

Temporal Trends Of Greywater And Tertiary-Treated Effluent Quality: Implications For Urban Reuse

^{1*}Salam Akinkunmi Alli, ^[2]Snigdhendubala Pradhan, ^[2]Jayaprakash Saththasivam,

^[1]Gordon McKay

^[1] Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University

^[2] Qatar Environment and Energy Research Institute (QEERI), Hamad Bin Khalifa University ^{[1]*}saal35568@hbku.edu.qa, ^[2] spradhan@hbku.edu.qa,

^[2]jsaththasivam@hbku.edu.qa, ^[1]gmckay@hbku.edu.qa

*Corresponding Author: saal35568@hbku.edu.qa

I. ABSTRACT

The effective reuse of wastewater is essential in water-stressed urban regions. A longitudinal study was conducted over 8 weeks to evaluate the short-term variability and storage-related changes in raw greywater (GW), tertiary-treated sewage effluent (TSE), and tap water (TW) as the control. Weekly samples were collected from the inlet (INL) and storage tank (STK) for GW and TSE, while TW was collected only from the laboratory tap.

GW was found to be highly biodegradable, with turbidity averaging 67.68 ± 53.63 NTU, and organic fractions: COD, BOD₅, and TOC values of 122.54 ± 93.1 ppm, 53.33 ± 25.25 ppm, and 21.12 ± 7.76 ppm, respectively. The BOD₅/COD ratio (0.23 - 0.79) confirmed the presence of biodegradable organic and ammonium-N (2.18 ± 0.81 ppm). Conversely, TSE presented low organic levels (COD < 40 mg/L, BOD₅ < 8 ppm) but higher ionic loads, with EC of 1685.60 ± 116.54 μ S/cm, sodium of 125.07 ± 17.24 ppm, chloride of 274.32 ± 30.01 ppm, and sulfate of 268.40 ± 22.72 ppm. The residual chlorine content was in the following order: GW>TW>TSE. More importantly, variations in INL and STK demonstrated that storage conditions influenced water quality, with greater differences in GW solids/organics and slight ionic accumulation in the TSE. These findings underscore the importance of source-specific treatments, including removing solid and organic matter for GW and controlling salinity and nutrients for TSE. Implementing these targeted strategies can improve the sustainability of urban wastewater reuse, particularly in arid regions (e.g., Qatar), and support circular water management efforts in advanced reuse systems (i.e., the Netherlands).

Keywords: longitudinal water quality, greywater treatment, treated sewage effluent, salinity control, wastewater reuse.

II. INTRODUCTION

Increasing water scarcity has intensified research on reclamation, focusing on greywater (GW) and treated sewage effluent (TSE) for non-potable uses, such as industrial process waters, irrigation, toilet flushing, and landscaping. The usefulness of these water sources depends on their quality, which varies according to user practices, treatment methods, and natural conditions. Although numerous studies have assessed wastewater quality at discrete time intervals and have largely focused on treatment efficiency, they have limited capacity to resolve temporal dynamics [1], [2], [3]. However, to adaptively incorporate growth uncertainties and vulnerabilities into the decentralized water management planning process for different projected futures, long-term longitudinal data are necessary to capture short-term variability for effective reuse planning.

In water-stressed countries, such as Qatar, and technologically advanced nations, like the Netherlands, where sustainable water management is of national interest, the value of

such research is particularly high. Qatar relies heavily on desalination, a process that is both energy-intensive and expensive. Consequently, wastewater reuse presents an economically attractive alternative for supplementing urban water demand. On the other hand, the Netherlands has taken a lead internationally on integrated water and circular water management with a focus on wastewater reuse, nutrient recovery, and climate-resilient reuse systems [4]. Continuous monitoring of source quality is necessary to maintain long-term acceptance and sustainability [5]. This study also provides longitudinal information on the variability in GW and TSE during storage, which is important for both regional contexts: enhancing decentralized reuse opportunities in arid Gulf States and improving quality assurance frameworks for highly urbanized water recycling systems.

This study aimed to fill this gap by conducting an eight-week monitoring campaign for GW and TSE, using tap water as a reference. Physical, chemical, and nutrient parameters were analyzed for weekly samples, from which both temporal trends were observed, and comparisons were made regarding the stability between the sources.

Many researchers have highlighted the significant variability of greywater and its constituents, including turbidity, organic matter, and nutrient content, which makes the direct reuse of greywater challenging [6]. TSE is more stable but still contains residual chlorine, nutrients, and dissolved organics that may interfere with irrigation or reuse [7]. To the best of our knowledge, very few studies have systematically monitored both streams simultaneously over time with parallelization for several key parameters, such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), total organic carbon (TOC), total nitrogen (TN), orthophosphates (PO_4^{3-}), and major ions in water. Measuring these water qualities over time in our environment provides a more accurate picture of the trends in wastewater contamination than a stationary controlled source, such as tap water.

This study presented a comparative analysis of raw greywater (GW) and treated sewage effluent (TSE) over an 8-week monitoring period at both inlets and storage locations. It revealed how short-term storage shaped the distinct quality of both streams (GW and TSE), highlighting organic and solid instability in GW samples compared to mild ionic buildup in TSE streams. The findings of this study could create a clear, fit-for-purpose roadmap for urban reuse, which is often hidden in real system behavior rather than in single-snapshot measurements.

Our objectives were to (i) measure raw mixed greywater and tertiary-treated sewage effluent over an eight-week period, (ii) compare inlet samples with the corresponding storage tanks for each source to represent a full range of collection points relevant to reuse, (iii) use tap water (TW) for benchmarking analytical consistency owing to its stability, and (iv) evaluate temporal trends in physical, organic, nutrient, disinfection, and ionic parameters that are useful for reuse planning. Additionally, sampling from both the inlet and storage tanks is crucial to distinguish the quality of newly supplied water from that of stored irrigation water. The quality of both sampling points (inlet and storage tanks) provides a more realistic basis for evaluating the safety of reuse and its environmental impact (e.g., soil quality).

III. RESEARCH METHODOLOGY

An eight-week wastewater quality monitoring assessment was conducted on Hamad Bin Khalifa University's premises within Education City, Doha. Three water sources were selected: raw mixed greywater (comprising bath, washbasin, and laundry wastewater) collected from a tank behind the university dormitory, tertiary-treated sewage effluent from the municipal wastewater treatment plant's distribution network, and laboratory tap water, serving as a control. Two sampling locations were tracked for both GW and TSE: raw feed inlets and storage tanks. The tanks were dedicated to irrigation: TSE storage water was used for a vegetated green roof on the dormitory's roof, and GW storage water contributed to modular green walls at the back of the dormitory.

Approximately 80% of the stored water was used for irrigation twice a day. Regular inflows of fresh wastewater were automatically filled in the tanks using inlet pumps for continuous operation. For comparison, samples were collected from the laboratory tap as tap water samples. Storage conditions were maintained, and fouling was reduced through regular cleaning of all storage tanks every 3 months, especially in GW tanks. All samples were collected separately in a clean (carbon-free) 1 litre bottle (Duran, Germany). In-situ field parameters (temperature, pH, EC, and free chlorine) were measured on-site from grab samples using portable calibrated electrodes (Thermo Fisher Scientific, USA) and powdered chemical kits (Hach, USA). All analyses not involving on-site assessments were conducted in the university's Division of Sustainable Development (DSD) laboratory within 48 h after sampling. Table 1 presents a concise workflow summary of the field experiment, including the study design and sampling strategy, and clarifies how inlet and storage samples from GW and TSE were monitored over an 8-week period.

Table 1. Summary of the monitoring design and sampling points across the water sources.

Components	What was done	Key Details/Outputs
Study design	Longitudinal monitoring study	8-week campaign comparing GW and TSE, with TW as control/water quality benchmark.
Study setting	Campus-scale decentralized reuse system	Sampling on HBKU premises (Doha, Qatar); irrigation-linked storage tanks for green walls (GW systems), and green roofs (TSE systems).
Water Sources	Three sources were evaluated	Raw mixed GW (bath, washbasin, laundry), TSE (distribution network), laboratory TW as control
Sampling points	Two points were tracked for GW and TSE	Inlet/feed water and storage tank water; TW sampled from the lab tap.

Sampling frequency and duration	Repeated sampling over time	Weekly grab samples for 8 weeks; comparisons made across sources and between inlet vs storage.
Operation context of Storage	Decentralized reuse conditions under an arid environment	Tanks for irrigation; 80% of stored water used twice daily; tanks were refilled automatically via inlet pumps; tanks were cleaned every 3 months.
Sample collection and holding	Standardized collection and handling	Samples collected separately in clean 1L carbon-free bottles (Duran); laboratory analyses were performed within 48 hrs.

GW = greywater, TSE = tertiary-treated sewage effluent, TW = tap water, HBKU – Hamad Bin Khalifa University.

Physical and chemical analyses were performed using standard methods [8]. A spectrophotometric technique was used to measure turbidity (Turbidimeter, Hach) and apparent color at 455 nm, whereas suspended solids (TSS, VSS, and VSS/TSS) were evaluated by gravimetric methods. The Hach dichromate digestion vial method was used to measure the chemical oxygen demand (COD) of each sample. Biological oxygen demand on the fifth day (BOD₅) was measured using a mercury-free respirometric method (Velp Scientifica, Italy), while filtered samples (using 0.45 µm syringe filters) were analyzed for organic carbon and nitrogen; organic carbon was measured as non-purgeable organic carbon (NPOC) and nitrogen contents as total nitrogen (TN), respectively, using a TOC analyzer with a TNM module (Shimadzu TOC-L, USA).

Nutrients such as ammonium nitrogen, nitrate (NO₃⁻), phosphate (PO₄³⁻), and other anions (Cl⁻ and SO₄²⁻) were measured colorimetrically at 660 nm (Skalar Sans ++, Netherlands) and by ion chromatography (Metrohm, USA). The reactivity of organic matter was described using UV₂₅₄ absorbance (UV-Vis Spectrophotometer, Shimadzu), and specific ultraviolet absorbance (SUVA) was estimated theoretically [9]. The major cations (Ca, Mg, Na, and K) were evaluated using inductively coupled plasma optical emission spectrometry (ICP-OES; Agilent 5110). Triplicate analyses, calibration checks, and deionized water were used as a reference control to maintain quality assurance among the samples.

II-A. DATA HANDLING AND PROCESSING

All measurements were compiled in a Microsoft (MS) Excel spreadsheet, and data analysis was conducted in a Python environment within Microsoft Visual Studio Code (VS Code). The workflow included data cleaning and validation, aggregation of replicate measurements, and computation of descriptive statistics (mean ± standard deviation) for each water source and its respective sampling location. Temporal patterns and inlet-storage differences were visualized using Seaborn and Plotly (e.g., boxplots) to reveal variability, central tendency, and storage-related shifts across the 8-week monitoring period. Table 2 provides a concise summary of the analytical methods, quality assurance, and data-processing workflow. This is intended to clarify how the resulting dataset was generated and interpreted for insights relevant to reuse.

Table 2. Summary of analytical workflow and data analysis across the water sources

Components	What was done	Key details/outputs
Onsite measurements	Immediate field tests	Temperature, pH, and EC were measured with portable, calibrated probes; free chlorine was measured with Hach powdered kits.
Physical parameters (DSD-L)	Solids and optical properties	Turbidity (Hach turbidimeter), apparent color at 455nm, TSS/VSS via gravimetric methods
Organic content (DSD-L)	Bulk organics and biodegradability	COD by Hach dichromate digestion methods; BOD ₅ by mercury-free respirometric method (Velp); TOC as NPOC via Shimadzu TOC-L; UV ₂₅₄ via Shimadzu UV-Vis; SUVA computed from UV ₂₅₄ and DOC/TOC.
Nutrients and anions (DSD-L)	Major nutrient/anionic fractions	NH ₄ ⁺ -N, NO ₃ ⁻ , PO ₄ ³⁻ via Skalar Sans++; Cl ⁻ and SO ₄ ²⁻ via ion chromatography.
Cations (DSD-L)	Commonly found metal contents	Ca, Mg, Na, and K were measured using ICP-OES (Agilent 5110)
QA/QC (DSD-L)	Analytical Quality Assurance	Triplicate analyses, calibration checks, and deionized water as blanks/reference controls to ensure consistency.
Data analysis and visualization	Processing, statistics, and plots	Analysis conducted in a Python environment within an MS VS Code; descriptive statistics and graphical representation via Seaborn/Plotly (e.g., boxplots)

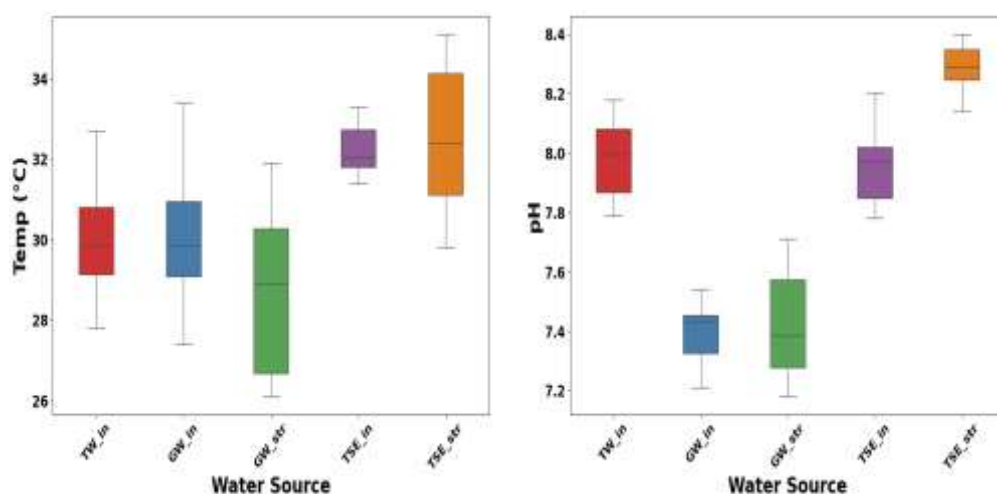
DSD-L = Division of Sustainable Development lab, EC = electrical conductivity, QA/QC = Quality assurance/checks, TSS/VSS = total/volatile suspended solids, TOC = total organic carbon, NPOC = non-purgeable organic carbon, UV-Vis = ultraviolet/visible spectrum, DOC = dissolved organic carbon, NH₄⁺-N = ammonium-nitrogen, NO₃⁻ = nitrate, PO₄³⁻ = orthophosphates, Cl⁻ = chloride, SO₄²⁻ = sulfate, Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, ICP-OES = inductive coupled-plasma optical emission spectroscopy, MS = Microsoft, VS = Visual Studio.

IV. RESULTS AND DISCUSSION

III-A. PHYSICAL PARAMETERS

Figure 1 reveals the main differences in the patterns of GW, TSE, and Tw across the key physical parameters. Temperature distributions were generally similar but somewhat (consistently) higher in the TSE storage due to additional outdoor exposure during summer, when tanks absorb solar radiation and ambient heat. The pH was neutral to slightly alkaline across all samples, with lower pH values in greywater (≈ 7.2 – 7.5) compared to TSE storage (>8.0). This increased alkalinity is partly attributed to residual treatment chemicals, such as chlorine and alkalis (e.g., lime or NaOH), used for disinfection and pH adjustment. In arid regions, where desalinating seawater is the primary source of domestic water use, treated effluents often exhibit alkaline characteristics and elevated ionic content due to post-treatment remineralization [10]. TSE had a much higher saline content (≈ 1500 – 1800 $\mu\text{S}/\text{cm}$) than greywater (between 200 – 300 $\mu\text{S}/\text{cm}$) and tap water (roughly 200 $\mu\text{S}/\text{cm}$), reflecting its higher dissolved salt concentration.

Turbidity also showed significant variability, with higher values in greywater storage, ranging from low to high (exceeding 150 NTU), followed by TSE, which remained low, whereas Tw was almost free of turbidity. In general, this result confirms differences between greywater, which is driven by particulates and associated turbidity; TSE, which is more saline and alkaline but physically clearer; and tap water, which serves as a more stable reference baseline for this study.



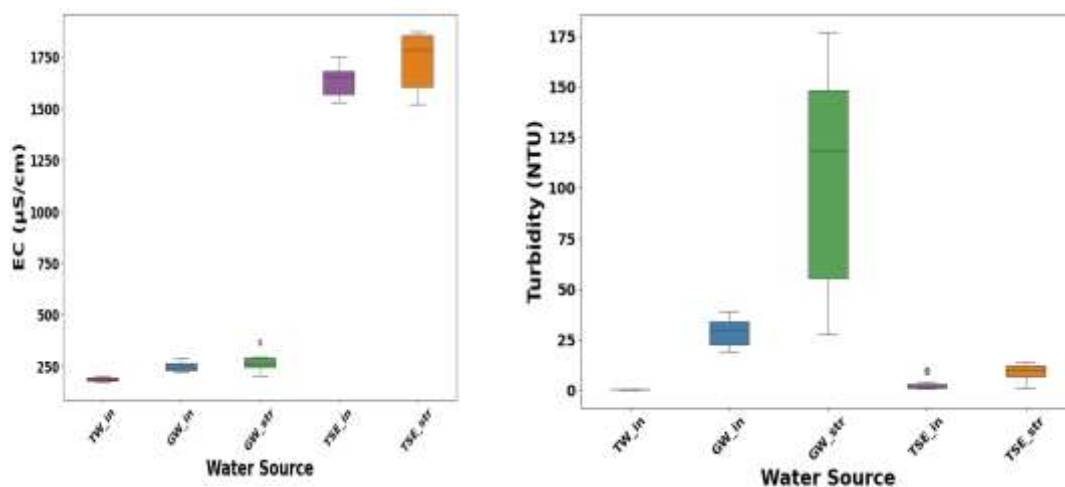


Figure 1. Evaluation of the physical parameters (Temperature, pH, Electrical conductivity, and Turbidity) of the various water samples (sources and points) for 8 weeks.

Key: TW_in – Tapwater from a tap mouth, GW_in – inlet greywater samples, GW_str – greywater samples from a storage tank, TSE_in – inlet TSE samples, TSE_str – TSE samples from a storage tank.

III-B. APPARENT COLOR AND SOLID CONTENTS

The solid composition and color metrics enabled the clear discrimination of greywater from treated sewage effluent (TSE) and tap water (Figure 2). GW, especially in the storage tank, showed the highest color (600 Pt-Co) and the greatest variation in TSS and VSS, due to higher levels of particulate and organic matter, typically from laundry and bathroom effluents. The VSS/TSS ratio in GW (inlets and storage tanks) was 0.4-0.5, indicating that approximately half of the suspended solids were organic and therefore easily degradable.

Conversely, TSE had significantly lower color, TSS, and VSS, with VSS/TSS ratios that approached zero, indicating that the effluent was predominantly composed of inorganic and mineral solids after tertiary treatment. The tap water concentrations remained constant and were close to zero for all parameters, indicating the accuracy of the measurements. These results highlight that GW has higher variability in suspended solids and organic concentrations, with potential for microbial development. Even though TSE is clearer and more stable, TSE samples taken from the storage tank also show a slight presence of particles; therefore, special attention is required when reusing the water.

TSE initially leaves the treatment plant with low or negligible turbidity and suspended solids, as shown in inlet TSE samples (Figure 2), but increasing particle concentrations can be associated with the storage. Several mechanisms could explain this observation. First, resuspension of fine solids might take place during pumping or inflow turbulence, which could reintroduce previously settled material [11]. Second, biofilm sloughing from the tank walls is frequent under warm conditions: microbial colonies accumulate over time within the patches on the walls and then peel off intermittently, causing loose organic flocs to move through the water column [12]. Third, it can proceed by chemical precipitation, as TSE is often a source of high concentrations of Ca^{2+} , Mg^{2+} , and SO_4^{2-} , and pH or temperature changes may result in the formation of particulate scale (e.g., CaCO_3).

Lastly, the decomposition of free chlorine during storage reduces disinfectant power, promoting the growth of microorganisms and microbial aggregates that contribute to turbidity and total suspended solids (TSS) [13].

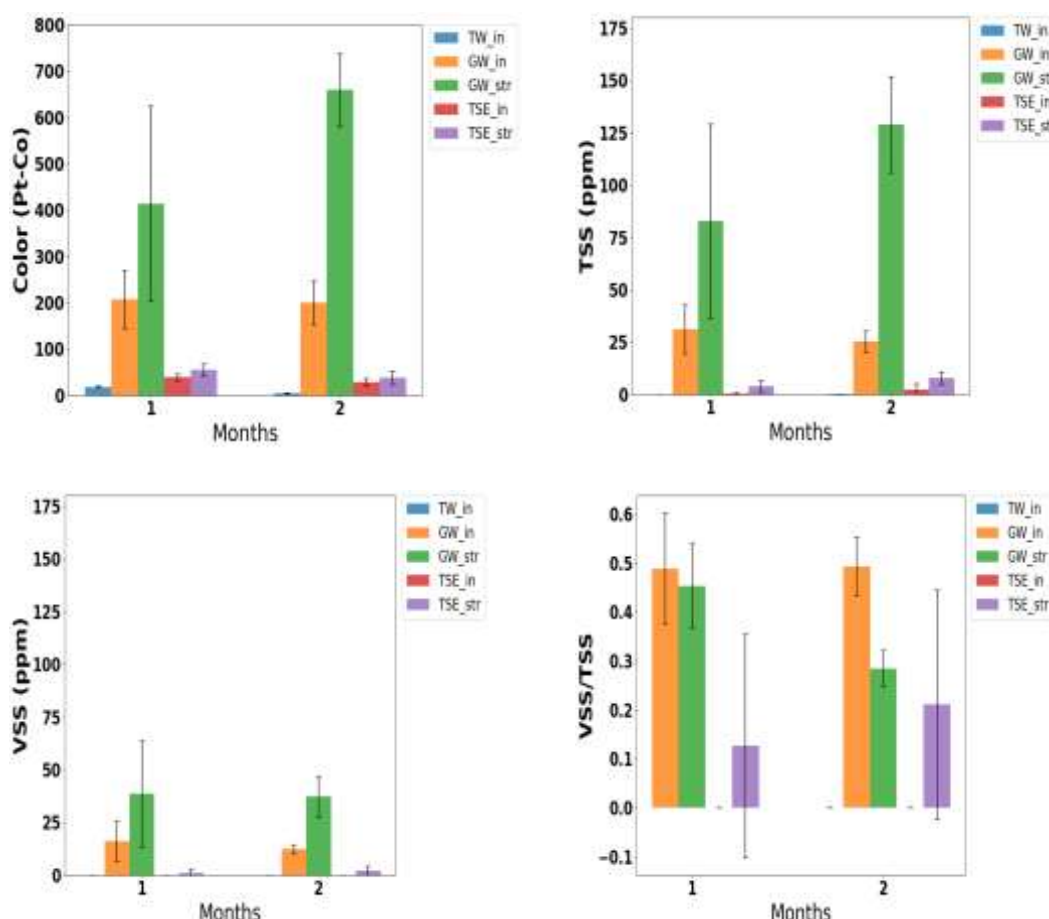


Figure 2. Evaluation of color (apparent) and suspended solids (total suspended solids = TSS and volatile suspended solids = VSS) across various water samples (sources and points) for 8 weeks.

Key: TW_in = Tapwater from a tap mouth, GW_in = inlet greywater samples, GW_str = greywater samples from a storage tank, TSE_in = inlet TSE samples, TSE_str = TSE samples from a storage tank.

III-C. ORGANIC PARAMETERS

The organic load values presented an interesting contrast between GW, TSE, and tap water (Figure 3). GW, especially in storage, exhibited the maximum values of total organic carbon (TOC), chemical oxygen demand (COD), and biochemical oxygen demand (BOD₅) over a 5-day period. The COD was above 250 ppm, and the BOD₅ was above 80 ppm even after 2 months, indicating substantial biodegradable organic matter. The BOD₅/COD ratio of GW ranged from 0.4 to 0.6, indicating a readily biodegradable fraction and suggesting it is easily amenable to biological treatment.

In contrast, TSE had very low values for all organic indicators, specifically COD less than 40 ppm and BOD₅ almost zero, indicating that most biodegradable material had been removed at the treatment plant. All parameters settled around zero for tap water, indicating reliable measurements. Collectively, these results indicate a significant, yet variable, biodegradable load within GW, as opposed to the stability and low organic content of TSE, presenting specific challenges (related to GW qualities) and treatment opportunities for reuse in decentralized water systems.

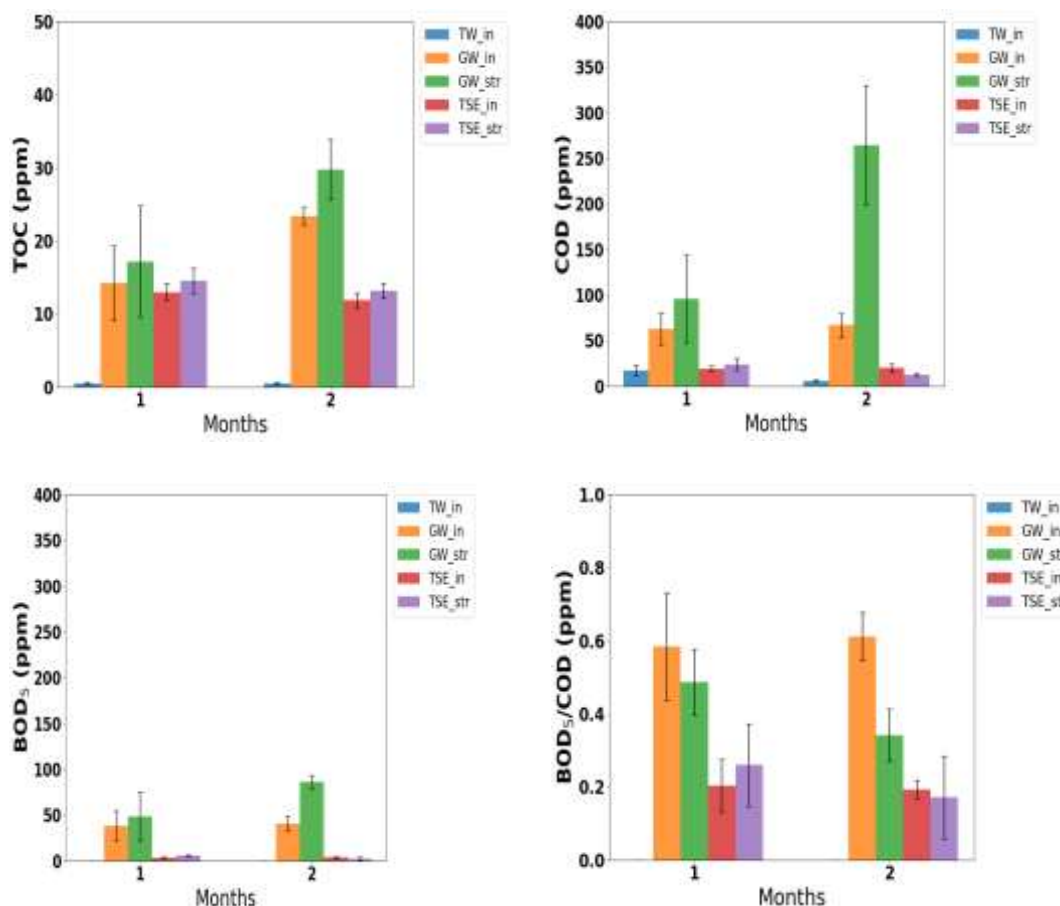


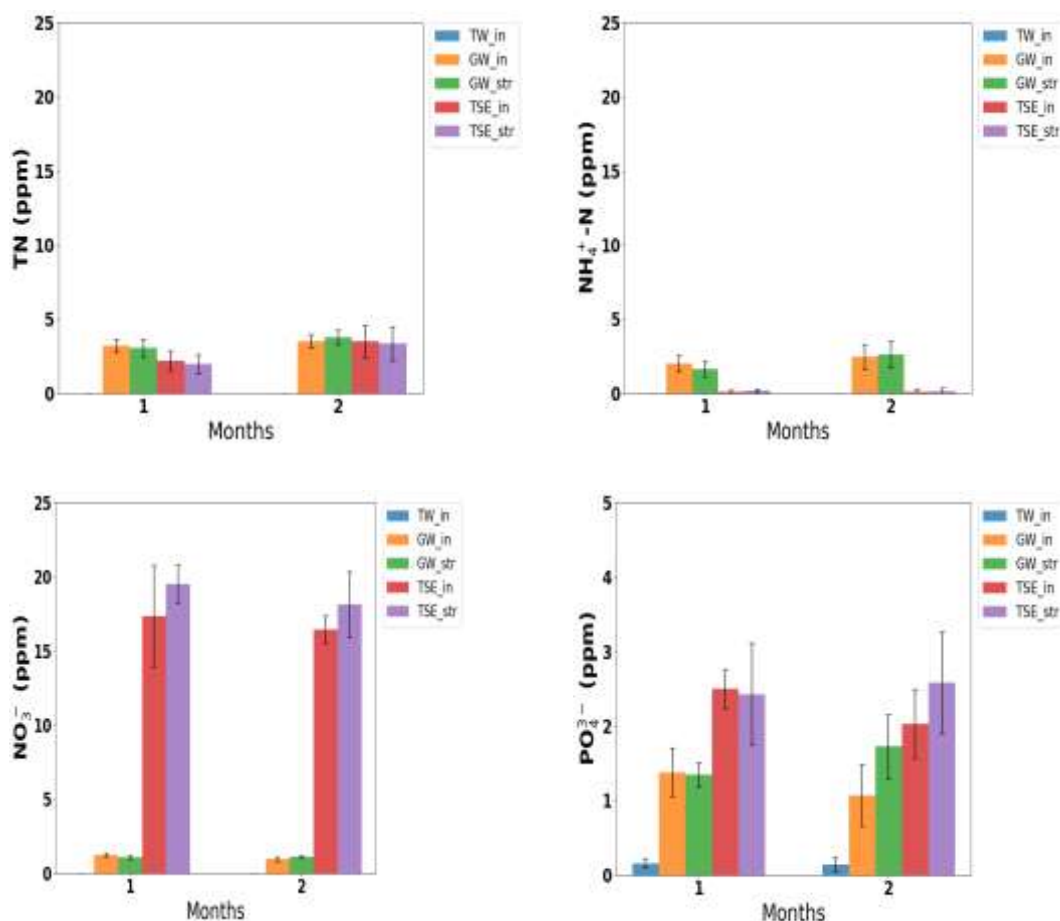
Figure 3. Evaluation of organic content (total organic content – TOC, chemical oxygen demand – COD, biochemical oxygen demand at day 5 – BOD₅) of the various water samples (sources and points) for 8 weeks

Key: TW_in – Tapwater from a tap mouth, GW_in – inlet greywater samples, GW_str – greywater samples from a storage tank, TSE_in – inlet TSE samples, TSE_str – TSE samples from a storage tank.

III-D. NUTRIENT CONTENTS

Source-specific variations in the nitrogen and phosphate fractions were apparent from nutrient analysis (Figure 4). GW had moderate total nitrogen (TN) content ($\approx 2\text{--}4$ ppm), with ammonium nitrogen ($\text{NH}_4^+\text{-N}$) accounting for approximately half of the TN, yielding $\text{NH}_4^+\text{-N}/\text{TN}$ ratios of 0.5–0.6. The findings demonstrate the dominance of low-nitrogen forms, which are commonly found in domestic laundry and bathroom effluents. In contrast, TSE contained very low ammonium nitrogen but continually high nitrate concentrations (approximately 18–20 ppm), indicating effective nitrification during treatment and incomplete nitrogen removal.

Orthophosphate (PO_4^{3-}) was present in both sources but was more abundant in TSE ($\approx 2\text{--}3$ ppm) than in GW ($\approx 1\text{--}1.5$ ppm), demonstrating the presence of phosphorus salts after tertiary treatment. Tap water contained no nutrients, and all concentrations were approximately zero. However, the data indicated that GW had a lower, more degradable nitrogen load, whereas TSE retained oxidized nitrogen and phosphorus, which is sufficient to meet irrigation requirements, such as landscape irrigation practices. Hence, both water sources (GW and TSE) provide irrigation benefits by meeting nutrient requirements, potentially reducing fertilizer costs.



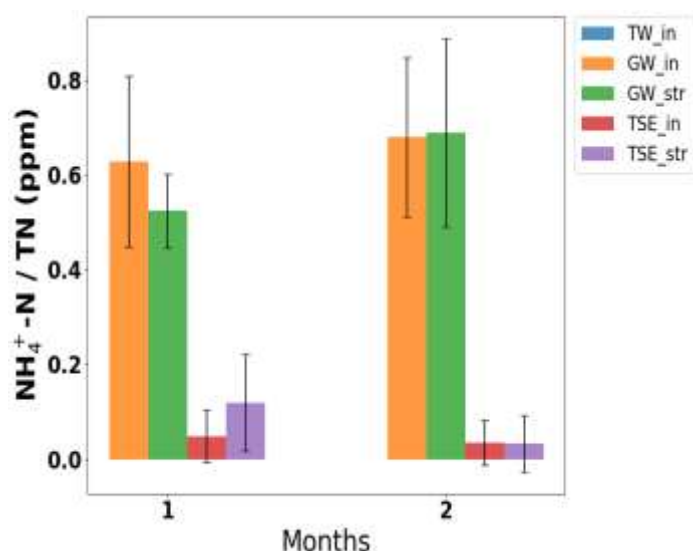


Figure 4. Evaluation of the nutrient content (total nitrogen – TN, ammonium nitrogen – TAN, NO₃⁻ - nitrates, PO₄³⁻ - orthophosphates) of the various water samples (sources and points) for 8 weeks.

Key: TW_in – Tapwater from a tap mouth, GW_in – inlet greywater samples, GW_str – greywater samples from a storage tank, TSE_in – inlet TSE samples, TSE_str – TSE samples from a storage tank.

III-E. DISINFECTION AND ORGANIC REACTIVITY

The findings showed significant differences in residual disinfection and organic matter quality among GW, TSE, and Tw (Figure 5). Tap water consistently contained free chlorine, confirming effective chlorination, whereas TSE had the lowest average level (0.06 ± 0.01 ppm). GW (both inlet and storage) showed variability, indicating that disinfection was not systematic and that detergent or household chemical use could vary by product type and amount. For instance, active chlorine can be introduced into the bathroom and handwash GW using chlorine-based disinfectants, cleaners, and personal care products containing chlorine compounds [14].

Free chlorine levels, which serve as indicators of disinfection strength, can also pose a risk of ecological toxicity in plants at elevated concentrations. For example, GW storage samples revealed significantly increased chlorine levels in Month 2, exceeding 0.5 ppm. This concentration can damage sensitive crops and hinder the microbial activities necessary for essential nutrient recycling. TSE samples (both inlets and storage tanks) consistently maintained low chlorine levels (< 0.1 ppm), which aligns with the WHO recommendations for safe irrigation (below 0.3 ppm). Although chlorine is necessary for maintaining microbial safety in the environment, its overuse may alter soil biology and plant physiology.

UV₂₅₄ absorbance, which reflects the presence of aromatic organic compounds, was notably higher for TSE than for GW and Tw in Month 1, indicating the presence of aromatic or unsaturated organic materials that may not be fully degraded during treatment. High UV₂₅₄ levels are related to the presence of hydrophobic organic matter, which has fouling potential in irrigation systems and may reduce water infiltration into soils [15]. Their

recalcitrant nature ensures long-term persistence in the environment and can affect root zone oxygen availability, especially in poorly aerated soils [16].

Specific UV Absorbance (SUVA), an indicator of the aromatic character of organic carbon, revealed clear differences across the water sources. Tap water exhibited a notable increase in SUVA levels (3 L/mg.m in Month 1 to 6 L/mg.m in Month 2). The relatively high SUVA values observed in tap water may be due to very low organic matter content relative to its UV_{254} value. In comparison, the SUVA values of GW samples (inlets and tanks) were consistently low (<1 L/mg.m), indicating that the organic matter in GW is mainly hydrophilic, more biodegradable, and less reactive. The SUVA values for the TSE were moderate (roughly 2-2.5 L/mg.m in Month 1, and somewhat lower in Month 2), revealing a blend of natural organics with relatively low reactivity and moderate hydrophobicity. Regardless of time, both GW and TSE were mostly hydrophilic, with a more irrigation-type application tendency, and were at a lower risk of DBP formation or adverse soil interactions. Tap water was chemically clean (TOC below 1 ppm) as shown in Figure 3. However, it contained free chlorine (as high as 0.2 ppm), which may be harmful to sensitive plants if used for irrigation [17].

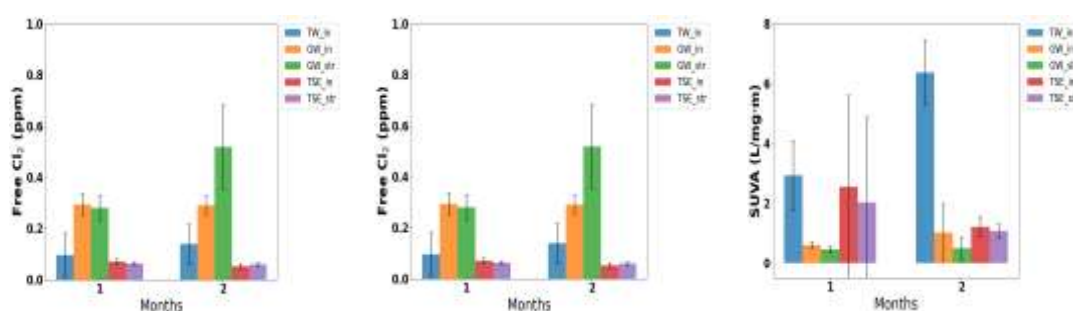


Figure 5. Evaluation of the nutrient content (Free Cl₂ – Free chlorine, UV₂₅₄ – Ultraviolet absorbance at 254nm, SUVA – specific ultraviolet absorbance) of the various water samples (sources and points) for 8 weeks.

Key: TW_in – Tapwater from a tap mouth, GW_in – inlet greywater samples, GW_str – greywater samples from a storage tank, TSE_in – inlet TSE samples, TSE_str – TSE samples from a storage tank.

III-F. INORGANIC PARAMETERS

METAL CONTENTS

The ionic values indicated clear differences between GW, TSE, and Tw. TSE samples consistently had higher levels of Ca and Mg than either GW or tap water, reflecting the influence of treatment processes and the characteristics of the domestic water supply (i.e., desalinated source). Similar trends in elevated calcium (Ca) and magnesium (Mg) levels in reclaimed water and their implications for reuse have also been observed in studies from Tunisia and Qatar [18]. Potassium (K) levels in tap water and GW were very low, whereas they were considerably higher in TSE, particularly in stored samples. This aligns with the findings from Qatari central wastewater treatment plants, where potassium concentrations were below 27 ppm [10]. The most fluctuating values were sodium concentrations; TSE always had more than 120 ppm, whereas GW had much less (< 40 ppm), and tap water had negligible amounts of sodium.

This result indicates a potential salinity risk from the reuse of TSE for long-term irrigation applications. In general, these trends indicate that while GW carries low ionic loads from detergents and household uses, TSE carries much higher concentrations of Ca, Mg, Na, and K.

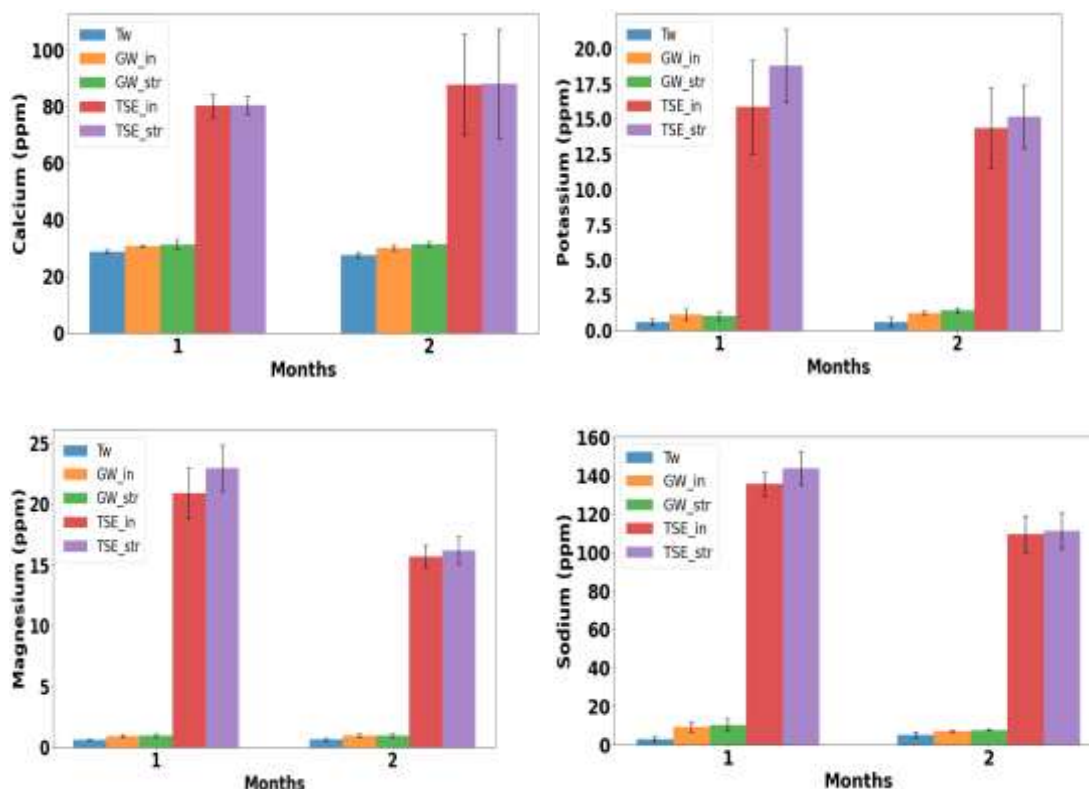


Figure 6. Evaluation of the commonly found metals (Ca – Calcium, K – Potassium, Mg – Magnesium, and Na – Sodium) in various water samples (sources and points) for 8 weeks.

Key: TW_in – Tapwater from a tap mouth, GW_in – inlet greywater samples, GW_str – greywater samples from a storage tank, TSE_in – inlet TSE samples, TSE_str – TSE samples from a storage tank.

ANIONIC CONCENTRATIONS

The chloride (Cl^-) and sulfate (SO_4^{2-}) concentrations in the TSE (both inlets and storage tanks) were higher than those in GW and Tw, averaging over 250 ppm throughout the eight weeks of the sampling period (Figure 7). In comparison, GW residuals were consistently below 40 ppm, and tap water had low levels of residual organics. By contrast, TSE contained markedly higher concentrations of soluble salts despite undergoing tertiary treatment, including ultrafiltration (UF). This result was expected, since the purpose of UF is essentially to remove suspended or colloidal particles, and it cannot effectively remove dissolved ions such as Na^+ , Cl^- , SO_4^{2-} , or other mineral salts. Although these values generally fall within international irrigation water reuse standards [10]. However, repeated application over long periods can still lead to the gradual accumulation of salts in soils, potentially inducing salinity and sodicity risks. In contrast, lower and more consistent anionic levels were observed in GW, suggesting a lower risk of soil salinization; however, variability is expected depending on the detergent used (laundry activities).

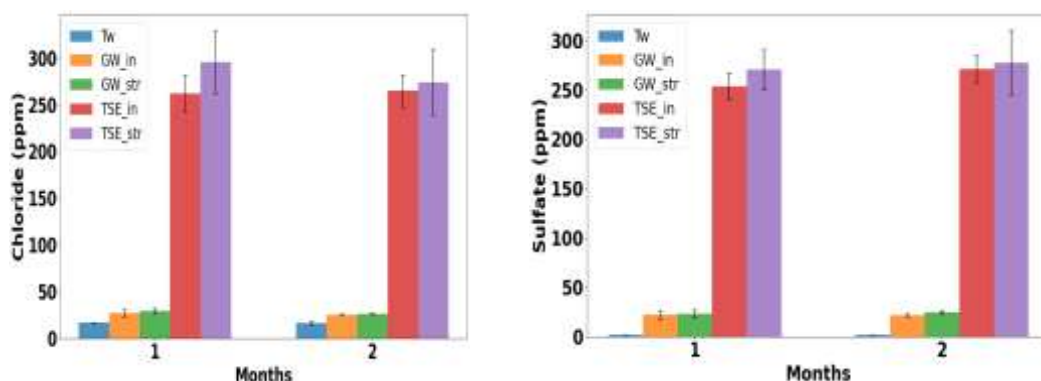


Figure 7. Evaluation of the anionic content (Cl^- = Chlorides and SO_4^{2-} = sulfates) in various water samples (sources and points) for 8 weeks.

Key: TW_in = Tapwater from a tap mouth, GW_in = inlet greywater samples, GW_str = greywater samples from a storage tank, TSE_in = inlet TSE samples, TSE_str = TSE samples from a storage tank.

III-G. REUSE IMPLICATIONS

GW and TSE have different physicochemical characteristics that must be considered when reusing them. GW shows moderate electrical conductivity (200-300 $\mu S/cm$) and near-neutral pH (7.2-7.5), and there is also substantial fluctuation in turbidity (over 150 NTU), which may be attributed to particulates and detergents. The high COD, BOD₅, and TOC concentrations and BOD₅/COD ratios between 0.4 and 0.6 indicated a high biodegradable organic load, with ammonium nitrogen being the most abundant fraction of the total nitrogen. These properties make GW inappropriate for direct reuse, but it is ideally suited to biological/solids removal treatments and biochemical reactors, such as wetland filters or planted green walls, which stabilize effluents and convert nutrients into plant-available forms. Similar findings highlighted that variability and solids load in GW restrict direct reuse but can be treated effectively when combined with NBS or filtration systems [6], [19].

In contrast, TSE exhibited higher salinity (electrical conductivity 1500-1800 $\mu S/cm$), an alkaline pH (>8.0), low turbidity, and color, reflecting an efficient removal of solids and organics, but at the same time a high ionic and nutrient load (Na , Cl^- , SO_4^{2-} , NO_3^- , PO_4^{3-}). Monitoring residual chlorine has also been shown to be useful for disinfecting potable water and reducing microbial risk. Nevertheless, salts and nutrients remain consistently high in TSE, which limits irrigation, and prolonged reuse may result in salt accumulation, sodicity, and nutrient leaching (as shown in Table 3). Similar trends have been reported, emphasizing soil salinization and nutrient accumulation due to the continuous application of treated wastewater [20], [21]. These findings illustrate the need for source-specific treatment strategies.

Regarding disinfection and organic reactivity, the overall findings indicated that both GW and TSE could be used for irrigation applications, though with some caution. GW is often low in complex organic matter, but it can contain excessive active chlorine, which could be harmful to plants and soil biota. Conversely, TSE showed more signs of persistent organic material, but at levels that can be managed and are safe for reuse applications. Careful testing and regular monitoring are vital to control chlorine levels (GW) and organic matter content (TSE), ensuring they support environmental safety and healthy plants with minimal long-term side effects. Both streams offer reuse opportunities, but must be tailored to specific applications, with nature-based solutions and advanced polishing methods increasingly recognized as fit-for-purpose approaches [22], [23], [24].

Table 3. Physical and chemical properties of the observed different water sources (greywater and TSE) and their reuse applications

Indicator/Parameters	Greywater (GW)	TSE	Tap water	Reuse Implications/Treatment Needs
Physical (Temp, pH, EC, Turbidity)	Moderate EC (200-400 $\mu\text{S}/\text{cm}$), neutral pH (7.2-7.5), very high turbidity (>150 NTU), high color (>600 Pt-Co)	High EC (1500-1800 $\mu\text{S}/\text{cm}$), alkaline pH (>8.0), low turbidity, and color	Stable baseline	GW: clogging risk, unstable quality, requires solids/organics removal. TSE: saline, may cause soil stress – requires blending/management.
Solids (TSS, VSS, VSS/TSS)	High VSS/TSS ratio, indicating organic solids	Low VSS/TSS ratio – mostly inorganics	Negligible	GW: promotes microbial regrowth, requires pretreatment. TSE: low risk, suitable for fine filtration if drip irrigation is adopted.
Organics (COD, TOC, BOD ₅ , UV ₂₅₄ , SUVA)	High COD (>250 ppm), BOD ₅ (>80 ppm), TOC (> 12 ppm), BOD ₅ /COD ratio: 0.4-0.6, moderate UV ₂₅₄ and low SUVA	Low COD (< 40 ppm) negligible BOD ₅ , low TOC, moderate UV ₂₅₄ and SUVA levels	Stable baseline, high SUVA values	GW: biodegradable organics, amenable to biofilters/wetlands. TSE: stable but DBP precursors persist, require polishing/UV. SUVA levels in tap water may be inflated due to low DOC; chlorine levels management is critical for irrigation use.
Nutrients (TN, NH ₄ ⁺ -N, NO ₃ ⁻ , PO ₄ ³⁻)	Moderate TN (2-4 ppm), dominated by NH ₄ ⁺ -N (NH ₄ ⁺ -N/TN = 0.5-0.6)	High NO ₃ ⁻ (18-20 ppm), and PO ₄ ³⁻ (2-3 ppm), negligible NH ₄ ⁺ -N	Negligible	GW: nutrient-rich, useful for localized irrigation after stabilization. TSE: risk of nutrient leaching/eutrophication requires dilution, blending, or soil management

Ions/Salts (Na, K, Ca, Mg, Cl^- , SO_4^{2-})	Moderate levels, mostly from detergents; lower Na^+ and Cl^- than TSE	Elevated Na^+ (>120 ppm), Cl^- , and SO_4^{2-} (>250 ppm), higher K, Ca, and Mg levels	Negligible	GW: safe for short-term irrigation application but may cause detergent accumulation in the long term. TSE: high salinity/sodicity risk, requires dilution, blending, or soil management
Disinfection (Free Cl_2 , microbial risk)	Residual chlorine levels (0.3-0.6) increase microbial risk, especially for chlorine-tolerant microbes.	Low residual chlorine (<0.1) promotes microbial regrowth potential	Stable baseline, higher than TSE	GW: requires solids/organics removal for effective disinfection. TSE/tap water: safe microbiologically, but DBP management is required.

Key: GW = greywater, TSE = tertiary-treated sewage effluent, TW = tap water, EC = Electrical conductivity, DBP = Disinfection by-products, TN = total nitrogen, Cl^- - Chloride, SO_4^{2-} - Sulfate, K = potassium, Na = sodium, Ca = calcium, Mg = magnesium, NH_4^+ -N = ammonium nitrogen, NO_3^- = nitrate, PO_4^{3-} = orthophosphate, BOD_5 = biochemical oxygen demand, COD – chemical oxygen demand, TOC = total organic carbon, UV_{254} = ultraviolet absorbance at 254nm, SUVA = specific UV absorbance. **References:** [6], [9], [20], [21], [24], [25], [26], [27], [28], [29], [30].

V. IV. CONCLUSION AND FUTURE STUDIES

This study demonstrated the specific longitudinal profiles of water quality for greywater (GW) and TSE. GW showed high turbidity, color, total suspended solids (TSS), and volatile suspended solids (VSS), along with large variations in these parameters. TSE was clearer and more stable but slightly more alkaline. Tap water consistently showed low concentrations of all parameters. For the organic load, GW showed elevated and variable levels of COD, BOD₅, and TOC, with a BOD₅/COD ratio of 0.4-0.6, indicating an easily degradable fraction of organic matter. In contrast, TSE showed low and stable organic content, indicating efficient organic removal during treatment. In terms of nutrient dynamics, GW exhibited moderate TN levels, primarily consisting of ammonium nitrogen. However, the TSE was dominated by low ammonium nitrogen, yet it maintained high nitrate and phosphate levels, indicating successful nitrification and impaired nutrient removal.

Regarding ionic composition and disinfection, higher levels of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl⁻), and sulfate (SO₄²⁻) in TSE than in GW indicate the potential for salinity or sodicity of water for reuse. Regarding disinfection and organic reactivity, GW contained soluble and reactive organics that readily consumed chlorine and could form disinfection by-products, whereas TSE, having undergone treatment, contained less reactive fractions.

GW presents challenges due to the variability and organic load of particulates, whereas TSE is less variable but carries a high dissolved-salt load, which may compromise both soil and crops. These results highlight that GW and TSE have distinct reuse concerns; thus, source-specific strategies must be developed for decentralized water systems, particularly in water-stressed environments such as Qatar and highly urbanized settings like the Netherlands.

Further research is needed to extend the observation period beyond 8 weeks by incorporating seasonal and monthly sampling campaigns to better understand long-term variations and weekly trends in the data. The adoption of ecologically friendly water treatment approaches, such as nature-based solutions (NBS) like planted pots or vertical green walls, and constructed wetland-inspired systems, presents ideal opportunities for in-situ treatment of raw GW or polishing TSE to make them more fit-for-purpose for non-potable applications. Such systems can assist in removing turbidity, colloidal organic content, and nutrients, as well as treating the salt and sodium hazards associated with TSE reuse.

Furthermore, evaluating plant tolerance and soil responses to irrigation with these sources will provide important insights into the long-term effects on soil structure, nutrient cycling, microbial dynamics, and vegetation performance. Including NBS in the reuse program could improve sustainable development and decrease dependence on energy-intensive desalination and advanced treatment.

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