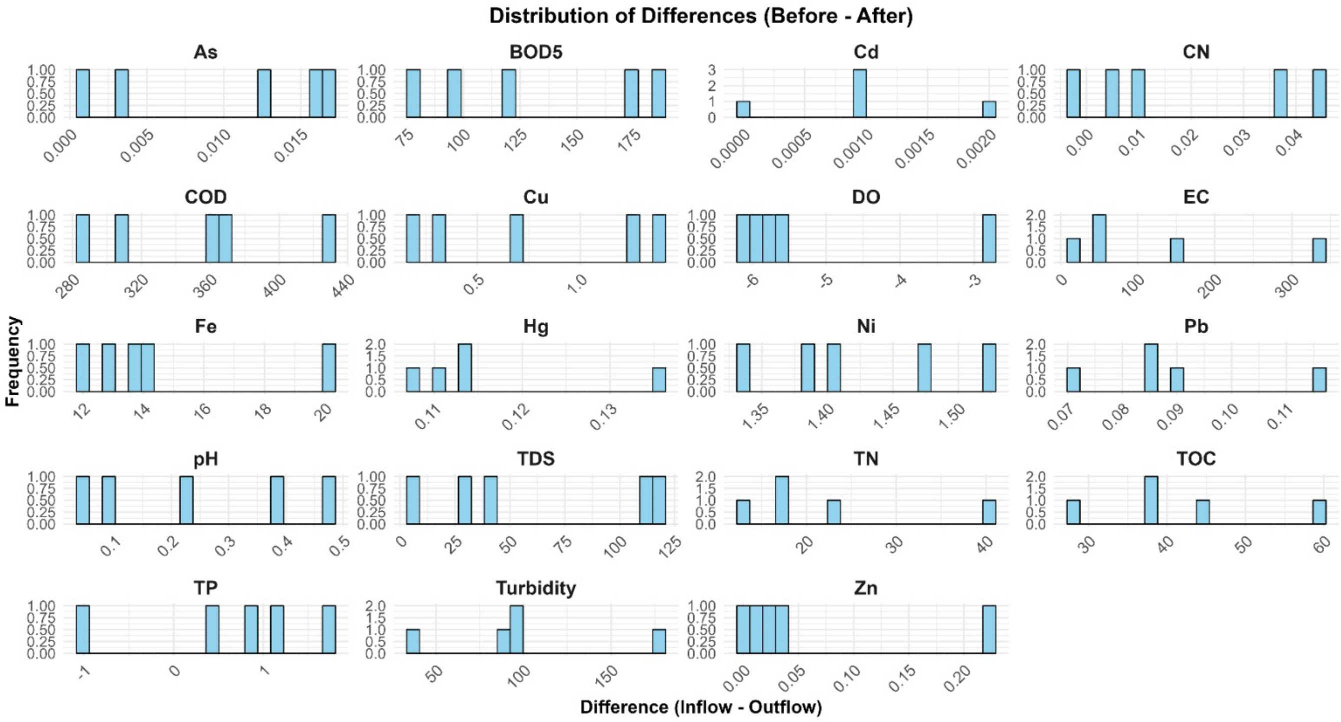

Fig 3: Distribution of before–after differences (inflow minus outflow) for 19 wastewater quality parameters. Each panel shows the frequency of observed differences across all samples for a single parameter; positive values indicate reduction due to treatment

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

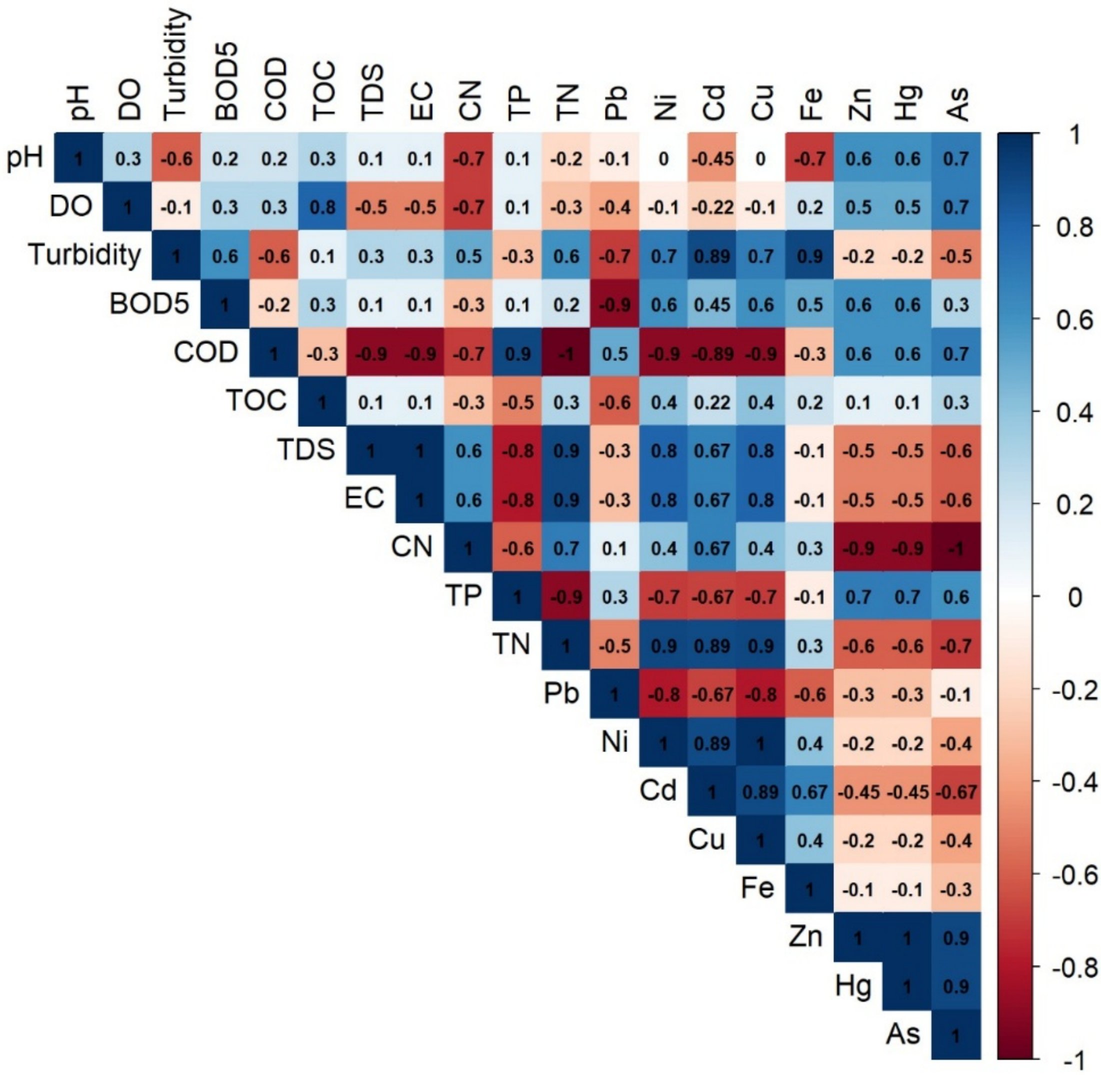

Fig. 4: Correlation heatmap for 19 wastewater quality parameters. Each cell represents the Pearson correlation coefficient between two parameters, with color and value indicating the strength and direction of the relationship (red: negative, blue: positive, white: weak/no correlation). Strong clusters among heavy metals and nutrients highlight potential linked behaviors in the treatment process

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

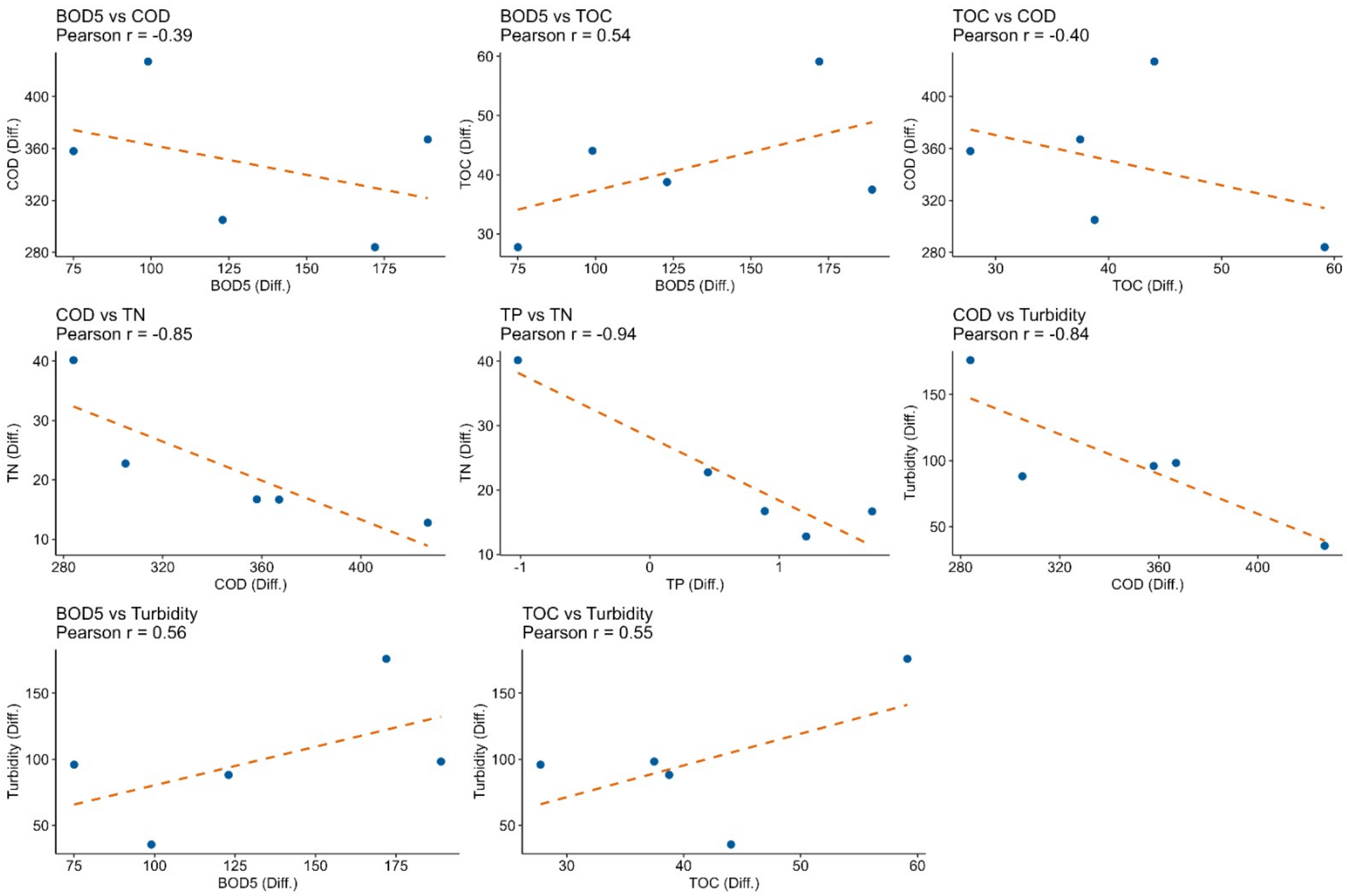

Fig. 5: Matrix of scatterplots showing bivariate correlations and Pearson r coefficients between the removal (inflow minus outflow) of major wastewater parameters. Each panel displays individual data points, a regression line, and r value, illustrating the range of positive and negative associations among organic, nutrient, and aggregate indicators across treatment plants.

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

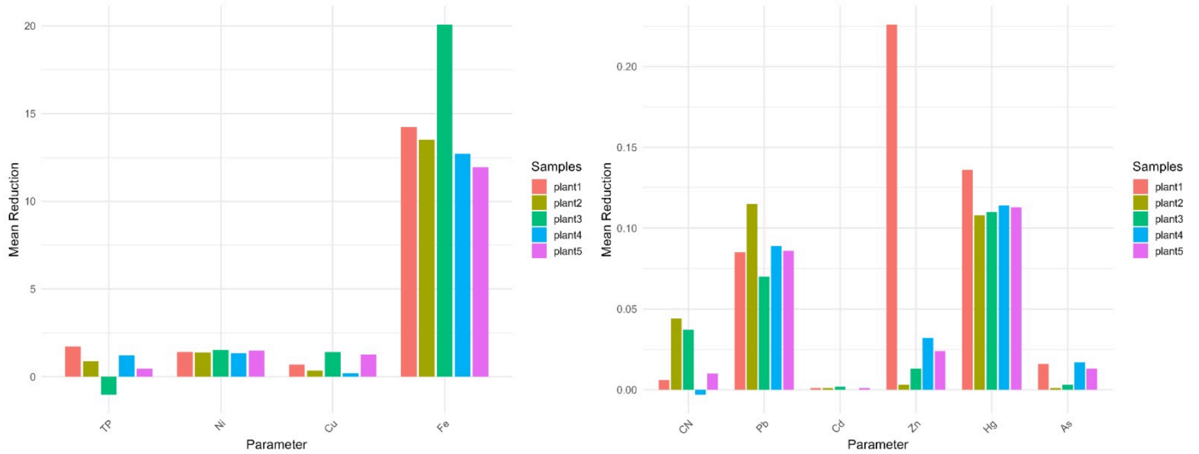

Fig. 6: Mean reduction of physicochemical and heavy metal parameters in influent samples from five Egyptian WWTPs. The left panel illustrates mean reductions for TP (total phosphorus), Ni (nickel), Cu (copper), and Fe (iron), while the right panel focuses on CN (cyanide), Pb (lead), Cd (cadmium), Zn (zinc), Hg (mercury), and As (arsenic). Bars represent the results for each plant, highlighting both spatial variability and element-specific removal efficiencies.

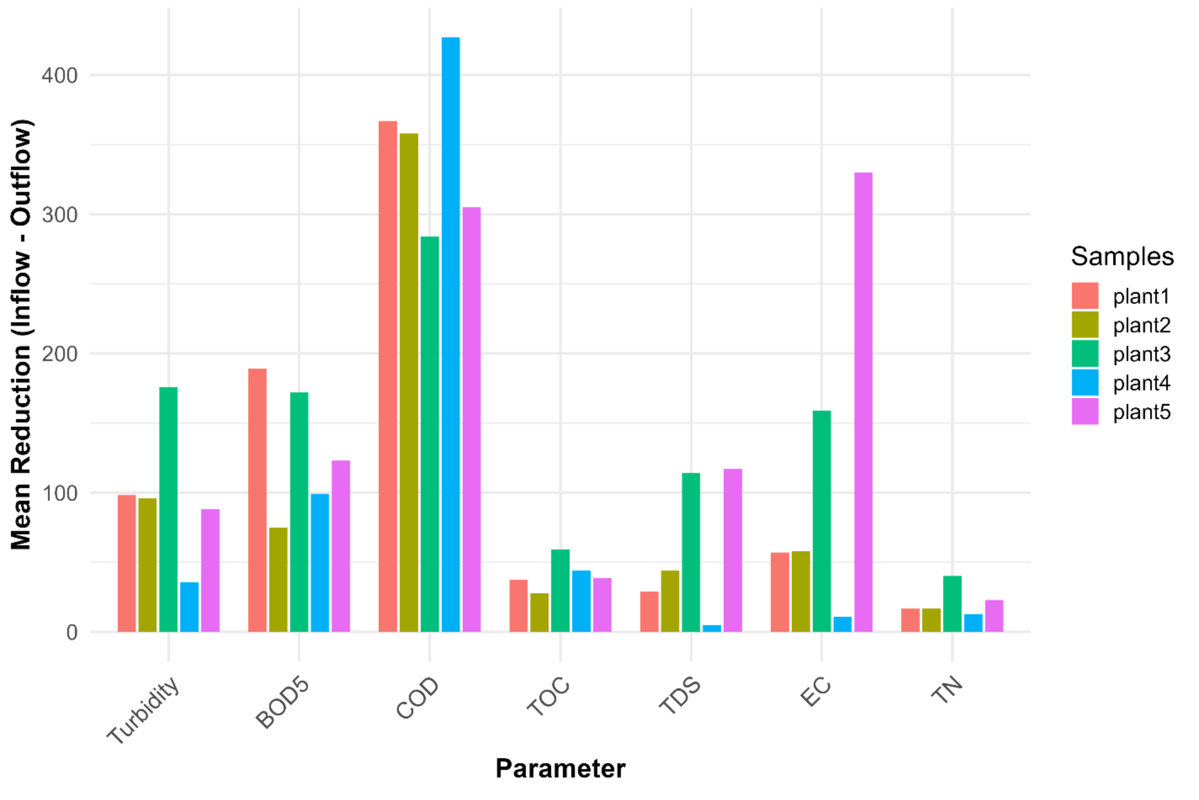

Fig. 7: Grouped bar chart shows the mean reduction (inflow minus outflow) and standard deviation for Turbidity, BOD5, COD, TOC, TDS, EC, and TN across multiple treatment plants. Bars represent the average removal efficacy for each parameter per plant, with error bars indicating variability among samples. The figure highlights strong organic and aggregate pollutant removal performance and differences in treatment consistency.

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053

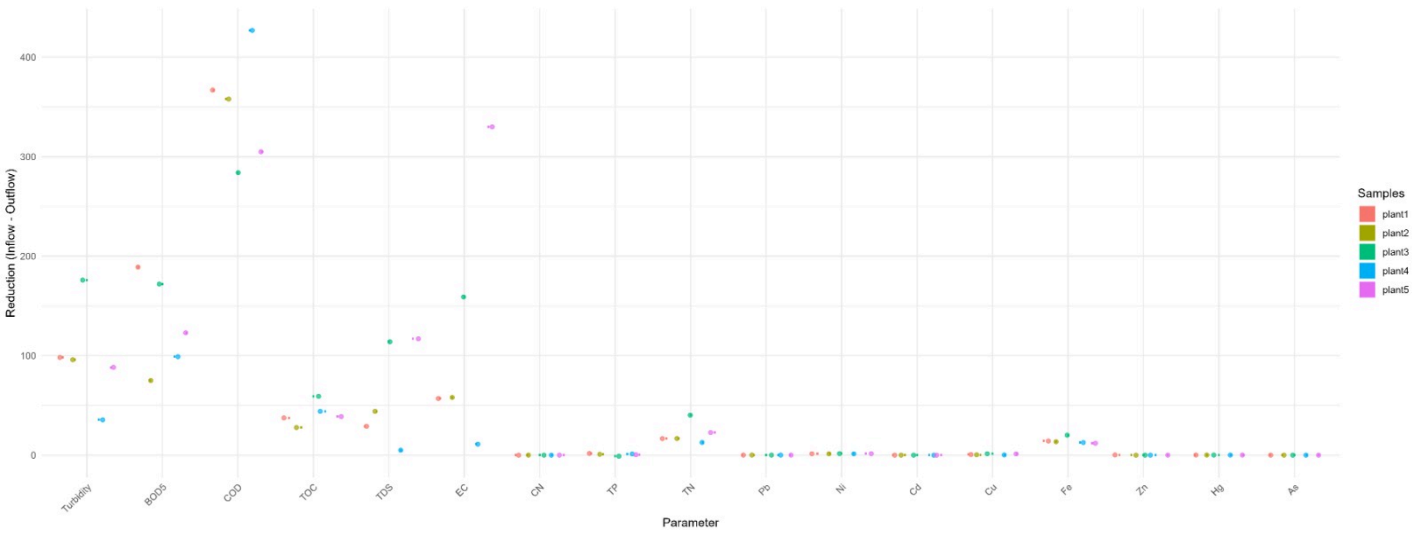

Fig. 8 Raincloud plot illustrating the reduction efficiency (inflow minus outflow) for 19 wastewater quality parameters across treatment plants. Each parameter displays a distribution (half-violin), boxplot, and individual data points colored by plant, revealing variability in removal performance and distributional characteristics among parameters and plants.

Online ISSN: 2537-1045
Print ISSN: 1110-1423
DOI: 10.21608/vmjg.2025.424015.1053