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Review

Systematic review on the effects of wastewater chemical composition on crop yield under fertigation practices

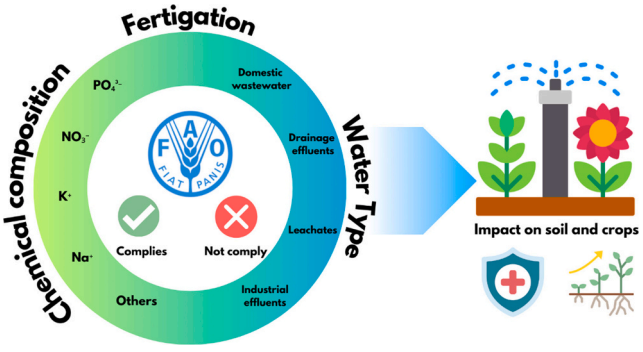
Aahilyn Osorio [a], Antonio Panico [b], Gianluigi Busico [a], Micòl Mastrocicco [a,*]

[a] Department of Environmental, Biological and Pharmaceutical Sciences and Technologies (DiSTABiF), University of Campania "Luigi Vanvitelli", Via A. Vivaldi 43, 81100 Caserta, Italy
[b] Department of Engineering, University of Campania "Luigi Vanvitelli", Via Roma 29, 81031 Aversa, Italy

HIGHLIGHTS

- Fertigation requires precise adjustment soil conditions for optimal effectiveness.
- Wastewater reuse enhances agricultural sustainability.
- Elevated Na^+ and K^+ levels in wastewater limit nutrient uptake and yield.
- Consistent NO_3^- and PO_4^{3-} levels in treated wastewater boost plant growth.

GRAPHICAL ABSTRACT



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ABSTRACT

The escalating global demand for freshwater resources poses significant challenges to sustainable agricultural practices. This systematic review examines the influence of inorganic ions' concentration in wastewater on crop yields under fertigation, with a particular focus on compliance with the recommendations of FAO water quality standards. The review reveals that key nutrients, such as nitrates (NO_3^-) and phosphates (PO_4^{3-}), largely meet established thresholds, while sodium (Na^+) and potassium (K^+) frequently exceed permissible levels, threatening crop productivity, especially in salinity-sensitive species. Additionally, the study explores the effects of nutrient variability on crop performance across different soil types and cultivation environments. Statistical analyses were performed to assess chemical composition and their correlation with agricultural yields. The findings emphasize the critical need to adapt fertigation practices to the specific characteristics of soil and environmental conditions to optimize the benefits of wastewater reuse.

1. Introduction

The global growing freshwater demand poses increasingly relevant challenges, as the availability of this resource diminishes progressively. Projections indicate a significant increase of demand by 2030, expected to exceed 160 % of the total available volume (Ricart and Rico, 2019).

* Corresponding author.
E-mail address: micol.mastrocico@unicmpania.it (M. Mastrocicco).

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This exponential rise is exacerbated by both degradation and depletion of freshwater resources (Busico et al., 2021; Gleick and Cooley, 2021), posing significant threats to the sustainability of crops, heavily reliant on this resource (Sidhu et al., 2019). The growing competition for water resources among agricultural, industrial, and domestic sectors represent a critical challenge to achieve a sustainable water management, driving the search for innovative solutions (Jeong et al., 2020).

Among these solutions, the utilization of treated urban wastewater stands out as a valuable resource to meet agricultural needs, including irrigation (Gava et al., 2023). This shift in focus highlights the importance of adopting sustainable practices such as fertigation, a method that combines the application of fertilizers with irrigation systems, delivering nutrients directly to the root zone to enhance crop growth and resource efficiency.

Fertigation emerges as a multifaceted strategy that simultaneously addresses various agricultural challenges. Fertigation relieves pressure on drinking water sources, and harnesses nutrient-rich wastewater to improve agricultural productivity. This method effectively exploits the high nutrients presence in effluents, particularly biogenic compounds such as total nitrogen (N) and phosphorus (P) (Mainardis et al., 2022). The effluents from wastewater treatment plants are often abundant of macronutrients like N, P, and potassium (K^+) and therefore they could serve as fertilizer for plants' growth (Silva et al., 2016).

In agricultural practices, fertigation with treated wastewater presents challenges related to public health and regulatory compliance as wastewater may contain harmful pathogens and organic and inorganic micropollutants. This makes it essential to implement effective treatment protocols that adequately mitigate health risks, ensuring the safety of both crops and consumers (Radini et al., 2023). However, one of the most critical issues is represented by the presence of emerging contaminants, such as pharmaceuticals, hormonal compounds, industrial chemicals (Kasonga et al., 2021), and microplastics (Viaroli et al., 2022). These contaminants can accumulate in soil, water, and ultimately in the food chain, requiring specialized management and treatment to avoid environmental and health risks (Chojnacka et al., 2020; Mainardis et al., 2022).

Furthermore, to ensure the safety of fertigation practices, the use of treated wastewater must strictly comply with regulatory standards, such as those established by European legislation, including the Regulation (EU) 2020/741 of the European Parliament and of the Council (25th May 2020), which sets minimum requirements for water reuse in agriculture. These standards are complemented by the Food and Agriculture Organization (FAO) guidelines for wastewater reuse in agriculture, which provide a detailed framework to ensure sustainable and safe practices (Radini et al., 2023).

FAO has developed specific water quality recommendations adapted for agricultural applications, emphasizing the importance of regulating nutrient levels in irrigation water to prevent negative effects on soil quality and crop productivity. These guidelines set permissible limits on critical nutrients such as N and P dissolved compounds, ensuring that fertigation with treated wastewater does not result in soil degradation, water contamination, or harmful accumulation of toxic elements (FAO, 1992).

Data from the European Environment Agency (EEA) indicate that up to 90 % of urban wastewater undergoes treatment, highlighting a substantial potential for its safe reuse in agriculture, provided that nutrient concentrations also comply with FAO standards. Adhering to FAO recommendations ensures the protection of public health and the environment while fostering confidence in fertigation as a sustainable strategy for water management and agricultural production (EEA, 2021).

The relevance of this approach becomes even more pronounced when considering that agricultural reuse of effluent from wastewater treatment plants can significantly reduce nutrient loads to surface waters (Lahlou et al., 2021) and groundwater (Azad et al., 2020). Moreover, fertigation offers a promising strategy for mitigating greenhouse gas emissions by optimizing nutrient supply and minimizing the need for energy-intensive wastewater treatments (Lahlou et al., 2020). However, extensive adoption of this technique necessitates a thorough understanding of its environmental and ecological impacts across diverse agricultural systems (Alessandrino et al., 2023; Chauhan and Kumar, 2020). This requires careful evaluation of its effects on water resources, including potential water pollution and its broader consequences for aquatic ecosystems.

As indicated by Chojnacka et al. (2020), the use of secondary effluents for fertigation reduces the amount of nutrients discharged into surface waters, thus decreasing their environmental load. The application of biogenic compounds to soil could potentially increase groundwater pollution, making monitoring necessary. This effect can be offset by lower doses of N and P in the form of chemical fertilizers applied to crops (Ebrahimian et al., 2014). Thus, it is essential to examine the potential associated risks, such as nutrient loss and agrochemical leaching, and their implications for water quality and ecosystem health.

In the soil domain, it is crucial to understand the effects of fertigation on health, fertility, and sustainability. Special attention should be given to soil microbiota, as they play a key role in nutrient cycling and soil ecosystem function (Raza et al., 2019; Torres et al., 2023). Microbial activity contributes to organic matter decomposition, nutrient release, and soil structure improvement (Ahmed et al., 2024).

Investigating fertigation effects on plant physiology and growth implies examining nutrient absorption mechanisms and the biochemical responses involved in these processes (Aftab and Hakeem, 2020). Nutrient availability in soil, influenced by fertigation, directly affects crop growth, development, and production. Understanding plant responses to fertigation with treated wastewater is essential for optimizing yield and promoting sustainable agricultural systems (Ahmed et al., 2024).

A thorough review of the literature was conducted for this study to investigate the effects of nutrients as well as other inorganic ions' concentration in wastewater on crop yield when applied to plants in greenhouses and fields, comparing their concentration with that recommended by FAO standards for water quality in agriculture. The specific objectives of this review are: i) to corroborate potential correlation between inorganic ions' concentration in wastewater and crop yield under fertigation; ii) to identify whether nutrients concentration in the wastewater used for fertigation comply with water quality standards established by FAO; iii) to discuss how this correlation varies across different soil types and growing conditions; and iv) to assess the impact of wastewater fertigation on the long-term sustainability of agricultural systems. The structure of a systematic review was maintained to ensure objectivity in literature screening and to facilitate a critical discussion of the collected data.

2. Methodology

2.1. Search strategy and data sources

This systematic study started with a preliminary investigation in the academic databases Scopus and Web of Science, utilizing the phrases "fertigation" and "wastewater reuse" to assess the consistency and comparability of the results from both platforms. Upon verifying the consistency of the results, it was resolved to utilize Scopus as the primary database for the compilation of the search.

A comprehensive search method was developed to incorporate pertinent papers about the utilization of wastewater in fertigation and its effects on crop yield. The search focused on studies published from 2005 to 2024, intending to include both contemporary advancements and studies that illustrate the evolution of technology and approaches over time. The search string was specifically designed to answer the key research questions and ensure that the selected studies adequately addressed the objectives of the systematic review. These questions are:

- How does the concentration of inorganic ions' concentration in wastewater affect the yield of different crops under fertigation in field and greenhouse conditions?
- Is inorganic ions' concentration in the wastewater used for fertigation in line with the established quality standards, and how does this impact crop yield?
- What is the correlation between the concentration of inorganic ions in wastewater and crop yield in different soil types and growing conditions?

Studies that provided quantitative data on the inorganic ions' concentration such as N, P, and K^+, and analyzed their impact on different crop types, both in greenhouses and open fields, were prioritized. In addition, studies that evaluated the effect of inorganic ions on various soils and growing conditions were included, to establish a clear correlation between wastewater quality and crop yield. The final search string was as follows:

(ALL (fertigation AND fertiliz) AND ALL (wastewater OR reuse OR sewage OR sewer* OR effluent) AND ALL (yield OR produc* OR crops) AND ALL (concentration OR impact)) AND PUBYEAR > 2004 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English"))*

The search string returned 2440 papers, which were exported in .ris format and integrated into the Rayyan platform (https://www.rayyan.ai/) to simplify the systematic screening of the studies. A verification of the search string was subsequently done, identifying benchmark studies in the research field of interest. The benchmark studies employed in this phase are reported in Table 1. This verification was crucial to confirm that the search terms effectively covered the pertinent and representative literature on the topic.

2.2. Selection process

The articles' selection procedure is divided into multiple stages, adhering to the criteria set by the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Fig. 1 shows the methodology employed for articles' selection. In the selection process, inclusion and exclusion criteria were implemented at every stage, from the preliminary assessment of abstracts to the comprehensive reading of full articles, to guarantee that the chosen articles sufficiently addressed the research questions. Table 2 reports the inclusion and exclusion criteria applied at this stage.

2.3. Analysis procedure

The analysis procedure for the selected studies began with the organization of studies into a database, where essential information was recorded to enable a quantitative and structured evaluation of the results. The parameters extracted were the concentrations of inorganic ions present in wastewater, such as N, P, K^+, and other essential elements for crops. Additionally, data on crop yield under different fertigation conditions, the types of crops studied, and the soil types were included, as well as growth conditions, whether in greenhouses or open fields.

To analyze the relationship between the occurrence of inorganic ions in wastewater and crop yield, descriptive and graphical methods were used to identify patterns and correlations in the data. Independent cross-checks were performed to ensure data accuracy, resolving discrepancies and assessing potential outliers using graphs and statistics to ensure uniformity and consistency of the database. Additionally, an initial assessment of the diversity of the studies was performed through comparative schemes. Missing data were addressed using the mean of similar parameters in the study set and included comparative analyses of various water types and culture conditions to validate the robustness and consistency of the results.

Table 1
Summary of benchmark articles on fertigation with wastewater in agricultural systems.

Reference	Keywords	Study Objective	Conclusions
Chojnacka et al. (2020)	Fertigation, Wastewater, Transition, Challenges, Opportunities.	Analyze the transition from conventional irrigation to fertigation with reclaimed wastewater, identifying opportunities and challenges.	Fertigation with reclaimed wastewater offers significant advantages but requires overcoming technical, regulatory, and social challenges for effective implementation.
Garcia-Caparros et al. (2017)	Water management, Fertigation, Intensive horticulture, Sustainability.	Evaluate the integral management of irrigation water in intensive horticultural systems, focusing on water and nutrient use efficiency.	Fertigation increases water and nutrient use efficiency and is essential for sustainability in arid and semi-arid regions.
Gava et al. (2023)	Reuse, Drainage water, Sustainability, Greenhouses.	Evaluate the reuse of drainage water and substrate in Mediterranean greenhouse crops to improve environmental and economic sustainability.	Reusing water and substrate improved environmental sustainability and reduced resource use in greenhouses.
Groenveld et al. (2019)	Nutrient efficiency, Fertigation, Aquaculture, Agriculture, Nitrogen.	Optimize nitrogen use efficiency through fertigation management in an integrated aquaculture-agriculture system.	Controlled fertigation improves nitrogen efficiency, reducing losses and environmental impact.
Jiménez-Benítez et al. (2020)	Wastewater, Fertigation, Economic viability, CO_2 emissions.	Evaluate the economic and technological feasibility of fertigation with treated wastewater, considering CO_2 emissions in EU case studies.	Fertigation with treated wastewater is economically viable and can reduce CO_2 emissions though it requires significant initial investment.
Mainardis et al. (2022)	Wastewater, Fertigation, Water management, Circular economy.	Analyze the challenges and opportunities of using wastewater in fertigation, focusing on water management and the circular economy.	Wastewater fertigation improves agricultural sustainability but faces technical and social barriers.
Savvas et al. (2023)	Recycling, Fertigation, Effluents, Greenhouse crops, Water use efficiency.	Explore new technologies to recycle fertigation effluents in soilless greenhouse systems to maximize water and nutrient use efficiency.	Emerging technologies improve water and nutrient use efficiency in greenhouses, promoting sustainability in intensive crop production.

To ensure data consistency and comparability, a process of unit homogenization was conducted for each parameter analyzed. For crop yield, all units were standardized to tons per hectare (ton/ha). Similarly, inorganic ions' concentrations were normalized to milligrams per liter (mg/L). Furthermore, error values were included for each measurement, covering both concentrations and crop yield, to provide an accurate assessment of data variability and reliability.

The collected data undergo statistical analysis and descriptive graphs, allowing the visualization of trends and correlations between

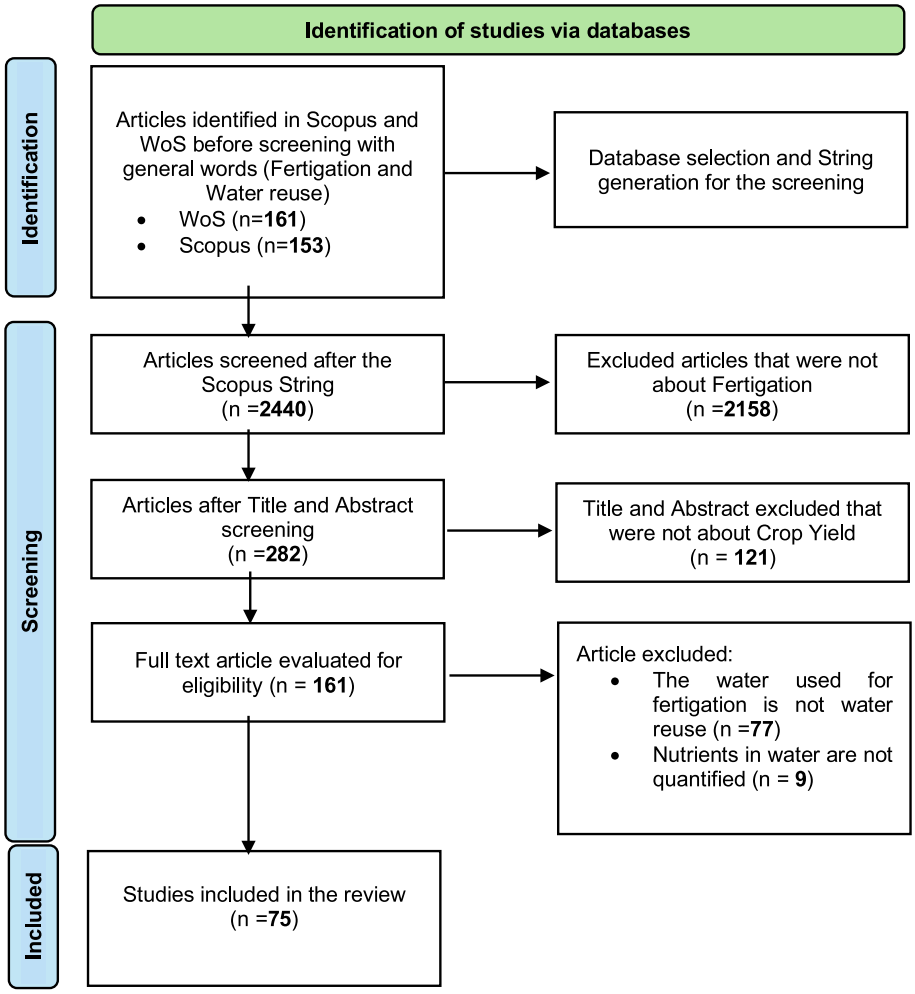


Fig. 1. The PRISMA flow diagram for the systematic review detailing the database searches, the number of abstracts screened, and the full texts retrieved.

Table 2
Inclusion and exclusion criteria applied in the selection.

Criteria	Included	Excluded
Type of water	Studies using wastewater, greywater, or industrial effluents in fertigation	Studies using only irrigation water with fertilizers or conventional water
Nutrient concentration	Studies providing quantitative data on nutrients in wastewater	Studies not presenting quantitative data on nutrient concentration
Impact on crop yield	Studies evaluating the impact of fertigation with wastewater on crop yield	Studies not including results on crop yield or not using fertigation
Growth conditions	Studies detailing growth conditions (greenhouse, field) and soil type	Studies not specifying growth conditions or soil type
Water quality	Studies including an analysis of the chemical composition of the wastewater used	Studies not providing details on the quality of water used
Type of document	Research articles and reviews published in scientific journals	Conference papers, book chapters, non-peer-reviewed reports
Language	Studies published in English	Studies in other languages

inorganic ions' concentrations and crop yield in different agricultural contexts. The graphs included comparative analyses of inorganic ions' concentrations in relation to: (i) productivity, (ii) yield according to different crop types and types of water used, and (iii) the influence of growing conditions. Additionally, an analysis of the compliance of the water used was carried out, using the FAO *Guidelines for irrigation water quality* as a reference to assess the quality of wastewater after the articles' selection. Detailed information on all measured parameters as well as the graph generated are available in the Supplementary Material.

3. Results and discussion

This section presents the results obtained from the systematic review, focusing on the analysis of inorganic ions' concentrations in wastewater used for fertigation and their impact on the productivity of various crops under different agricultural conditions. An evaluation is conducted on the effects of adequacy to FAO water quality standards on the crop yield. Additionally, fluctuations in water quality based on its source are investigated, examining the effects of these variations on both agricultural productivity and soil health, depending on the type of crop. Lastly, the correlation among the concentration of essential nutrients and agricultural performance in different soil types and growth conditions is explored, offering a holistic perspective on the feasibility and sustainability of using wastewater for fertigation in the context of long-term sustainable agriculture.

3.1. Compliance of inorganic ions in wastewater according to FAO guidelines

Fig. 2 is a graphical representation of the studies examined, which demonstrate a high level of non-compliance with the FAO guidelines for irrigation water quality regarding the concentration of inorganic ions present in wastewater used for fertigation. To provide a clearer

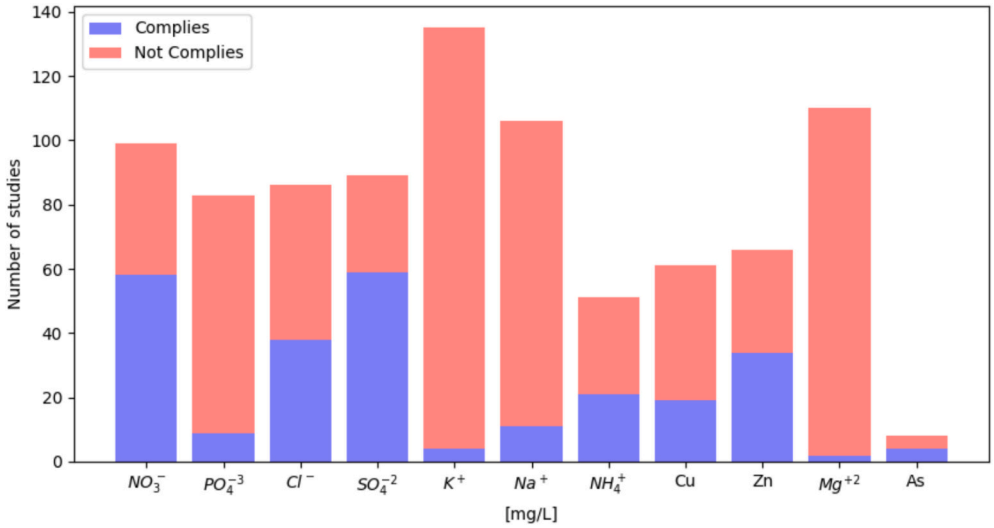


Fig. 2. Recommendations compliance of the reviewed literature.

comparison, the FAO establishes maximum recommended concentrations for key inorganic ions in irrigation water, which include NO_3^- (15 mg/L), PO_4^{3-} (2 mg/L), Cl^- (250 mg/L), SO_4^{2-} (500 mg/L), K^+ (2 mg/L), Na^+ (40 mg/L), NH_4^+ (5 mg/L), Cu (0.2 mg/L), Zn (2 mg/L), Mn (0.2 mg/L), and As (0.1 mg/L).

Essential micronutrients for plant development, such as K^+ and Na^+, are particularly notable for their high rates of non-compliance (Odone et al., 2024). This discrepancy raises significant concerns regarding the variability in wastewater composition and the multiple factors influencing elevated ion concentrations. The disparities observed suggest that wastewater characteristics are strongly influenced by its source, the efficiency of treatment processes, and local agricultural practices (Chojnacka et al., 2020; Elgallal et al., 2016). In regions where secondary and tertiary treatments are inadequate or inconsistently applied, excessive ion accumulation can be exacerbated, leading to progressive soil degradation (Rezapour et al., 2021). Persistent exposure to high concentrations of these ions may alter soil physicochemical properties, affecting water retention capacity, nutrient availability, and overall soil fertility, with potentially long-term consequences for sustainable agricultural productivity (Azad et al., 2020; Mainardis et al., 2022).

In contrast, nutrients such as NO_3^- and PO_4^{3-} showed higher compliance with the guidelines, which may be associated with the implementation of optimized wastewater treatment practices in certain regions or the effectiveness of treatment systems in reducing the concentrations of these compounds. This constitutes a positive finding, as NO_3^- is an essential nutrient for plant development, thus its presence at appropriate levels can promote healthy plant growth and adequate production (Aftab and Hakeem, 2020; Ahmed et al., 2024).

This contrast in compliance may indicate that, although some wastewater meets specific recommendations, selective non-compliance with other inorganic ions may significantly diminish the potential benefits of using such water for fertigation. For example, Na^+ can hinder the assimilation of other essential micronutrients, disrupting the soil's ionic balance and reducing the long-term effectiveness of fertilization (Abdel-Aziz et al., 2016). Additionally, the accumulation of salts from the use of wastewater with high Na^+ and Cl^- content can reduce soil permeability, adversely impacting crop health and agricultural sustainability (Penserini et al., 2024).

An additional point to highlight is the high Na^+ and Cl^- content detected in certain studies, which underlines the need to optimize wastewater management practices before its use in the agricultural sector. It is important to consider mitigation strategies, such as dilution or alternation with freshwater sources, to minimize the impact that these elements could have on soil and plants (Radini et al., 2021).

Non-compliance with FAO recommendations for certain inorganic ions could affect agricultural yield in the short term and have detrimental long-term repercussions for soil health and the viability of agricultural systems. Therefore, it is important to implement appropriate management strategies that enable the efficient and responsible use of wastewater in fertigation, ensuring agricultural productivity without compromising available natural resources.

3.2. *Correlation between inorganic ions' concentrations and yield in field and greenhouse conditions*

The correlation between inorganic ions' concentrations in wastewater and crop productivity under fertigation in field and greenhouse conditions is a crucial aspect of contemporary agriculture, especially in systems where effective water management and nutrient and micronutrient optimization are fundamental for maximizing productivity (Yasuor et al., 2020). Fig. 3 illustrates the influence of various inorganic ions' concentrations on agricultural productivity, particularly showing the effects of either compliance or non-compliance with FAO water quality recommendations. The numerical data corresponding to this figure can be found in the Supplementary Materials.

When analyzing NO_3^-, it is evident that appropriate concentrations tend to optimize yields in both greenhouse and field conditions. In greenhouse environments, yields are higher and more consistent, reflecting improved N uptake by plants. In open-field conditions, environmental factors introduce greater variability in yields due to challenges in controlling processes such as leaching, mineralization, and denitrification, which depend on soil conditions and temperature (Savvas et al., 2023). This can explain the observed fluctuations in productivity when optimal conditions are not maintained.

Regarding PO_4^{3-}, as depicted in Fig. 3, especially in greenhouse environments, yields are more stable when concentrations of this inorganic ion fall within recommendations. This suggests a direct relationship between PO_4^{3-} availability and plant uptake efficiency in a controlled environment. In field conditions, PO_4^{3-} can be subject to fixation processes in the soil, particularly in soils high in Ca^{2+}, Fe^{2+}, or Al^{+3}, which tend to immobilize this nutrient, reducing its availability to plants (Ahmed et al., 2024). Additionally, soil pH plays a crucial role in PO_4^{3-} solubility. For example, in acidic soils, PO_4^{3-} may settle out as Fe- or Al-PO_4, which could explain why yields vary more in the field when the recommended limits are not met (Penn and Camberato, 2019).

This observation aligns with research indicating that applying P fertilizers in open-field environments may require additional management techniques, such as localized application, to increase PO_4^{3-} use

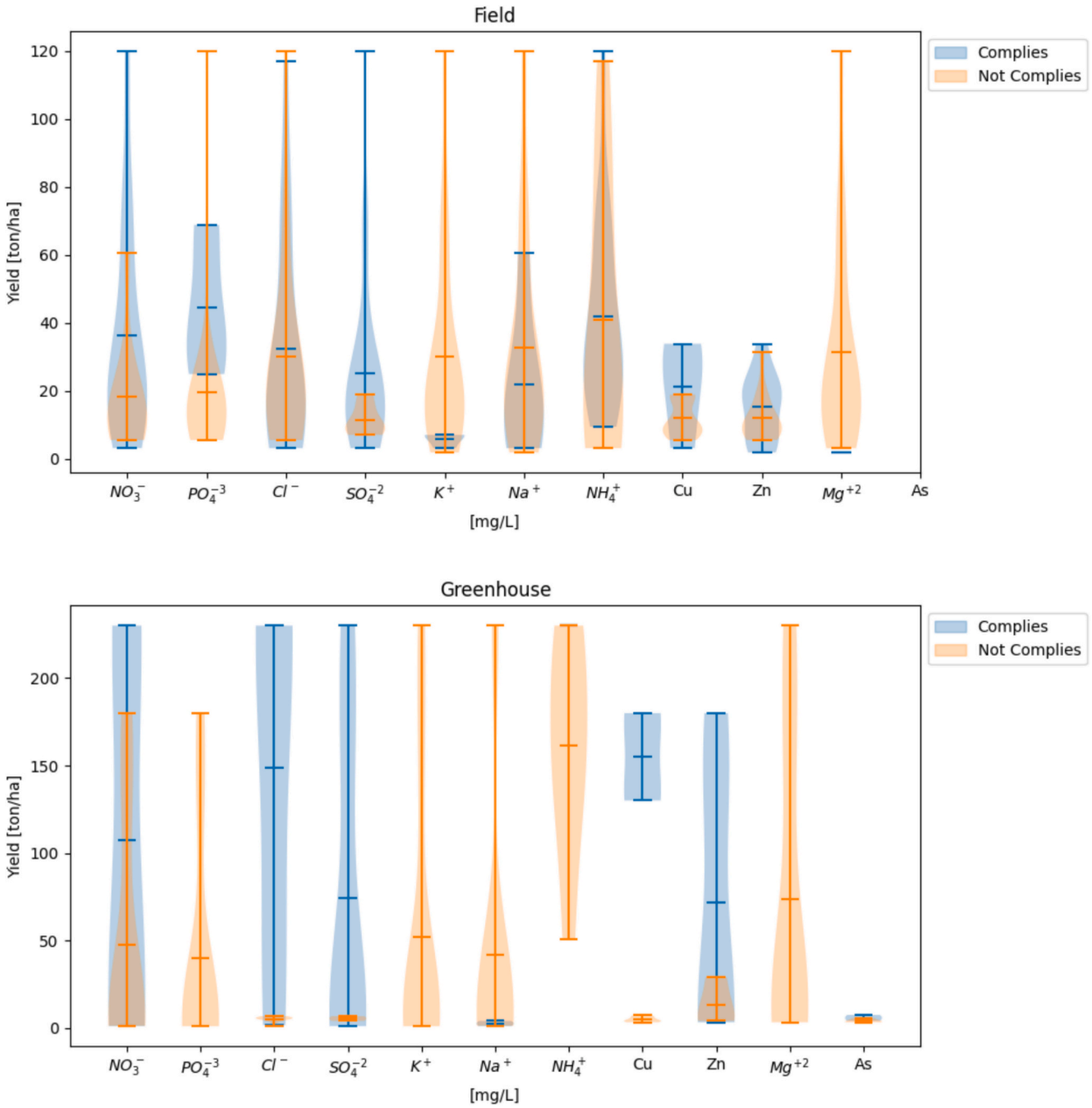


Fig. 3. Distribution of crop yield (ton/ha) as a function of chemical composition in wastewater under greenhouse and field conditions. Violin plots show the difference between studies that comply (blue curve) and do not comply (orange curve) with FAO water quality guidelines.

efficiency (Bindraban et al., 2020; Ibrahim et al., 2022). In this context, the application of fertilizers through irrigation with wastewater containing high PO_4^{3-} levels may be insufficient if other soil factors, such as pH and organic matter content, are not considered, as they can affect the availability of this nutrient.

K^+ and Na^+, which are essential in plant osmotic regulation, exhibit different behaviors depending on the cultivation environment, as shown in Fig. 3. Both graphs show a notable variability in production outcomes when concentrations exceed the established recommended limits, particularly detrimental in field environments. Salt accumulation in the soil, a common occurrence when using wastewater with high Na^+ concentrations, may be the cause of this behavior. Na^+ accumulation can increase soil salinity, affecting soil composition and, consequently, the roots' ability to absorb water and nutrients (Dagianta et al., 2014).

In greenhouse studies, although variability is also observed, the controlled environment seems to buffer some negative effects. However, the dispersion in yields suggests that even under optimal conditions, an excess of Na^+ or K^+ can reduce the efficiency of other essential nutrients' absorption. This result is consistent with the literature, where excess soil salts have been associated with reduced hydraulic conductivity and water availability for plants, potentially leading to induced water stress, even in soils with sufficient moisture (Chtouki et al., 2024; Rápalo-Cruz et al., 2024).

NH_4^+ is an essential nutrient in soil nitrification and ammonification. In greenhouses, its behavior is more predictable, leading to stable yields when recommended thresholds are met. In open-field conditions, studies that do not adhere to these recommendations show greater yield variability, likely due to NH_4^+ volatilization or its conversion to NO_3^- under

suboptimal conditions (Hurtado et al., 2024). Cl^- and SO_4^{2-} are necessary in small concentrations but can be harmful when they are present in large amounts. In field conditions, for instance, high Cl^- concentrations may be related to soil salinization, reducing the roots' ability to absorb water and causing osmotic stress in plants (Ahmed et al., 2024). In greenhouse studies, while variability in yields is also observed, it is smaller, suggesting that the controlled environment may mitigate some of the negative effects of salt accumulation, allowing for more efficient nutrient management (Dousova et al., 2016; Michael et al., 2015).

Finally, from the graphs obtained by analyzing the studies, micronutrients such as Zn, Cu, and Mn, while having a lower impact compared to macronutrients, show lower variability in both environments. This observation suggests that their concentration in wastewater may be more constant over time (Masunaga and Marques Fong, 2018; Plaza et al., 2021). This stability could be attributed to their lower solubility or reduced reactivity in wastewater treatment systems, often resulting in more predictable residual concentrations (Chauhan and Kumar, 2020).

In addition, plants require these elements in significantly lower quantities compared to macronutrients, which may further contribute to the observed stability in their uptake patterns (Ahmed et al., 2024). Previous studies have shown that the accumulation of these micronutrients in soils fertigated with wastewater tends to remain within relatively stable ranges, without significantly affecting the absorption of other essential elements (Bindraban et al., 2020; Vandecasteele et al., 2018). However, the appropriate concentration of these micronutrients is crucial to avoid both deficiencies and toxicities that can compromise vital processes such as protein synthesis and plant energy metabolism.

3.3. Correlation between yield and crop type

Fig. 4 presents the result of a thorough analysis of the yield reported in the reviewed studies, categorized by crop type. It illustrates the distribution of agricultural outputs for different crop categories under fertigation. The graphical representation indicates significant variability in yields across several crop types. It can be noted that crops such as fruits and vegetables show a higher variability in yields throughout the assessed articles, indicating a more sensitive reaction to the chemical composition of wastewater (Ali et al., 2024). These crops, which have elevated nutritional demands, exhibit greater variability in yield, suggesting that the efficacy of fertigation with wastewater may be enhanced.

This variability is largely influenced by the interactions among different ionic species present in the wastewater. Essential macronutrients such as N, P, and K interact dynamically, affecting their bioavailability and uptake efficiency (Chauhan and Kumar, 2020). High Na^+ concentrations, for instance, can induce antagonistic effects, particularly limiting K^+ absorption due to competitive inhibition at the root level (Yasuor et al., 2017). This phenomenon is critical for K^+-dependent crops like tomatoes and peppers, where K^+ plays a key role in enzymatic activation and osmotic regulation (Nikolaou et al., 2021). Furthermore, imbalances in the Ca^{2+}: K^+ ratio can weaken cell wall structure, increasing susceptibility to biotic stressors and physiological disorders (Alves et al., 2017). Mg^{2+} plays a key role for chlorophyll synthesis, influencing yield outcomes, while an excess of SO_4^{2-} can potentially reduce PO_4^{3-} solubility in soil, further impacting nutrient uptake (Bindraban et al., 2020; Ibrahim et al., 2022).

Crop categories including grains and legumes demonstrate less yield variability, suggesting that these crops are more resilient to variations in the chemical composition of wastewater. This could be due to their ability to adapt to varying nutritional conditions or their lower dependence on certain essential nutrients compared to other plants (Dutta et al., 2022). The increased stability observed in these groups may indicate improved nutrients' utilization, thus reducing their dependence on external factors.

The yields variability observed in certain crops may also be affected by the soil or environmental conditions, including greenhouse and field crops. As previously stated, factors such as N retention capacity, leaching, and soil pH significantly influence nutrients' availability and in turn agricultural productivity (Yasuor et al., 2020). Still, this resilience does not necessarily imply optimal growth conditions. While cereals and legumes may exhibit lower yield fluctuations, their ability to maintain stable productivity might be linked to long-term physiological adaptations, including modifications in root exudation patterns and rhizosphere interactions that influence nutrient solubilization and microbial activity (Arcas-Pilz et al., 2021; Ibrahim et al., 2022). The presence of certain ions, particularly in excess, can trigger adaptive mechanisms such as increased root biomass allocation or differential expression of transport proteins, allowing these crops to cope with fluctuations in nutrients' availability (Hashmat et al., 2021). Nevertheless, these

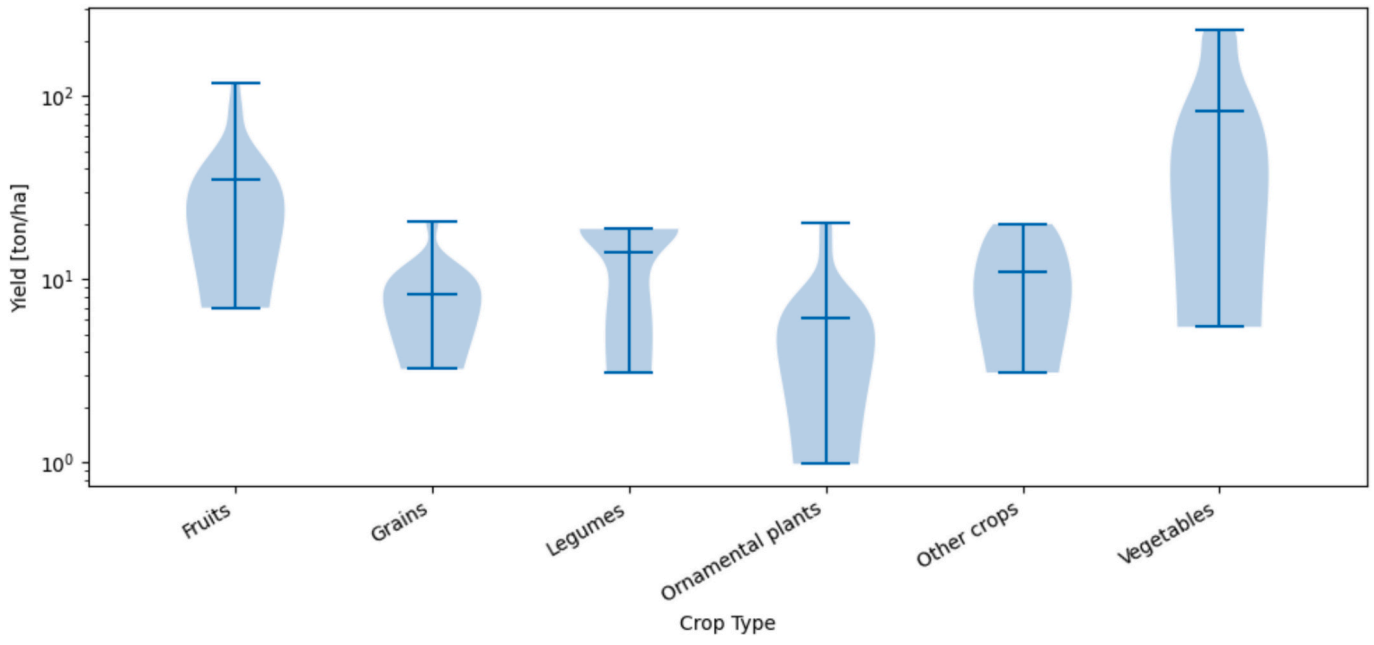


Fig. 4. The violin plots show the yields (ton/ha) for different crop groups under fertigation with wastewater.

adaptations may not be sufficient under prolonged exposure to imbalanced ionic compositions, warranting further investigation into the cumulative effects of wastewater fertigation on soil-plant dynamics (Gava et al., 2023; Plaza et al., 2016).

Some plants can be stressed by the type of wastewater used in fertigation. This stress response is not only linked to the absolute concentration of nutrients but also to their relative proportions and temporal availability. Crops with high metabolic demands require precise nutrient ratios at different developmental stages, and deviations from optimal concentrations can trigger physiological imbalances, reducing nutrients' use efficiency. For example, an excess of NH_4^+ relative to NO_3^- can acidify the rhizosphere, altering root respiration and microbial community structure, further impacting nutrients' assimilation. This shows the relevance of carefully control the chemical composition in soil to obtain better productivity results and maintain high yields. By incorporating a deeper understanding of ion interactions and plant physiological responses, fertigation strategies can be optimized to minimize nutrients' antagonism, prevent soil degradation, and enhance yield stability across different cropping systems (Azad et al., 2020; Chauhan and Kumar, 2020). Studies have demonstrated that different irrigation techniques and N management strategies can significantly influence soil quality and nutrients' efficiency, impacting long-term agricultural sustainability (Demir and Özbahçe, 2021). Future research should focus on developing predictive models that account for seasonal variations in wastewater composition and their long-term effects on plant health and productivity, ensuring more sustainable and effective wastewater reuse in agriculture (Jeong et al., 2020).

3.4. Effect of the water source on yield

The results obtained from the analysis of the agricultural yield in the reviewed articles are presented in Table 3 and Fig. 5. These indicate that crops irrigated with domestic wastewater exhibit higher yields, with an average of 62.31 tons/ha and a median of 33.57 tons/ha. The high yield observed can be attributed to the abundant presence of essential macronutrients for plant growth, such as N, P, and K^+ in various bioavailable forms, which can partially meet crop nutritional needs (Rietra et al., 2022).

The classification of domestic wastewater is critical, as untreated wastewater, despite its high nutrient content, poses risks due to organic load, pathogens, and heavy metals (Silva et al., 2016). It frequently exceeds permissible limits for COD, BOD, and microbial contamination under EU legislation 2020/741 (Jiménez-Benítez et al., 2020; Penserini et al., 2024). Additionally, emerging contaminants and persistent organic pollutants may accumulate in soil and enter the food chain, making untreated wastewater unsuitable for safe agricultural use (Hänel et al., 2022; Tzortzakis et al., 2020).

In comparison, crops irrigated with industrial effluents show an average yield of 15.95 tons/ha, suggesting that nutrient concentrations are insufficient to fully meet crop requirements without additional fertilization (Chojnacka et al., 2020).

Analyzing the composition of water used in irrigation systems reveals that its origin directly influences its chemical and nutritional properties. Domestic wastewater contains organic matter and essential plant nutrients derived from food waste and human metabolism byproducts, giving it significant agronomic potential (Libutti et al., 2018). In contrast, industrial effluents come from treatment processes that remove a large portion of organic and inorganic compounds, lowering its nutrient content but also reducing the presence of unwanted contaminants (Elgallal et al., 2016; Mainardis et al., 2022). Meanwhile, effluents such as drainage water and leachates have a highly variable composition, reflecting the accumulation of nutrients, salts, and potentially toxic elements (PTEs) from agricultural runoff, industrial discharges, and other human activities, which does not make them optimal for irrigation in most cases (Rezapour et al., 2021).

The detailed analysis of water quality used in these irrigation systems reinforces the idea that domestic wastewater provides adequate concentrations of essential inorganic ions, such as NO_3^- and PO_4^{3-}, optimizing crop growth without causing significant nutritional imbalances. Additionally, it has been demonstrated that using reclaimed wastewater can reduce the need for commercial fertilizers, thereby decreasing energy demand and greenhouse gas emissions (Barbosa et al., 2022), contributing to more sustainable agriculture (Perulli et al., 2019). Although, the long-term impact of using wastewater from different sources must be carefully considered. While nutrient-rich effluents, like domestic wastewater, may initially enhance crop productivity, prolonged use can lead to unintended consequences, such as soil nutrient imbalances, salinity accumulation, and alterations in microbial communities (Coelho et al., 2020). The high Na^+ and Cl^- concentrations in industrial effluents, for instance, pose a significant risk of osmotic stress, which reduces plant water uptake and can lead to yield decline over time (Yasuor et al., 2020). Furthermore, heavy metals and emerging contaminants present in certain wastewater types may gradually accumulate in soil, affecting soil fertility and food safety (Tzortzakis et al., 2020). Although fertigation employing wastewater shows many advantages, there is still a chance that water contaminants, like PTEs will accumulate in soil. This is a critical concern that must be managed properly (Dagianta et al., 2014). The presence of elements such as Cu, Zn, and As, particularly in drainage effluents and leachates, suggests a potential risk of soil contamination that could compromise long-term

Table 3
Summary of median and average chemical composition (mg/L) and crop yields (ton/ha) by irrigation water type from the systematic review.

	Median			
Type of water	Domestic wastewater	Drainage effluents	Leachates	Industrial effluents
Yield[ton/ha]	33.57	5.58	5.66	9.49
Compound				
NO_3^- [mg/L]	16.59	285.8	328.6	236.0
PO_4^{3-}[mg/L]	13.30	54.13	31.70	123.7
Cl^-[mg/L]	257.50	17.73	443.2	358.7
SO_4^{2-}[mg/L]	165.1	120.1	307.2	348.6
K^+[mg/L]	29.8	982.4	136.84	113.1
Na^+[mg/L]	135.7	204.8	345.0	138.4
P[mg/L]	11.46	57.73	45.00	17
N[mg/L]	60.00	286.9	900.0	84.34
NH_4^+[mg/L]	18.04	18.04	n.d*	118.7
Cu[mg/L]	0.05	1.63	0.02	2.38
Zn[mg/L]	0.29	0.55	0.02	4.11
Mg^{2+}[mg/L]	24.31	48.49	6.46	76.2
As[mg/L]	0.02	0.67	n.d*	n.d*
COD [mg/L]	163.1	n.d*	n.d*	1135.52
BOD [mg/L]	55.5	n.d*	n.d*	764.5
Average				
Yield[ton/ha]	62.31	6.95	4.45	15.95
Compound				
NO_3^- [mg/L]	143.8	368.0	385.0	326.6
PO_4^{-3}[mg/L]	25.71	54.13	60.59	150.9
Cl^-[mg/L]	281.5	17.73	467.9	565.1
SO_4^{2-}[mg/L]	388.6	120.1	658.0	631.0
K^+[mg/L]	67.53	2052	332.6	304.9
Na^+[mg/L]	149.6	339.7	573.3	307.8
P[mg/L]	12.55	80.29	45.00	78.25
N[mg/L]	54.7	591.3	900.0	143.0
NH_4^+[mg/L]	36.17	23.06	n.d*	377.8
Cu[mg/L]	0.20	3.01	0.06	3.19
Zn[mg/L]	2.03	0.58	0.43	6.60
Mg^{2+}[mg/L]	37.84	80.66	10.42	105.5
As[mg/L]	0.02	0.82	n.d*	n.d*
COD [mg/L]	743.31	n.d*	n.d*	1717.98
BOD [mg/L]	147.67	n.d*	n.d*	865.47
Total Studies	28	8	8	21

* *n.d = this information has not been found in the reviewed articles.*

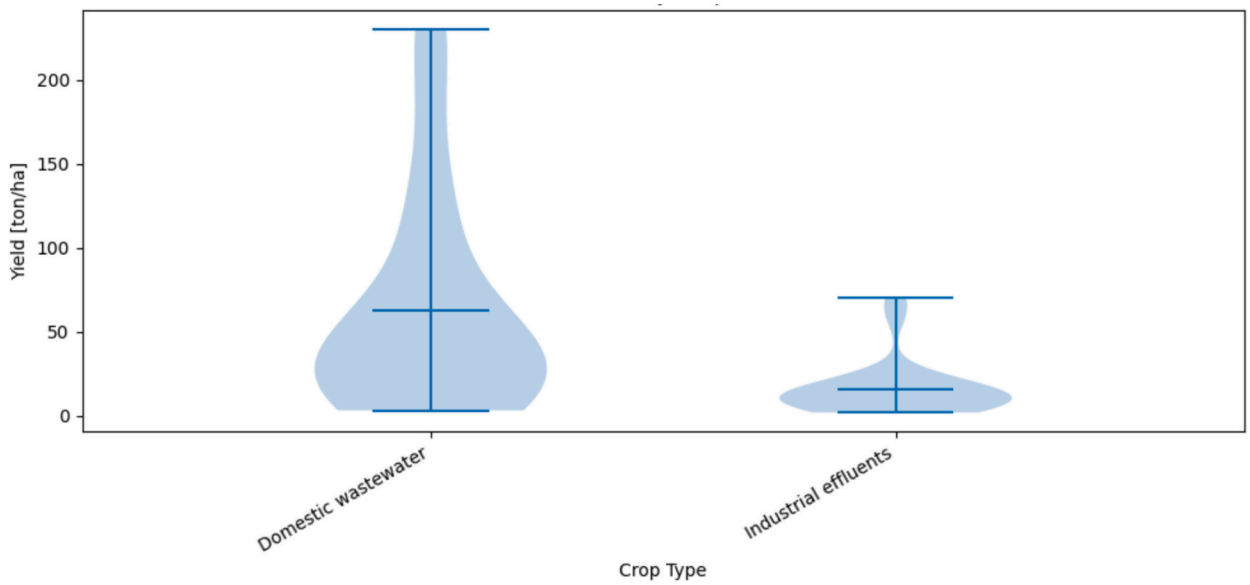


Fig. 5. The violin plots illustrate the yield dispersion (ton/ha) when using domestic wastewater and industrial effluents, highlighting variations for different crop types.

agricultural sustainability (Dousova et al., 2016). Variations in metal concentrations between different wastewater sources indicate that their origins and treatment methods play a crucial role in determining their suitability for fertigation (Rezapour et al., 2021). The accumulation of these compounds, particularly in fields irrigated with leachates and drainage effluents, could decrease productivity and jeopardize food safety due to the bioaccumulation of PTEs in agricultural products (Libutti et al., 2018; Naveed et al., 2018).

Treated wastewater can supply between 50 % and 100 % of the N and P requirements in crops such as wheat and maize, reducing production costs and greenhouse gas emissions (Lahlou et al., 2021; Maestre-Valero et al., 2019). However, the results of this review indicate that the N/P ratio (Table 3) in these effluents is unbalanced according to the needs for crops. This imbalance can affect fertigation efficiency, as N is generally sufficient to meet crop needs, while P may be inadequate without additional supplementation (Penserini et al., 2024).

In domestic wastewater, for example, the average N concentration (54.7 mg/L) is considerably higher than that of P (12.55 mg/L) and during treatment this gap tends to increase reflecting differences in the transformation and retention processes of these nutrients. While N, primarily in soluble forms such as NO_3^-, is highly mobile and remains in treated effluents at high concentrations, P tends to precipitate and adsorb, especially in the presence of coagulants used to remove solids (Chauhan and Kumar, 2020).

The insufficient reporting on wastewater treatment levels in most of the reviewed studies hinders the establishment of clear correlations between treatment processes and their effects on fertigation. 36 % of the articles analyzed did not report whether the water had been treated, while 64 % provided details. Regarding treatment levels, 37 % of the studies indicated that no treatment had been conducted, 16 % reported the application of primary treatment, 28 % mentioned secondary treatment, and 19 % referred to tertiary treatment. This omission represents a significant limitation, since the quality of wastewater used in irrigation directly depends on the treatment received.

Nevertheless, the average and median values of macronutrients reported in Table 3 suggest that domestic wastewater tended to present lower concentrations of NO_3^-, PO_4^{3-}, and K^+, suggesting that, in several cases, these waters could have been subjected to some level of treatment, although this was not explicitly reported. When considering domestic wastewater, 25 % of the studies indicated no treatment, 7 % reported primary treatment, 39 % referred to secondary treatment, and 29 % mentioned tertiary treatment. In contrast, industrial effluents showed relatively high concentrations of these nutrients, suggesting that treatment processes did not always result in a uniform reduction of key compounds for soil fertility (Mainardis et al., 2022). Within this category, 38 % of the cases reported no treatment, 33 % indicated primary treatment, 21 % referred to secondary treatment, and 8 % documented tertiary treatment.

Leachates and drainage effluents showed high variability in nutrient concentrations, with high dispersion likely influenced by factors such as localized fertilizer accumulation and variable runoff dynamics (Dousova et al., 2016). The absence of data on the treatment of these water sources hinders their accurate characterization and limits the assessment of their suitability for agricultural use. The significant proportion of studies that did not report treatment levels shows the necessity for more accurate and standardized documentation to better assess the implications of wastewater reuse in fertigation.

3.5. Correlation between soil type and yield

Soil texture is a critical factor influencing the retention and release of nutrients in the context of fertigation with wastewater. This textural variability, reflected in different combinations of sand, silt, and clay, directly affects the efficiency of nutrient supply and, consequently, agricultural productivity (Elgallal et al., 2016).

The reviewed studies indicate that nutrient supply through wastewater depends on soil heterogeneity, impacting crop yields. While clay and silt soils show higher nutrient retention due to their heterogeneous dual-domain structure, sandy soils, considered more homogeneous, tend to increase NO_3^- leaching, especially under high rainfall conditions, reducing nutrients' efficiency. This phenomenon, widely documented, is particularly significant in soils with low nutrient retention capacity, where essential compounds for plant growth are lost (Ogbenna and Tesfamariam, 2023). The rapid movement of NO_3^- through the soil profile limits its availability to plants, leading to variations in agricultural yield.

On the other hand, clayey soils, which have higher water and nutrient retention capacities, enable more stable nutrient absorption, potentially contributing to more consistent crop yields (Śpitalniak et al., 2021). However, this type of soil also presents an elevated risk of salt accumulation when nutrient-rich irrigation water is used. According to Tahir and Marschner (2017), soils with high cation exchange capacity,

typical of clayey soils, are effective at retaining specific nutrients like NH_4^+. However, this retention capacity may lead to salinization issues, which, in turn, affects soil structure and its ability to retain both nutrients and water (Yasuor et al., 2017). Moreover, salt accumulation can induce osmotic stress and ionic toxicity in plants, reducing photosynthetic capacity and, consequently, crop growth (Khan et al., 2022).

Fig. 6 presents a soil texture diagram that classifies and distributes soils used in the studies included in this systematic review. A marked diversity is observed in the percentages of sand, silt, and clay across the different studies, revealing extensive textural variability.

Although this texture-focused approach provides fundamental information to explain the physical dynamics of nutrient retention, future research should also incorporate the analysis of soil fertility and biological activity to obtain a more comprehensive view of their response to fertigation provided by wastewater (Coelho et al., 2018; Haddon et al., 2023; Hashmat et al., 2021). Aspects such as the presence of robust microbial communities and the amount of available organic matter play a key role in essential processes such as nitrification and P solubilization, favoring better nutrient utilization and higher agricultural yields (Moursy et al., 2022; Tzortzakis et al., 2020). In contrast, soils with low organic matter content or impoverished microbial communities may present greater nutrient leaching or immobilization, which would reduce the efficiency of fertigation (Savvas et al., 2023).

Integrating these variables (cation exchange capacity, key nutrient content, and microbial diversity, among others) in future studies will allow a more accurate understanding of the effects of physical, chemical, and biological factors on soil interaction in agricultural productivity and will contribute to the design of management strategies that optimize the use of wastewater in fertigation, thus minimizing risks such as salinization and contamination by excess nutrients (Chtouki et al., 2024).

4. Conclusions

The concentration of inorganic ions in wastewater used for fertigation exerts a considerable influence on the performance of various crops, both under field and greenhouse conditions. The results indicate that crop yields are more consistent and generally higher in controlled environments, such as greenhouses. This is because inorganic ions, especially NO_3^- and PO_4^{3-}, are better absorbed by plants. However, under field conditions, crop yields exhibit greater variability due to exogenous factors such as leaching and mineralization, which affect nutrients' availability. This behavior emphasizes the need for careful nutrients' management in open agricultural environments, where natural soil processes and changing environmental conditions can make challenging to ensure efficient nutrients' absorption by plants. To mitigate these uncertainties, site-specific fertigation strategies should be developed, integrating real-time soil monitoring and adaptive nutrients' dosing to optimize plant uptake while minimizing environmental risks.

In terms of compliance with the quality standards for wastewater used in fertigation, the findings indicate that while certain essential inorganic ions, such as NO_3^- and PO_4^{3-}, fall within the limits recommended by FAO, others, such as Na^+ and K^+, often exceed the suggested thresholds. This non-compliance adversely affects agricultural productivity, particularly in crops sensitive to salinity. The elevated concentration of Na^+ and Cl^- in wastewater, associated with increased soil salinization, generates osmotic stress in plants, reducing their ability to absorb water and other essential nutrients. This indicates that although wastewater may satisfy a portion of crop nutrients' requirement, its extended use without appropriate management could compromise both agricultural productivity and the long-term sustainability of soil health. To counteract these negative effects, strategies such as periodic freshwater irrigation cycles and crop rotation with salt-tolerant species should be considered to maintain soil structure and mitigate salinity buildup.

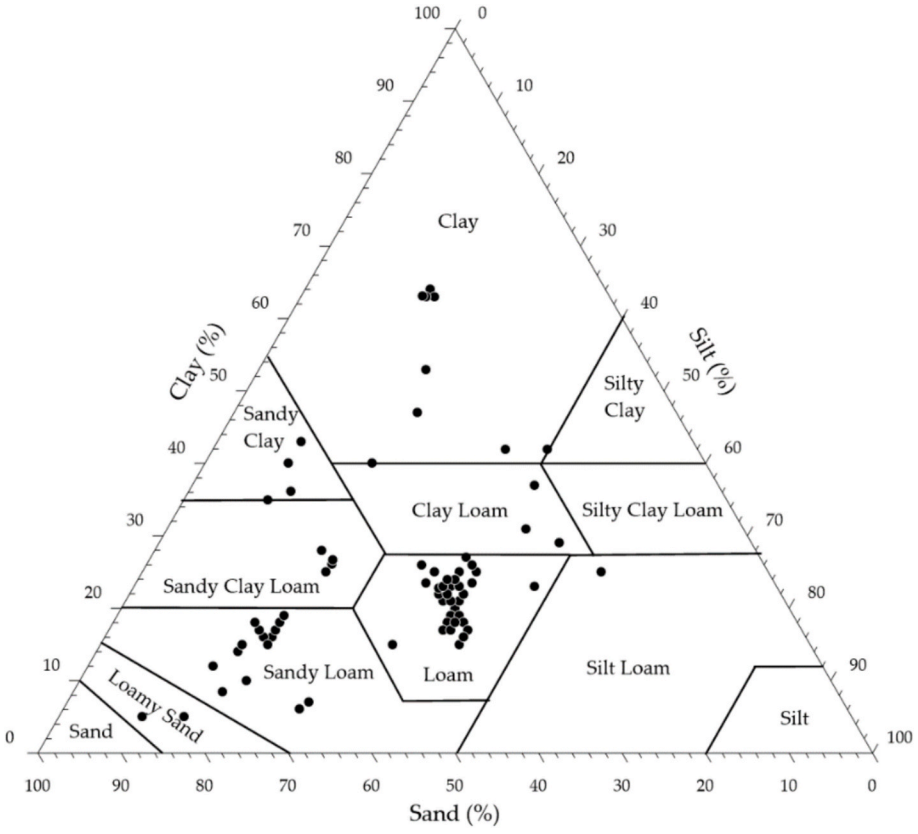


Fig. 6. Soil textural triangle displaying the classification and distribution of soil samples evaluated in this systematic review.

The correlation between nutrients' concentrations in wastewater and agricultural productivity also exhibits significant variation depending on soil type and cultivation conditions. NO_3^- leaching is more pronounced in sandy soils, reducing the availability of this essential nutrient for plants, potentially affecting yields and posing a threat to the environment. In contrast, crops yield in clayey soils characterized by a higher nutrient retention capacity may be more stable. However, the risk of salt accumulation is elevated, which could lead to salinization issues and long-term degradation of soil quality.

The recent update to the Urban Wastewater Treatment Directive (EU 2024/3019) establishes more stringent limits on inorganic contaminants, prompting the adoption of advanced treatment technologies such as membrane filtration, ozonation, and granular activated carbon filtration. These processes enhance water quality and facilitate its reuse; however, they can also alter nutrients' concentration, potentially affecting their suitability for agricultural fertigation. While the reduction in nutrients is not always substantial, it remains a factor to consider when optimizing wastewater reuse strategies.

The findings from this systematic review highlight the critical importance of adapting fertigation practices to the specific characteristics of soil types as well as crop growing conditions to maximize the benefits of wastewater use in agriculture. Future research should focus on optimizing fertigation protocols through precision agriculture techniques, evaluating microbial responses to wastewater irrigation, and assessing long-term impacts on soil health to ensure both productivity and environmental sustainability. Additionally, it is crucial to investigate the effects of advancements in wastewater treatment, particularly the implementation of nutrients' recovery and selective separation processes, on the suitability of industrial effluents for fertigation.

CRediT authorship contribution statement

Aahilyn Osorio: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Antonio Panico:** Writing – review & editing, Validation, Supervision, Conceptualization. **Gianluigi Busico:** Writing – review & editing, Validation, Methodology, Investigation. **Micòl Mastrocicco:** Writing – review & editing, Validation, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179257.

Data availability

Data will be made available on request.

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GREY WATER RECLAMATION FOR URBAN NON-POTABLE REUSE - CHALLENGES AND SOLUTIONS: A REVIEW

D. T. K. James[1*], S. Surendran[1], A. O. Ifelebuegu[1] , E. Ganjian[1] and J. Kinuthia[2]

[1]Coventry University, Coventry, UK
[2]University of South Wales, Pontypridd, UK
**E-Mail: jamesd19@uni.coventry.ac.uk, TP: +447470496184*

Abstract: The study shows the sustainable and effective way of managing growing water and wastewater problem is to reclaim and use greywater from bath/shower, hand basin and washing machine for outdoor and indoor non-potable purposes. A detail wastewater characterisation study by the past researchers indicates that grey water is polluted, but the quality is not similar to the domestic wastewater and therefore the traditional design criteria cannot be used for greywater reclamation. The study by the past researchers show grey water with detergent inhibit grey water reclamation process such as aerobic biological process and the appearance of reclaimed water with cloudiness, colour and excessive bubble formation reduce willingness especially for in-house uses than outdoor uses. Partially or untreated soapy grey water are useful for outdoor use and has useful nutrients, but some study shows excess detergent and other cleaning materials may cause harmful effects to the growth of plants and degrades soil structure. It may cause risk to the environment and human who makes close contact with grey water or inhale the spray. Currently most of the grey water reclamation systems are based on traditional wastewater and/or water treatment design and some have no proper design at all. In addition, due to the public perception ("yuck effect"), it is not acceptable for using reclaimed grey water for direct potable use. Also, globally there are standards for potable water quality and regulated widely, whereas only a few countries have non-potable water quality or grey water reuse standards and regulated properly. Therefore, when designing grey water reclamation, the above challenges needed to be considered. This paper presents review on grey water characteristics, health and environmental risks, public acceptability, regulatory requirement for non-potable use and on current grey water reclamation processes, particularly about the treatment of detergent and other cleaning materials and also identify natural geo or waste material for synthetic detergent removal from grey water.

Keywords: Detergent and surfactants; Grey water characteristics; Natural or waste material; Non-potable uses; Treatment systems.

Abbreviations: BOD - Biological oxygen demand, COD - Chemical oxygen demand, TSS - Total suspended solids, TDS - Total dissolved solids, TOC - Total organic carbon, WHO - World health organisation, WC- Water closet flushing

1. Introduction

The United Nation Office for Disaster Risk Reduction [1] reports that during 2005-15 due to over 4016 natural hazard events, 0.8 million people were killed worldwide and another 1831 million people affected, with $1.7 trillion damage. About 84% of the hazards are related to flood, storm, heatwaves and drought events led to 43% of fatality and 95% of people were affected. The UN's Intergovernmental Panel on Climate Change [2] has stated that climate change has accelerated faster than predicted, with the consequence of dryer summers and wetter winters with frequent droughts and floods with associated

pollutions. WWAP (World water assessment programme) [3] indicates more than 50% of the world population are living in cities and 30% of them are in slums.

Urban populations are expected to increase, particularly 93% of people in the developing countries will live in urban areas by 2050 and half of them will be in the urban slum. Climate Change and demographic changes due to mass urbanisation are the most urgent challenges of the 21st century and these are the key drivers for all water shortage and wastewater (flooding & pollution) problems.

Therefore, there is a need to manage the above water and wastewater problems by considering alternatives to conventional methods. The study carried out in Loughborough University during 1994-98 shows planned direct grey water from bath, shower, hand basin and washing machine with or without storm water from roof could be reclaimed and used for non-potable indoor (WC) and outdoor (gardening) purposes as a suitable additional option to solve the problem [4,5,6].

2. Grey water characteristics

In order to design the degree and type of greywater treatment, studying the grey water quality characteristics are very important. Surendran et al [4,5,6] collected grey water from a student accommodation hall in Loughborough University analysed for 17 parameters (Table 1)

Table 1: Characteristics of grey water / wastewater

Micro-biological, Physical & Chemical Parameters	Typical Greywater Quality			Domestic Wastewater Quality (See Key)
	Surendran et al [4,5,6]		Others (See Key for Ref)	
	No of Samples	Typical		
Thermo-tolerant Coliform (cfu/100ml)	221	320 - 1485	2022 (10)	10^7 (6)
Total Coliform (cfu/100ml)	73	1.6x10^5-5.2x10^6	1.9 x10^5-19.2x10^6 (1,9)	10^{12} (6)
Turbidity (NTU)	272	25-72.8	8.8-184 (1,2,3,4,5)	70 (6)
Tot Suspended Solids (mg/l)	303	24-53.7	19-397 (1,2)	1- 400 (6,7,8)
Tot Dissolved Solids (mg/l)	139	364-442.9	175 -397 (1,2)	540-800 (7)
Total Volatile Solid (mg/l)	139	145.8 - 251.3		320 (6)
Temperature - ^oC	123	20.4-22.4	19.7-24.4 (1,2,3,4)	
Conductivity - µS/cm^3	137	557-599.5	351-1225 (1,4)	
pH	142	7.3-7.72	6.6-10 (1,3,4)	6.6 - 7.9 (6,7,8)
BOD - mg/l	175	60.5-110.4	22 -149 (2,3,5)	12 - 360 (6,7,8)
COD - mg/l	31	138.4 - 173.2	23- 655 (1,2,3,5,9)	94-750 (6,7,8)
Tot. Org. Car (TOC)-mg/l	255	37.6-57	72.6 -181 (3,9,10)	29 (6)
Inorganic Carbon - mg/l	225	26.1-29.6		
Phosphate (PO_4) as P-	62	1.6-	0.29– 8.1	7.7-

mg/l		3.6	(1,4,5)	26.4 (6,7)
Nitrate (NO_3) as N-mg/l	62	0.81-1.21	0 – 5.5 (1,2,5)	2.8 – 25 (6,7,8)
Ammoniacal Nitrogen (mg/l)	9	1.6	0 – 8.2 (4,5)	45 (6)
Ammonia (mg/l)			5.43-13.23 (1,3,4)	
Dissolved Oxygen (mg/l)	37	5-7.6 (83%)	0.92 - 3.26 (1)	(54%) (6)
Anionic surfactant (mg/l)			143 (3)	1.1(6)
Sodium (mg/l)			141 (3)	
Cholride (mg/l)			23.6 (2)	400 (6)
Sulphate (mg/l)			43.6 (2)	0.5 (6)

Key: [1][7]; [2][8]; [3][9]; [4][10]; [5][11]; [6][12] ; [7][13]; [8][14], [9][15], [10][16].

The term "greywater" is defined as; "*untreated wastewater from wash basins, baths, showers and laundry facilities, that excludes WC, urinal, bidets, soiled laundry water, cleaner's sinks, kitchen sinks and dishwashers or other wastewater which are of non-domestic origin*". The grey water quality results from the Surendran et al [4,5,6] were compared with other grey water results found in the literature and shows that all of this results were almost similar and the grey water is polluted and cannot be used without some treatment.

There are small variations of greywater characteristics from different authors, this is due to nature of users and uses; e.g. Smith and Bani-Melhem [7] and Ghunmi et al [9] samples had higher suspended solids than Piduo et al [11] and Chin et al [8]. The variation is mainly due to the laundry activities done by the students in the hall, involved in sports [9] and from cleaning and hand basin activities in domestic household [7]. Suspended solids found in all the authors' samples were lesser than the domestic waste water. TDS concentration from Surendran [5] and Smith [7] was higher than Chin[8]. TDS has resulted from usage of soap and detergent from bathing, cleaning and laundry activities in all authors but sampling (grab/composite/continuous) techniques and the laboratory testing procedures are different. The TDS found in waste water is much higher than grey water samples and TDS in Surendran [5] sample was 44% lower than Final effluent. Similarly, Li [10], Ghunmi [9] and Smith [7] studies had the higher turbid grey water due to shower, laundry and cleaning activities.

Organic contents (BOD_5) and total coliform in grey water from Surendran [6], Winward [15] and Ghunmi [9] all were higher than others and the final effluent of waste water treatment plant [5]. This is due to University students taking part in sporting activities and showering afterwards. In addition of this, students in accommodation use their hand basin for washing food items and regular cleaning of student halls. BOD in Ghunmi's sample was about 58% lower than the domestic waste water. Even though the grey water does not include toilet waste, the fecal coliform in Jefferson [16] grey water results are bit high. This variation is due to washing diapers or children in the shower/bath or hand basin.

All most all the detergent and cleaning products used for cleaning or personal hygiene contain anionic surfactant. They also contain other element/compounds such as boron, sodium, ammonium, sulphate and sulfonates in them. Anionic surfactant in grey water are higher than waste water since the dilution is less in grey water. The ammonium content in grey water is higher in Li [10] than Ghunmi [9] and Piduo [11] that has been resulted from

shower. Even though Smith [7] sample which is collected from an office building that has no bathing and washing diapers but still it shows a higher ammonia content. This ammonia content may be resulted from anionic surfactant (alcyl amino acids), Cationic surfactant (linear akylamines and alkyl ammonium) or Amphoteric surfactant (Amino propionic acid) from cleaning and washing activities [17]. The ammonium and nitrates in wastewater are far higher than in grey water. This is because waste water includes toilet waste. Nitrogen is useful for plants but in nitrates form. Therefore, these ammonium content should be converted to nitrates for it to be useful for the plant as a fertilizer.

Phosphate concentration in domestic waste water is 7.7 - 26.4mg/l and was higher than the grey water samples. Surendran [5] and Li [10] experiments reported higher level of phosphate than others. These phosphates are mainly from the shower creams, cleaning liquids and detergents from bathing and cleaning activities (from the Sink and wash basins). Ghunmi [9] had more chloride in the sample than Smith [7] and Chin [8]. This variation was contributed from the bleaches in detergent from laundry activities that can harm the plants if they are found in large amounts [9]. Except for chin [8], the pH in grey water ranges from 7 to 8 in all the authors' experiments, had pH of 10. This variation can be due to higher detergent concentration since Chin collected the first discharge from the washing machine.

The results from Surendran [6] shows that organic and microbial qualities of greywaters are comparable with settled domestic wastewater. In some cases, the Grab grey water sample had higher values of BOD, COD and TOC than average settled domestic wastewater. The ammonia and bacterial content in the university greywater was lower than average domestic wastewater or the greywater from the household with young, old and disabled members where the Faecal Coliforms value could be as high as 3.2x105 per 100ml. The comparison of greywater quality with domestic wastewater shows that the quality is not similar and therefore the traditional design criteria cannot be used for greywater reclamation.

2.1 Health and Environmental risk

Pollutants from grey water can produce adverse effect if it accidently comes in contact or ingested by people during WC flushing or spraying during gardening. Microorganisms in grey water could contribute to health risk such as skin or eye infection [18]. Inhalation of aerosol during non-potable uses can cause severe breathing problem [19,20]. Un-treated greywater use (by close contact or spray) also may cause risk to the environment.

Partially or untreated soapy grey water are useful for outdoor use and has useful nutrients. Nitrogen, phosphorus and potassium from grey water are useful for the plant growth but not in excess amounts [18,19]. Therefore, if grey water with these parameters are used in gardening, it could reduce the fertilisers need. But the following studies shows excess detergent and other cleaning materials may cause harm to plants growth and degrades soil structure. Therefore, this concertation should be treated before watering the plants.

The most concerned parameters from grey water that could destroy the plants and environment are sodium, boron and Chlorine from detergents, surfactant and bleaches [18,19]. High levels of these contaminants could contribute to discoloration, burning of leaves, leaf cupping, can contribute to the alkalinity of the soil, prevents calcium ions reaching the plants, it also disturbs the soil's ability to absorb water by disrupting the osmotic pressure [19]. Ottoson [21] believes that untreated grey water with chemicals (Sodium) from detergent and surfactants can lead to harmful consequences such as soil degradation and WHO [19] reasons that this consequence is due to the reduced permeability and aeration due to high amount of sodium adsorption (Sodium from detergents). Ultimately not allowing the soil to support the plant. Boron is needed to

plants in small amounts. This amount is already given by the soil to the plant. Therefore, boron from grey water (even a little) would be in excess to the plant that is toxic and will cause severe damages [19].

Chin [8], Surendran [5,6], Eriksson and Christova-boal [8] studies addresses the other effects of un-treated grey water usage on treatment and pipework. Suspended solids in grey water can clog up pipework that transport grey water. Surendran [5] claims that high level of Total dissolved solids can cause corrosion and scaling on bathroom fixture when used directly for toilet flushing.

The study show grey water with detergent inhibit grey water reclamation process such as aerobic biological process and the appearance of reclaimed water with cloudiness, colour and excessive bubble formation reduce willingness especially for in-house uses than outdoor uses. High turbidity in grey water can make the treatment processes such as disinfection treatments inefficient [5] and the turbidity of non-potable water should be between 2 to 5 NTU according to the standards used in many countries [22]. Therefor the detergent should be removed to the quality acceptable to the users, regulators and other stakeholders.

2.2 Public acceptability to the greywater use

Surendran [5] says successful outcome of the development of water reclamation system would depend on the public attitudes, acceptability, affordability and willingness to pay for water recycling and related water and environmental benefits. The expected non-potable water quality depends on the legal requirements and public perception. This institutional survey [5] showed that over 95% of people questioned would accept and are willing to consider using the reclaimed water for toilet flushing, 97.3% for lawn irrigation and 98.4% for golf course irrigation, if the water was clear, colourless, odour free, carried negligible risk and gave cost-benefits. About 70% would invest an additional 9.8% of their water bill-equivalent to water management devices for long term benefit. In commercial terms this may also enhance the company or institution's reputation. Further, Surendran [4,5,6] studied public attitude prior to demonstration of recycling system at Royce hall. The major for the opposition of reclaimed water reuse are: (1) psychological repugnant and personal preference – 38%; (2) fear or worry about the water quality such as lack of purity & physical quality - 28%; (3) undesirable for bodily contact & cause diseases - 22%; (4) undesirable chemical added - 8%. (5) Operation & maintenance including corrosion & scaling - 2%; and (6) cost for treatment - 2%.

In a survey conducted by Jefferson [16] turbidity, colour, suspended solids and odour influence the public perception of reusing of grey water and reveals that turbidity is the parameter that mostly limits the reuse of grey water and willingness to reuse greywater for toilet flushing was more than watering the garden. Boyjoo [23] reasons the above statement that people oppose more to reuse of grey water when the grey water comes in close contact with them.

2.3 Requirements for non-potable use

The legal requirements are in practice to protect from associated risks of grey water (as stated above), exposed to human and environment [18] and the standards varies according to the end use. There is at present no official guidance on quality criteria for reclaimed greywater in the UK. In order to develop and evaluate the effectiveness of reclamation plants the following alternative sets of water quality guidelines were used in the UK (Table 2):

Table 2: Non-potable water quality standards

	WHO guidelines	UK/EU bathing water standards	EPA reclaimed water standard for WC flushing
Faecal Coliform (F_Coli)	Recreational waters: ≤100 for 50% sample and ≤1000 for 90% sample Irrigation of crops eaten uncooked, Sports fields, public parks and lawns: ≤1000 (all samples)	100(g)/ 2000(m) (g: guidance m: mandatory value)	≤14 for any sample 0 for median of samples from over 7 days monitoring Monitoring 1/day
Total coliform cfu/100ml		500(g)/10000(m)	
Faecal streptococci per 100ml	≤100 for 50% sample and ≤1000 for 90% sample	100(g)	
Enteric Viruses		0(m)	None
BOD_5 - mg/l			≤10 Monitor 1/week
Total suspended solid (TSS) - mg/l		Visibly absent	None
Turbidity (Tur)- NTU		Transparency in M -2(g) / 1(m)	≤2 NTU continuous monitor
Cl_2 residual -mg/l			>1 after 30 min contact Continuous monitoring
pH		6-9(m)	6-9 (monitor 1/month)

3.0 Current process for detergent s removal

Although there are limited guidelines for grey water reuse, reclaimed grey water should fulfil four main criteria for reuse namely; hygienic safety, aesthetics, environmental tolerance and economics [9,10,24].

To meet these criteria, various technologies have been assessed for the treatment of grey water. Treatment varies in both performance and complexities depending on the various target pollutants and the purpose of reuse. They vary from very simple treatment processes like filtration to advances processes like reverse osmosis. The various methods that has been utilised and the pollutants (Detergent characteristics and characteristics that affect public perception) treated are listed in table 3 below and they can be divided into physical, biological and chemical treatment processes.

Physical filtration involving sand and other coarse media are only able to remove large suspended solids and are not able to remove chemicals from detergent / cleaning material and microbiological parameters to levels required for potable reuse. To achieve potable reuse criteria more advances filtration involving nano filtration and reverse osmosis are required. Micro and ultra-filtration membranes can achieve excellent removal of solids, turbidity but not good removal of dissolved salts / Surfactant characteristics and organics. Adsorption, distillation and Reverse osmosis are the main physical methods used in the removal of surfactant characteristics from wastewater / grey water [25, 26].

Chemical processes including coagulation, Ozonation and ion exchanges have also been used for grey water treatment specially

in the removal of detergent characteristics [27]. These chemical methods are usually able to reduce organic substances (Surfactants) and turbidity to certain degree but usually not to levels that allows for potable reuse for high strength grey water [11,28]. To achieve potable reuse standards, chemical processes are usually combined with physical processes like filtration or membranes as a further polishing step [11].

Grey water has also been treated using biological processes including aerobic and anaerobic processes. Aerobic processes are usually good in achieving organic matter and turbidity removal while anaerobic process do not achieve good removal results [10,28]. Biological processes are not effective in removing microbiological parameters hence there is usually need for further filtration before potable reuse and also it is not effective in removal of detergent from grey water since the detergent characteristics will destroy the microorganism used in biological process.

Table 3: Treatment Process for different quality

Detergent characteristics DE - Detergent FO - Foam SU-Surfactant C/BL - chloride & bleaches BO - Boron SO – Sodium / its compounds A - Ammonium NI – Nitrates P – Phosphates	SE – Sulphate TDS – Total Dissolved Solids O/G – Oil / Grease (Oil attached to surfactant) **Public perception characteristics** CO - Colour OD - Odour TU - Turbidity TSS -Total suspended solids
Physical treatments	
Screening & grit removal	TSS
Dilution	A, P, NI, SU
Storage	FO, TSS
Sedimentation	FO, TSS
Aeration	OD
Floatation	DE, O/G, TSS
Slow filtration	DE, O/G, TU, TDS, TSS
Rapid filtration	DE, O/G, TU, TSS
Reverse osmosis	TDS, SU, BO, SO, SE
Distillation	SU, TDS, SO, SE
Adsorption	SU, BO, OD, CO
Biological treatments	
Suspended-growth	A, TDS, NI
Fixed-film reactor	A, TDS, NI
Bio. nutrient removal	P, NI
Reed bed	DE, TU, P, TSS, NI
Land treatment	DE, FO, C/BL, TU, P, TSS, NI
Chemical treatments	
Coagulation	DE, OD, TU, SU, TSS, BO
Chlorination	OD
Ozonation	SU
Ion exchange	TDS, SU, BO, SO, SE
Electro dialysis	TDS, SO

Source: [5], [29], [30]

3.1 Loughborough Grey Water Reclamation

Surendran [4,5,6] conducted a research and developed a bio-filter for reclaim greywater at a student accommodation in Loughborough University from 1994 to 1998. This research includes treatment process for grey water, this was a partly funded project by Anglian Water, Yorkshire Water and Entec Pollution Control.

This package unit was composed of four main stages (Fig 1) and the detail designs were given in Surendran [4,5,6]. Stage 1 was for balancing flows and buffering peak mass loads includes Screening, grit chamber,

(preliminary treatment) and Stage 2 for solid separation and digestion by sedimentation, roughening filter (primary treatment) to reduce sludge yield. Stage 3 was an aerated bio-filter (a modified activated sludge process with complete mix fluidized bed and up-flow sunken media filtration, (secondary treatment) to remove most organics and Stage 4 gravity fed deep slow filtration (tertiary treatment) to generate near potable quality.

The fifth stage is further polishing by adsorption and it was an option. This unit was tested and modified during two laboratory trials (Table 4).

Table 4: Results of Loughborough experiment

Water quality Parameters, monitored at Royce-5	Project 1 - monitored up to 57 weeks		Project 2 - monitored up to 46 weeks	
	Initial Influent	Final Effluent	Initial Influent	Final Effluent
Thermo-tolerant Coliform (cfu/100 ml)	900-1485	1.0 - 3.8	900-922.6	1.6 - 3.9
T/Coliform (cfu/100 ml)	160000	50.0 - 52.9	160000	50.0 - 64.7
Turbidity (NTU)	30.0-35.1	1.2-1.5	25-33.3	1.7-2.5
TSS (mg/l)	34.5-40.2	2.0-2.7	24-28.9	1.5-1.9
TS(mg/l)	414-426.2	338.5-361.4	449-458.5	418.6 - 440
TDS (mg/l)	364-379.7	335.8-356.6	427.5-428.4	417.1-437.9
Temperature (°C)	21.0-21.9	16.3-16.5	20.4	15.5-16
PH	7.3-7.4	7.6	7.4	7.8-7.9
BOD(mg /l)	78.1-83.1	3.0-4.0	60.5-70.2	1.8-2
COD(mg /l)	ND		138.4 - 162.9	9.8-10.8
Ammoniacal N (mg/l)	1.6	0.1-0.2	ND	ND

Source: [5]



Fig 1: Greywater reclamation Plant construction in Loughborough, source: [5]

3.2 Joint Chinese / German partnership grey water recycling project

A grey water reclamation system was jointly developed by Chinese / German partnership to cater a residential area of 60 apartments. The water sources were from showers and basins and it was reclaimed and used for non-potable use such as toilet flushing. Grey water was treated using a membrane bioreactor with a capacity of 10000l/day and was operating since June 2006. The treated water parameters met the EU bathing standard (Table 5) [31].

Table 5: Results from the Chinese/German project

Parameters	Inlet	Out let	Water quality standard for flushing
pH	7.8- 7.9	8.2 -8.4	6.5 – 9.0
TSS	22 – 65	0 – 2	10
BOD	86.2 - 123	1.8 - 3	10

COD	132 -200	12.9-14.1	50
Turbidity	48-74	1-2	10
TDS			1200
Ammonia	6.41-7.72	0.52-0.86	20
Total phosphorus	4.02-5.42	2.81-5.24	-

Source: [31]

4. Natural geo / By-product material to remove detergent characteristics

All Materials such as natural material, artificial material, geo material, plant material and waste materials can be used to treat water or wastewater or grey water using the following treatment methods.

- Coagulation and flocculation (i.e. Alum from bauxite are used as coagulants in water, they bind the pollutants together to form flocks, thereby increases settlement to the bottom or they make them to float).
- Adsorption (i.e. Granular activated carbon from charcoal have surface area of 800-1500 m2/g and their pore size is 1.8 – 3.0nm [33] and the particle size range from 1.2-1.6 mm. Activated carbon uses the mechanism of physisorption to adsorb the pollutants into their pores by means of Van der Waals forces).
- Disinfectant is killing of microorganism from water or waste water (i.e. moringa seeds are effective in killing 97.5 % total coliform, in the same time they also act as coagulant and adsorbent [34]).
- ion exchange process (i.e. Zeolites), the structure of zeolites places an important role in removing cations due to their resulted negative charge from their 3D alumino silicate structure [27].
- Medium for the growth of microorganism in biological processes (In Trickling filter sand, rock and gravel are used in which the microorganism from waste water get attached to the sand / rock bed, grow and break down pollutants in waste water.

The following natural geo materials e.g. bentonite [32], Hydrotalcite: Layered double hydroxide [33], Alumina from bauxite (Adak et al 2005), Perlite can be used to remove the anionic surfactant. Zeolites (Clinoptilite) can be used to remove the cationic surfactant and the cationic modified zeolites are being used in the removal of anionic surfactant [27].

Waste materials such as activated carbon from charcoal and coconut shell [33], fly ash [36] were used in the removal of detergent. Tyre rubber granules were used to remove 96.5% of anionic surfactant and in the same experiment it confirmed that the removal efficiency of tyre granules are slightly higher than activated charcoal [25]. Mussel shells are aragonites that are being used to remove phosphates that are being resulted from surfactant and builders. When the mussel shells are heated to 800°C, they are converted to lime, that uses the adsorption and precipitation property to remove phosphates from detergent containing water [26].

5. Conclusions

- Grey water characteristics are not similar to waste water characteristics therefore traditional wastewater treatment design criteria cannot be used to reclaim grey water.
- Grey water is polluted specially with the physical and chemicals properties of soap and detergents (surfactants and builders) from shampoos and washing/cleaning materials. Therefore it needs novel and a sustainable treatment for it to be used as a non-potable source and also it should achieve the quality required by the regulation and standards and also cater the public acceptability.
- Removal of detergent from the grey water is possible by using natural and/or waste or by-product. This study will lead to the development of an eco-

friendly mineral coated synthetic foam layers for effective detergent removal.

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Review

Greywater reuse as a key enabler for improving urban wastewater management

Arjen Van de Walle [a], Minseok Kim [b], Md Kawser Alam [b], Xiaofei Wang [a], Di Wu [c], Smruti Ranjan Dash [b], Korneel Rabaey [a, **], Jeonghwan Kim [b, *]

[a] Center for Microbial Ecology and Technology, Ghent University, 9052, Ghent, Belgium
[b] Department of Environmental Engineering, Program of Environmental and Polymeric Engineering, Inha University, 22212, Incheon, Republic of Korea
[c] Center for Environmental and Energy Research, Ghent University Global Campus, 119-5, Incheon, Republic of Korea

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ABSTRACT

Sustainable water management is essential to guaranteeing access to safe water and addressing the challenges posed by climate change, urbanization, and population growth. In a typical household, greywater, which includes everything but toilet waste, constitutes 50–80% of daily wastewater generation and is characterized by low organic strength and high volume. This can be an issue for large urban wastewater treatment plants designed for high-strength operations. Segregation of greywater at the source for decentralized wastewater treatment is therefore necessary for its proper management using separate treatment strategies. Greywater reuse may thus lead to increased resilience and adaptability of local water systems, reduction in transport costs, and achievement of fit-for-purpose reuse. After covering greywater characteristics, we present an overview of existing and upcoming technologies for greywater treatment. Biological treatment technologies, such as nature-based technologies, biofilm technologies, and membrane bioreactors (MBR), conjugate with physicochemical treatment methods, such as membrane filtration, sorption and ion exchange technologies, and ultraviolet (UV) disinfection, may be able to produce treated water within the allowable parameters for reuse. We also provide a novel way to tackle challenges like the demographic variance of greywater quality, lack of a legal framework for greywater management, monitoring and control systems, and the consumer perspective on greywater reuse. Finally, benefits, such as the potential water and energy savings and sustainable future of greywater reuse in an urban context, are discussed.

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1. Introduction

Sustainable water usage is becoming increasingly challenged by the effects of climate change, population increase, and urbanization. Because water management is not only strongly associated with public health but also with food security, human rights, ecosystem services, and education, increasing robustness in water management is a key development goal for many countries [1]. The solution of looking for reusable water sources locally has two main advantages over the long-distance solution: (1) it avoids moving water across long distances, potentially entailing large cost savings, and (2) it can add to the resilience and adaptability of the local water system [2,3]. Local reuse of (municipal) wastewater streams is often undervalued and only considered when existing water resources do not suffice [4].

Local reuse relies on decentralized water installations as standalone systems for the treatment of small wastewater flows. Deploying decentralized water management units, potentially complementary to a centralized grid, allows for the collection, treatment, discharge, and reuse of wastewater flows near the point of production and preferably near the point of use. Small-scale installations often suffer from challenges, such as uneven flow distribution, toxic shocks, and the need to remove nutrients as well as pathogens from a complex water stream. Source separation, which refers to splitting wastewater flows at the point of origin, can facilitate this by simplifying treatment solutions and increasing the

* Corresponding author.
** Corresponding author.
E-mail addresses: Korneel.Rabaey@ugent.be (K. Rabaey), jeonghwankim@inha.ac.kr (J. Kim).

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potential for resource recovery, especially from less encumbered streams [5].

Household wastewater can be most easily divided into blackwater (toilet wastewater) and greywater. Greywater includes wastewater originating from all household applications other than blackwater. For example, it includes water from the washing machines, dishwashers, showers, baths, and sinks. Greywater makes up 30–50% of the organic load and 9–20% of the nutrient load of the total wastewater produced in a household [6,7]. Furthermore, an average greywater production of 60–200 L per capita is common in developed countries, for which greywater reuse could thus theoretically entail a water savings potential of 50–80% [8]. The lower degree of fecal contamination and the relatively large quantity available make greywater an attractive water resource if it can be reused effectively. Interestingly, greywater availability coincides with human activity and thus can match water supply with water demand, provided a modest buffering capacity is in place.

Much research on the reclamation and reuse of greywater streams has been undertaken using physical (e.g., membrane filtration), chemical (e.g., coagulation), and biological (e.g., suspended growth) treatment technologies [9] (see Fig. 1), with some products already on the market as consumer products for a single household and many suppliers offering building level solutions. Overall progress in the field and implementation has been slow, however, due in part to difficult uptake in building projects (separate piping issues), public risk perception and associated "yuck factor", and due to limited innovation in the water sector, especially from technology "lock-in" effects [3,10]. The latter entails the phenomenon where a "random" early lead in innovation is sufficient for a certain technology to acquire dominance within a market, leading to a restricted advancement of other technologies [11]. Thus, investments in large-scale, centralized water systems, in particular, can cause a lock-in due to their associated high infrastructure costs.

In recent years, several comprehensive literature reviews have been published on the current status of greywater reuse in the urban context. For instance, Shaikh and Ahammed [12] provided an overview of the literature on greywater quality and quantity characteristics, and other recent reviews have delved into specific technologies for greywater reuse, such as nature-based solutions, and have often focused on constructed wetlands [6,13,14], the application of adsorbents [15,16], MBR [17], and general membrane technology applications [18]. Vuppaladadiyam et al. [19] provided a comprehensive review of past research on greywater characteristics, and treatment technologies, a discussion on reuse barriers related to quality characteristics, administrative obstacles, and public opinion, and an overview of greywater reuse experiences across the globe. Furthermore, Khalil and Liu [20] wrote a review on biological treatment technologies for greywater reuse, greywater biodegradability, and the associated issues and solutions. Despite the wide range of topics addressed by these recent review papers, a holistic and up-to-date overview of scientific progress on greywater treatment technologies has yet to be published. This review paper aims to cover this gap by providing a comprehensive overview of greywater characteristics, treatment technologies, challenges, and opportunities for decentralized wastewater management.

2. Reuse of greywater: general aspects

2.1. What is greywater?

As previously mentioned, greywater is defined as all household wastewater flows, excluding toilet wastewater (blackwater). As feces and urine are excluded, greywater is generally less subject to microbial contamination and contains lower concentrations of organics and nutrients than mixed municipal wastewater (Table 1).

2.2. Ionic composition of greywater

Greywater contains elevated concentrations of ionic species (anions and cations) due mainly to the application of counter ions (Na^+, Cl^-) or bleaching agents (B) in washing powders and detergents and additions from food processing and personal care products (PCPs) (see Table 2) [25,26], and the salinity of greywater has a large impact on its potential for reuse and infiltration [27,28].

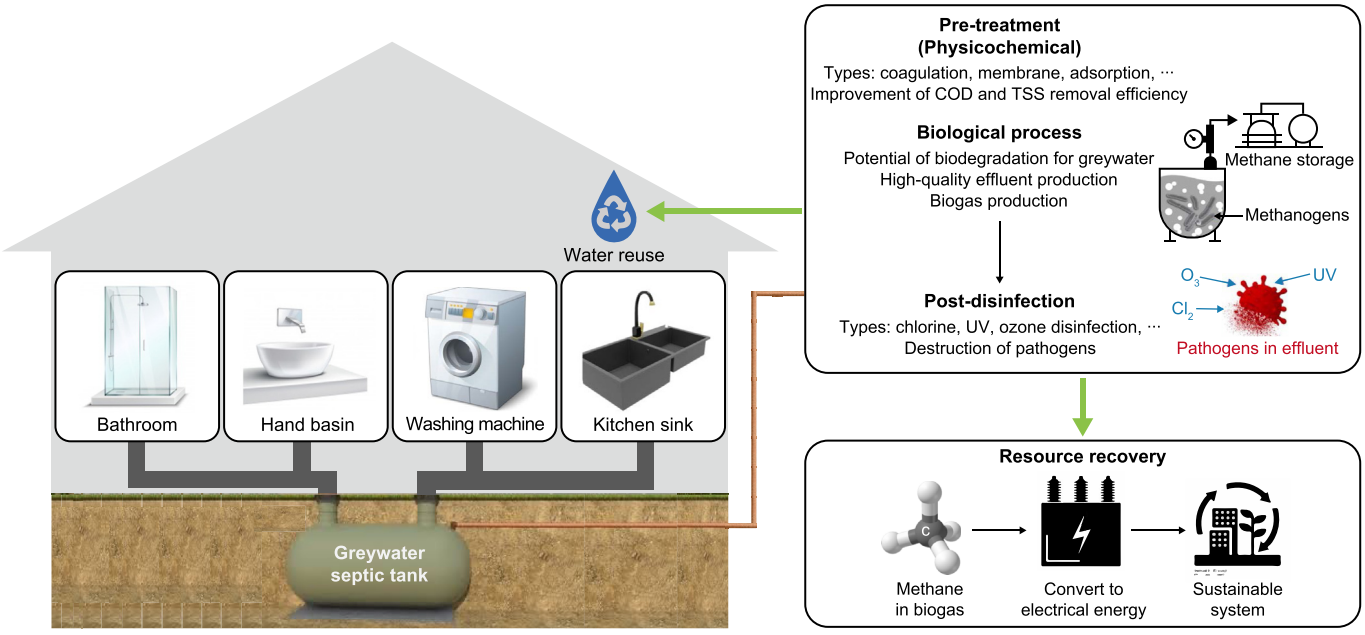


Fig. 1. Sources to collect greywater and integrated process for greywater treatment and resource recovery in household application.

Table 1
Characteristics of mixed greywater. Data adapted from Refs. [5,21–24]. BOD = Biochemical Oxygen Demand, COD = Chemical Oxygen Demand, TDS = Total Dissolved Solid, TSS = Total Suspended Solid, VSS = Volatile Suspended Solid, TN = Total Nitrogen, TP = Total Phosphorous, CFU = Colony-Forming Unit, FC = Fecal Coliforms, TC = Total Coliforms.

Parameter	Unit	Mean	Range
pH	-	7.1	6.1–8.4
BOD_5	mg L^{-1}	195	90–375
COD	mg L^{-1}	394	92–682
TDS	mg L^{-1}	377	280–597
TSS	mg L^{-1}	66	16–202
VSS	mg L^{-1}	39	-
Turbidity	NTU	80	37–173
TN	mg L^{-1}	9.7	8–11
NH_3–N	mg L^{-1}	4.1	0.6–9.2
NO_3–N	mg L^{-1}	0.8	0.4–2.5
TP	mg L^{-1}	5.5	0.9–11
FC	log10 CFU per100 mL	4.5	3.6–5.8
TC	log10 CFU per 100 mL	4.9	4.1–6

Much research has been performed on the longer-term effects of irrigation with (treated) greywater on soil characteristics and potential phytotoxicity due to elevated salt concentrations, leading to conflicting insights both in favor and against the practice [29–33]. Trace metals are present in relatively low concentrations, with the recent increase in plastic-based plumbing leading to even fewer instances of high zinc and copper concentrations [8,34]. However, longer-term irrigation with greywater may still lead to the accumulation of trace metals in soils exceeding regulations [35].

2.3. Microbial composition of greywater

Concerning microbial contamination, pathogen levels in greywater are generally reported to be considerably lower than in combined municipal wastewater and are typically similar to those present in secondary treated municipal wastewater (see Table 3) [40,41]. However, even this level of microbial contamination still entails significant public health risks while reusing untreated greywater [42]. Even after treatment, pathogens might pose a significant health risk during reuse practices, such as food-crop irrigation [43]. Important sources of pathogens in greywater include fecal contamination from washing practices (e.g., from bathing, showering, and the washing machine) and (incorrect) handling of contaminated foods (e.g., through the kitchen sink) [39,44]. Previous investigations on the presence of pathogens in raw greywater have indicated relatively high concentrations of *Salmonella* spp., *Pseudomonas aeruginosa*, *Staphylococcus aureus* (all ranging up to 10^4 CFU per 100 mL), *Legionella pneumophila* (ranging up to 10^5 CFU per 100 mL), and fecal coliforms (10^3–10^9 CFU per 100 mL), such as

Table 2
Prevalent elements in mixed greywater. Data adapted from Refs. [5,21,24].

Parameter	Unit	Mean	Range
Na	mg L^{-1}	182.2	7.4–480
Cl	mg L^{-1}	181	9–227
Ca	mg L^{-1}	162.08	31.6–437.61
S	mg L^{-1}	137.5	0.5–257
Mg	mg L^{-1}	55.69	5.30–140.01
K	mg L^{-1}	9.05	0.2–24
Al	mg L^{-1}	2.44	1.48–3.39
B	μg L^{-1}	600	-
Fe	μg L^{-1}	360	180–570
Zn	μg L^{-1}	64.4	55.3–77.8
Cu	μg L^{-1}	61.8	47.0–70.2
Ba	μg L^{-1}	18.2	15.5–21.8

Table 3
The microbial composition of mixed greywater. Data adapted from Refs. [26,36–39].

Parameter	Unit	Mean	Range
Fecal coliforms	log10 CFU per 100 mL	4.15	3.6–5.8
Total coliforms	log10 CFU per 100 mL	5.8	3–6.7
Fecal enterococci	log10 CFU per 100 mL	4.7	1.4–9
Escherichia coli	log10 CFU per 100 mL	4.1	3.6–6.3
Staphylococcus aureus	log10 CFU per 100 mL	0.3	-
Salmonella spp.	log10 CFU per 100 mL	3.5	0–3.9
Pseudomonas aeruginosa	log10 CFU per 100 mL	3.7	-

Escherichia coli (present up to 10^6 CFU per 100 mL) [26,36–39]. Furthermore, the presence of protozoa, helminthes, and other significant sources of microbial contamination has also been observed [39].

2.4. Xenobiotics

Xenobiotic organic compounds (XOCs) are artificially synthesized chemicals found in the environment, and municipal wastewaters mostly originate from household products, such as PCPs, preservatives, and detergents [45]. Greywater contains significant concentrations of XOCs, the majority of which reach concentrations up to 10 μg L^{-1} [46]. In the case of surfactants (often expressed as methylene blue active substances (MBASs)), the concentrations are often higher (>10 mg L^{-1}) [5].

Linear alkylbenzene sulfonates (LASs) are among the most prevalent domestically used surfactants and can be found in about 80% of household detergents. These chemicals comprise a hydrophobic alkyl chain and a hydrophilic head with a benzene ring and a sulfonate group that reduces the dissolved oxygen concentration by reducing the water's surface tension [47]. As such, these molecules contribute significantly to the total presence of detergents in greywater (in shower and washing machine wastewater in particular), with concentrations of up to 1 g L^{-1} in washing machine wastewater [48–50] and concentrations of 1–10 mg L^{-1} in domestic sewage [51]. Moreover, the presence of LASs in wastewater can cause problems such as a reduction in bacterial respiration rates and biodegradation [52]. In addition, A COD/BOD_5 ratio of up to 4 has been found for light greywater streams, which can be attributed to a large presence of nonbiodegradable chemicals [5,44,53]. Elevated concentrations of pharmaceuticals and biocides have also been reported in greywater [46,54,55]. The presence of many XOCs thus poses significant human health risks related to the potable reuse of greywater and consumption of plants irrigated with reclaimed greywater [56,57]. Furthermore, the environmental persistence of some XOCs poses a potential threat towards terrestrial and aquatic ecosystems as well [45].

2.5. How the variability of greywater influences treatment efficiency

In terms of quantity, as previously mentioned, greywater accounts for a large fraction (75–90%) of the total domestic wastewater flow, with a per capita production of 60–200 L day^{-1} in developed countries. Greywater production also temporally matches domestic water consumption, following a diurnal pattern [8,58,59]. The temperature of greywater can fluctuate substantially, ranging from common tap water temperatures (range 10–20 °C) to shower and bath (20–40 °C) temperatures and occasionally to high-temperature peaks (>60 °C) coming from the dishwasher and washing machine. These temperature fluctuations may affect treatment efficiencies and may also call for additional precautions against scaling [5,60].

Greywater characteristics are thus highly variable and mainly depend on the collected greywater flows, climatic and sociocultural influences, and the original water source [9]. This underscores the necessity of tailoring greywater treatment solutions to local circumstances. In order to select certain greywater characteristics, for instance, to improve reclaimed greywater quality, individual greywater flows can be excluded from reuse. A study by Friedler [25] showed that pollutants in combined greywater were unevenly spread among different household applications. The high concentrations of contaminants were found in kitchen sinks (42% of COD, 58% of VSS), and washing machine effluent (22% of COD, 37% of PO_4^{3-}, 40% of Na) only constituted 13–26% fractions of the total daily discharge of greywater.

3. Technologies for greywater treatment

3.1. Biological treatment technologies

3.1.1. Biofilm technologies

Fixed-bed biofilm technologies, such as the Rotating Biological Contactor (RBC), which consists of stacks of rotating discs (Fig. 2a), have been widely used to treat household greywater as they allow for high flexibility and system reliability [61]. Pathan et al. [62] obtained 50% organics (BOD_5) removal with a 40% immersion in greywater, and the organic removal efficiency improved to >90% with an organic loading rate at 5.0 g BOD_5 m^{-2} day^{-1} when using multi-stage RBC [63].

Moving-bed biofilm reactors (MBBRs) use free-moving biocarriers (with large surface areas of 500–3000 m^2 m^{-3}) for organics and nitrogen removal (Fig. 2b) and are also widely applied in municipal wastewater treatment [64]. MBBRs have also been tested for the treatment of greywater. For instance, Al-Wasify et al. [65] used an aerated MBBR to treat greywater in Egypt and achieved an effluent quality fit for irrigation purposes. In Brazil, a pilot-scale MBBR was installed to treat greywater (influent 247 mg per L COD) and maintained 70% COD removal [66]. Another study conducted in Germany by Saidi et al. used a multistage MBBR system to treat greywater (8–11 m^3 d^{-1}) with an HRT of 1.2–1.6 days. The system consisted of ten tanks, each with a capacity of 1.3 m^3. The first eight tanks and the 10th were MBBRs, while the 9th was a sedimentation tank, achieving 94% COD removal overall and yielding 22 mg L^{-1} of COD in the MBBR effluent [67]. MBBR technology, in combination with other approaches, has also been commercialized for household greywater reuse.

The membrane biofilm reactor (MBfR) method combines biofilm technology with a membrane unit (see section 3.1.2) and allows biofilm formation by supplying a gaseous substrate through a porous membrane. This technology is also called a membrane-aerated biofilm reactor (MABR). An MBfR has been shown in the literature to be able to remove organic and inorganic contaminants, such as surfactants and nitrogen, in greywater [50,68,69]. Zhou et al. [50] reported an MBfR successfully achieved 93.8% of surfactant removal and 80% of TN removal at an organic loading rate of 4.26 g COD m^{-2} day^{-1}.

3.1.2. MBR technologies

The MBRs can produce excellent effluent qualities by controlling hydraulic retention time (HRT) and solid retention time (SRT) independently and enabling the filtering of suspended solids [70,71]. In most cases, these systems are aerated; thus, the removal process is aerobic. A pilot-scale MBR has been operated at 2 h HRT to treat the greywater generated from households with more than 80% of COD removal efficiency irrespective of the sludge age [72]. When porous membranes are used, undetectable coliform levels cannot be guaranteed in the permeate produced by the MBR [17,71], however. This and other particles coming through cause severe biofouling on reverse osmosis (RO) systems downstream. To combat this, biocarriers can be combined with MBR to yield more than 95% surfactant removal [73–75]. Anaerobic membrane bioreactors (AnMBRs) have also been tested, and these combine an anaerobic bioreactor with membrane filtration, as shown in Fig. 2c. AnMBRs reduce operational energy demands significantly because aeration is not required while producing renewable energy in the form of methane. Since employing AnMBR to treat greywater is nascent compared to aerobic MBR, there is limited evidence to judge its performance in a decentralized set up, however.

There has been considerable attention to surfactants that might limit microbial activity in anaerobic circumstances [76]; concentrations of only 18.9 and 6.3 mg L^{-1} of LAS have been found to inhibit acidogenic and methanogenic activities, respectively, and micro-aeration in AnMBR allows disintegration of aggregated biomass, thereby enhancing the biodegradation of anionic surfactants [77]. A linear relationship between fouling rate and LAS concentration has also been observed in the AnMBR treatment of sewage [78], highlighting the fouling risk these compounds represent. Other approaches to reduce membrane fouling in AnMBR include dislodging the cake layer under high cross-flow velocity on the membrane surface or via biogas sparging along the membrane surface, which can be applied to mitigate the fouling rate [79]. This sparging is decreased in anaerobic fluidized bed membrane bioreactors (AFMBRs), limiting energy demand to 0.05 kWh m^{-3}, accomplished using biocarriers, such as granular

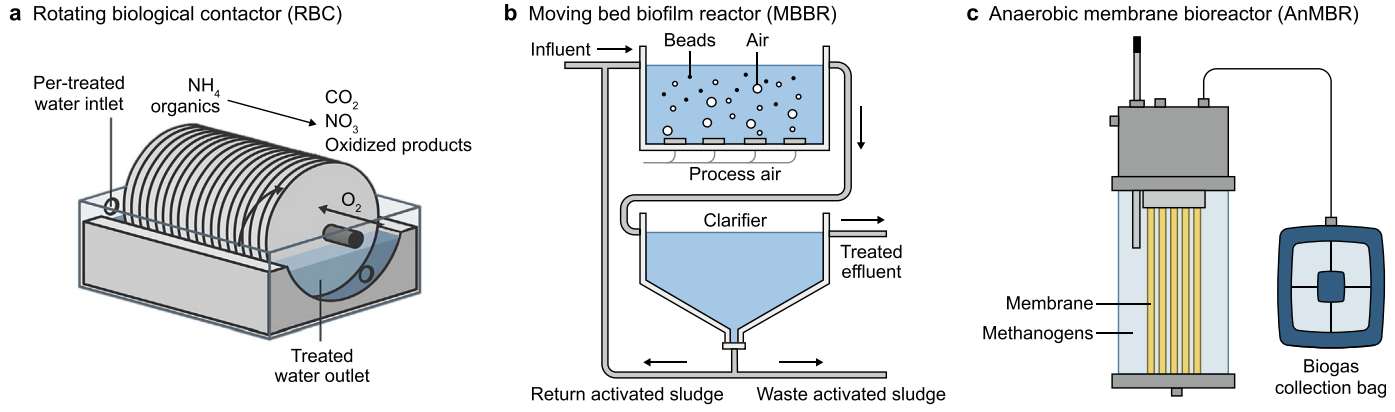


Fig. 2. Schematic representation of rotary biological contactor (**a**), moving-bed biofilm reactor (**b**), and anaerobic membrane bioreactor (**c**) for biological greywater treatment technologies.

activated carbon (GAC), fluidized by recirculating a bulk suspension in the absence of biogas sparging [80].

Membrane-less anaerobic systems such as anaerobic filters or even up-flow anaerobic sludge blanket reactors (UASB) have also shown up to 60–70% BOD_5 removal efficiency [81,82]. This is lower than with membrane filtration alone but more straightforward from an operational perspective. Anaerobic filters have been deployed for greywater treatment in public areas such as airports and have also been integrated with ultraviolet (UV) disinfection as a post-treatment to meet international reuse recommendations [81].

3.1.3. Comparative analysis of treatment technologies

A key issue for greywater reuse is the variation in greywater characteristics depending on the demography, seasonal variations, and living standards. Thus, there is no single universal treatment strategy. Thus, modular architecture for greywater treatment allows for a wide range of options that can be applied as fit-for-purpose deployments and adapted, for instance, to changes in demography [83]. The overall biodegradability of greywater can be characterized by its COD/BOD_5 ratio, and conventional wastewater measurements on untreated greywater generally demonstrate favorable COD/BOD_5 ratios for biodegradation [84].

A detailed comparative analysis of the various treatment strategies employed in different case studies is presented in Table 4. Laundry greywater contains high concentrations of chemical compounds (such as soaps and oils) as well as a significant amount of non-biodegradable fibers. This leads to a considerable increase in the COD/BOD_5 ratio, thereby discouraging the use of traditional biological methods. The preferred treatment method in most cases circles around physio-chemical techniques such as coagulation and ultrafiltration (UF) methods, and these methods yielded a comparatively higher quality treated effluent (laundry wastewater) with the removal of BOD_5 of up to 94.33%. Bathroom greywater can contain organics like hair, and fecal matter along with surfactants and XOCs found in personal care products. Treatment here thus depends on the end use of the treated water and may require post-processing. An extensive review of the efficacies of various treatment strategies for greywater and the impact of different operating parameters has been performed by Khalil and Liu [20], in which the authors concluded that an improved characterization of greywater could help determine the appropriate treatment strategy (although this may be difficult to implement in practice).

As seen in Table 4, two-stage water treatment systems were shown to have a better performance than other singular treatment strategies. However, with current advances in membrane and electrochemical technologies, the use of single-staged MBR systems could suffice to reach required effluent standards. The technical feasibility of greywater treatment with modular construction offers great flexibility in adapting to a catchment area's dynamic development.

3.2. Physico-chemical methods

3.2.1. Membrane filtration

Membrane reactors appear to be ideal for decentralized greywater treatment due to their small footprint and the fact that it is not sensitive to toxic pulses or highly uneven flows. Microfiltration (MF), UF, nanofiltration (NF), and RO membranes can be tailored for greywater treatment depending upon the target contaminants to be removed. However, the biggest disadvantage is that a concentrate is made, and nothing is actually removed by using the membranes themselves. With an MF membrane, particle materials are rejected by membrane filtration almost completely, generating suitable permeate qualities for immediate water reuse purposes. Increasing the transmembrane pressure (TMP) or feed flow rates tend to increase membrane rejection because the cake layer formed on membrane can play a role as a secondary membrane [88]. Indeed, porous membranes, such as MFs, provide relatively small rejection efficiency associated with organic impurities compared to NF and RO membranes, thus requiring suitable post-treatment [89]. This issue is not present with MBR, however, as smaller organic compounds are typically almost completely removed in this case.

Membrane fouling is unavoidable and also adds a barrier to greywater conveyance [84,89,90] as well as a requirement for cleaning strategies, including chemical additions. With greywater, a membrane fouling rate is typically proportional to organic foulant

Table 4
Performance evaluation of various strategies for greywater treatment.

Treatment technologies	Parameters/Permissible limits[a]	Typical values	Effluent concentration	Removal %	References
Coagulation and sand filtration (Laundry wastewater)	BOD_5 (mg L^{-1})/<10	**Refer Table 1**	17.00 ± 8.00	94.30	[85]
RBC	TSS (mg L^{-1})/10		2.00 ± 0.50	95.80 ± 1.00	[86]
	BOD_5 (mg L^{-1})/<10		4.50 ± 0.30	95.00 ± 0.30	
	COD (mg L^{-1})/100		13.00 ± 1.20	95.70 ± 0.40	
	Total N (mg L^{-1})/10		0.55 ± 0.10	93.90 ± 1.60	
Submerged MBR	pH/6–9		6.90	-	[23]
	COD (mg L^{-1})/100		45.00	88.00 ± 9.50	
	Total N (mg L^{-1})/10		3.57	88.00 ± 7.30	
	Total P (mg L^{-1})/0.1		0.74	56.00 ± 18.00	
	Anionic surfactant (mg L^{-1})		4.58	90.00	
MBR	BOD_5 (mg L^{-1})/<10		4.00 ± 2.00	97.00	[75]
	COD (mg L^{-1})/100		16.00 ± 4.00	91.00	
	Total N (mg L^{-1})/10		2.18 ± 0.30	58.00	
	Total P (mg L^{-1})/0.1		0.05	88.00	
UASB	BOD_5 (mg L^{-1})/<10		96.95	67.50	[87]
	COD (mg L^{-1})/100		165.42	57.80	
	TKN (mg L^{-1})/2		28.00	14.10	
	Total P (mg L^{-1})/0.1		10.45	78.40	
UASB + MBR (Two stages)	BOD_5 (mg L^{-1})/<10		6.10	97.40	[87]
	COD (mg L^{-1})/100		8.50	97.80	
	TKN (mg L^{-1})/2		0.95	94.40	
	Total P (mg L^{-1})/0.1		0.05	89.70	

[a] WHO Guidelines for Drinking water quality (WHO, 2006).

content, as discussed above [90]. In general, membrane fouling caused by organic compounds is not removed easily by permeate backwashing because of membrane pore blocking. To reduce the fouling, a ceramic diffuser can be installed underneath the hollow-fiber MF membrane (0.1 μm) to treat greywater [91], where the aeration provided by the ceramic diffuser causes a scouring action to clean the membrane. The use of a ceramic membrane thus has great potential for greywater treatment over polymeric membranes due to its excellent chemical resistance and membrane hydrophilicity.

In addition, membrane functionality can be improved by integrating with various unit technologies, such as chemical oxidation. For instance, a photocatalytic membrane reactor with TiO_2 particles under UV illumination has already been applied to treat greywater [92]. However, a reconcentration step must be considered here in a subsequent process to recover the catalysts such as TiO_2 particles. Otherwise, they may escape from this hybrid membrane reactor [93].

3.2.2. Sorption and ion exchange

Elucidating the mechanisms of the adsorptive behavior of organic pollutants present in greywater is an area of intense research. The charge of adsorbents, such as activated carbon, may play an important role in the adsorption capacity of surfactants from greywater. For example, LASs can be adsorbed into positively charged adsorbents to yield more than 90% removal efficiency, which is more than negatively charged or nonionic resins allow (0.6–1.7 vs. 0.02–0.6 g LAS g^{-1}) [16,94], and here the solution pH above or below the point of zero-charge of the adsorbent is a critical parameter. With greywater, adsorption equilibria can be described by Langmuir isotherms [95]. Thus, the adsorption capacity with respect to the organics present in greywater may be limited by the monomolecular layer formed on the adsorbent without interactions between adsorbate molecules [94], as illustrated in Fig. 3a.

Adsorbents can also be used as biofilter media to induce biodegradation and physicochemical adsorption [95,96]. After the adsorption sites of GAC are saturated by organics, bacteria subsequently accumulate to form biological activated carbon (BAC). In an integrated MBR-BAC process, biodegradation has already been found to be the most dominant organic removal mechanism, particularly in the upper region of the filter bed [96]. Nevertheless, an overall removal efficiency of less than 26% based upon greywater TOC was observed [95]. A similar level of TOC removal efficiency (25–42%) has been observed by operating a pilot-scaled BAC filter in greywater treatment showing that these systems perform less than their fully biological analogs described earlier [95,97].

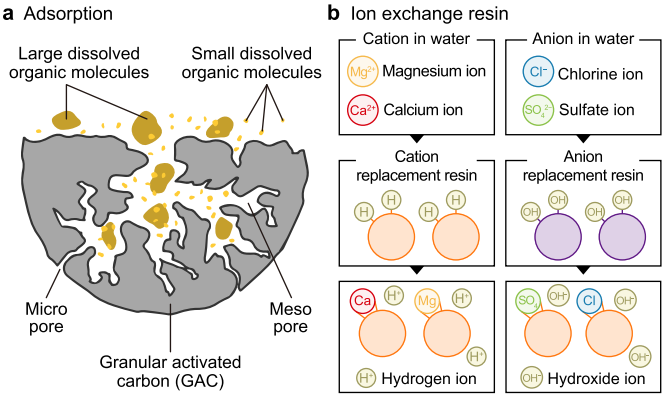


Fig. 3. Removal mechanisms of organic molecules and ionic species of greywater with GAC adsorption (**a**) and ion exchange resin (**b**).

Natural zeolites are also considered to be adsorbents in greywater treatment due to their excellent ion-exchange ability and adsorption capacities, as illustrated in Fig. 3b. The aluminum (Al^{3+}) atom substitution for silicon (Si^{4+}) in the zeolite framework generates a negative charge for high cation-exchange capacity [97]. About 97% of NH_4^+-N can be removed from greywater through natural zeolites, and adjusting the solution pH from 4 to 6 determines the amount of removal of NH_4^+-N more than other parameters [98]. Magnetic ion exchange resin with strong-base functional groups has also been designed to remove dissolved organic carbon in greywater [99], but here combining coagulation is necessary to prevent the agglomeration of resin [99,100].

3.3. Nature-based solutions

Nature-based solutions (NBSs) have also been investigated for greywater treatment due to their inherent advantages of low-energy demand and organic removal efficiency [101]. Constructed wetlands (CWs) may be considered the cornerstone NBS for greywater treatment, whereas other available NBS, like green roofs and walls, can also mimic the technique of conventional CW treatment processes [6]. Both biodegradation and physicochemical functionality, such as precipitation, filtration, and adsorption through CWs, improve organic removal efficiency [14,102]. For example, Collivignarelli et al. [103] observed 89% COD removal through CW treatment of greywater. Planted wetlands lead to better COD removal efficiencies than unplanted set ups through oxygenation of the beds, causing aerobic degradation in the root zones [104] and in nutrient uptake. Thus, CWs may be suitable as a post-treatment for biological greywater treatment [105].

CWs can also efficiently remove nutrients present in greywater [106]. Wetland plants can assist with the removal of nitrogen and phosphorus because these can be adsorbed into their roots [102]. Fecal coliforms can also be removed by CWs (94–98%) [107]. Nevertheless, the effluent in CWs typically needs further disinfection to meet reuse standards [103,107]. CWs have also been successfully utilized to remove propylene glycol (PG), and trimethyl amine (TMA) from different sources of greywater [102,107,108], and one study showed that sodium dodecyl sulfate (SDS), a representative anionic surfactant, frequently found in greywater, was removed at 94% by CWs alone [108], which is a better rate of removal than MBRs [102]. Finally, the substrate, as well as plant litter, can decompose inside the wetlands [109], and effluent quality can be maintained by controlling its hydraulic retention time [109,110].

4. Challenges to greywater reuse

4.1. Tailoring treatment processes for greywater reuse and quality control

The superior quality of greywater relative to mixed domestic wastewater is the basis for an important argument in favor of increased greywater recycling and reuse. However, as discussed in the introduction, elevated levels of contaminants, such as organic micropollutants, salts, and pathogens, require the need for greywater treatment, even for low-quality applications, such as irrigation. When a high degree of circularity is pursued in a (small-scale) water system, excessive accumulation of these contaminants must also be considered [111]. Furthermore, variability in greywater quality necessitates a certain level of robustness in the treatment process. As was illustrated in previous sections, sufficient attention must be paid to disinfection practices in order to tackle (in-line) microbial regrowth, for instance, by applying in-line (e.g., in contact

chambers or through residual disinfectants) or post-line disinfection (e.g., UV disinfection) [5]. Particular attention is required when direct human exposure to the reused water is conceivable through accidental ingestion of treated greywater or inhalation of aerosols. However, if greywater treatment follows existing guidelines, epidemiological research suggests no significant health impact [112,113].

Greywater covers a wide range of contaminants, including particulates, colloidal materials, microbiological contents, dissolved organics, and inorganics. The compounds present in the water vary from source to source and depend on lifestyle, customs, installation types, for example, kitchen, bathroom or laundry, and use of chemical household products [55]. The complexity of contaminants introduced by various human activities brings an additional challenge to producing high-quality reclaimed water from greywater beyond conventional processes. So far, a large range of technologies has been developed for greywater reuse, from simple staged processes consisting of prefiltration followed by disinfection to advanced physicochemical and biological processes [99], as discussed above. Nevertheless, technologies for greywater treatment suffer from the variability of feed and shock loading such that these processes need to be optimized and intensified for greywater reuse purposes. For water reuse and energy production, system flows throughout the greywater treatment process should also be designed holistically. For example, organics present in greywater can be maintained at a high level in the concentrated flow due to membrane filtration, which can be treated anaerobically for bioenergy recovery.

4.2. Legal framework

In many countries, a lack of a legal framework for greywater management obstructs the development and implementation of wastewater reuse systems. This is especially the case for urban reuse purposes or when considering specific household applications, as a direct personal judgment of target water qualities is often required. On greywater reuse specifically, guidelines are often based on recommendations by inter-governmental organizations, such as the World Health Organization, covering greywater reuse for agricultural irrigation [114], and the National Sanitation Foundation (NSF/ANSI standard 350), which provides water quality guidelines for nonpotable urban applications (toilets and irrigation) [115]. Water quality guidelines often focus on a small range of aesthetic (e.g., turbidity and BOD) and hygienic (e.g., total coliforms) parameters as well, and no international reuse guidelines for the direct potable reuse of greywater have been introduced as of yet.

For existing reuse guidelines, the water quality parameters considered and the categorization of reuse options are not generally in sync between nations and organizations, which hampers effective comparison between the policies of the two [116,117]. In Europe, a new regulation has recently been approved on the minimum requirements for agricultural reuse of wastewater streams that will come into force in June 2023 [118]. In addition, plumbing codes in California, USA [119], Chile [120], and Queensland, Australia [121] already provide regulations and guidance on the installation and operation of (closed-loop) greywater reuse systems.

4.3. Monitoring and controlling greywater systems

As greywater reuse is most often considered on a decentralized and small scale, a faster response to treatment process malfunctions is required than for centralized and larger scale systems. This requires rapid, preferably online, monitoring practices. No single parameter sensor can indicate the water quality as a whole, and as such a multi-parameter approach becomes necessary [122]. In reuse systems that apply membrane technology, membrane integrity could, for instance, be monitored by continuously tracking turbidity, TOC, conductivity, and/or sulfate levels as key parameters [123]. Moreover, fluorescence spectroscopy can effectively detect the presence of low concentrations of organic compounds in effluent [124]. Today, the possibility for online detection of microbial contamination in decentralized water systems is limited, but microbial fingerprinting techniques are promising [125]. However, these technologies are not yet cost-efficient in smaller-scale installations.

Another obstacle to adopting reuse systems is the lack of effective and standardized testing procedures to evaluate health and environmental risks associated with specific treatment systems for specific (micro-)pollutants [126]. Legislation surrounding greywater reuse is often implemented in a one-size-fits-all manner, pinning down high-quality standards for reuse and thus simplifying compliance and control and minimizing perceived risks by the public. However, this ignores the benefits of a fit-for-purpose approach to decentralized water recycling and discourages certain reuse applications, and leads to potentially unnecessary treatment costs [114,127].

4.4. The consumer perspective

The consumer perspective is another crucial factor before implementing greywater reuse systems. This perspective sits on a more local and household-level scale. Decentralization (at least partly) shifts responsibility from larger institutions, such as public water providers, to the individual level, in certain cases demanding behavioral changes from users that range from choices of detergents to the use of water itself.

In many cases, building developers are the primary client for greywater systems. However, they are often influenced by their own end customer and their requirements in a more direct manner. Consumers themselves have been shown to have varying degrees of acceptance of greywater reuse systems, depending on a wide range of factors. One major factor in public acceptance of greywater reuse is the degree of human contact with the reclaimed water, with the consumer being most reluctant to accept potable reuse [128]. In light of this, the “yuck-factor” is often mentioned, a term describing the instinctive reaction of disgust associated with reclaimed water, independent of the actual water quality [129].

However, more reasoned arguments also determine consumer acceptance of greywater reuse. For example, economic incentives, such as cost savings on water expenditures, lead to a higher degree of acceptance towards water reuse practices, and this sits alongside evidence that reducing personal environmental impact can be a strong driver of acceptance [130–132]. Trust in authorities also determines the acceptance of water reuse [128].

Some authors also consider “social justice” in terms of water equity, another important aspect that governs the social acceptance of decentralized technologies [2]. Additionally, research by Garcia-Cuerva et al. [130] indicates that regions that have recently experienced a drought have a higher percentage of reclaimed water supporters. Another important factor is the quality of the operational regime that can be put in place, which entails maintenance aspects and frequency of system malfunctions (e.g., unpleasant odors), which has been shown to influence acceptance to a large extent [133]. When it comes to the communication necessary to increase public acceptance of greywater reuse, a mix of addressing all of these concerns is recommended as acceptance is to a large extent influenced by both [134], and addressing an individual's normative beliefs, both social and personal, has been shown to

influence behavior and acceptance [132,135].

However, consumer perception of centralized water supply systems might be the most important factor that influences the perception of decentralized systems. Since the dawn of centralized water supplies, incidents with contaminants and deteriorated water quality have occurred regularly [136], negatively influencing public trust in tap water [137].

5. Opportunities for greywater reuse

5.1. The potential for high water savings: the first and foremost driver of greywater treatment

Water savings and the resulting alleviation of stress on water bodies, together with the associated cost reductions, are key arguments in favor of greywater reuse, and this can be attributed to the large availability of greywater, up to 90% of all domestic wastewater produced [59]. Key water savings come from avoiding water transport via piped networks, which is of special interest, particularly in large, growing cities. Greywater reuse for toilet flushing alone could allow for water savings of up to 30% for households and up to 60% for office buildings [138]. Additionally, considering reuse for garden irrigation can increase savings by 40% for households [139]. Considering average wastewater quantities in developed countries and assuming complete reuse of all greywater streams, total water savings of up to 80% could theoretically be achieved [8].

Alongside the available quantities of greywater, recycling is also preferable because greywater production temporally matches water consumption, in contrast to variable rainwater harvesting. The greywater flows are available for reuse depending on the number of occupants and their associated water use, with a higher number of users leading to more stable greywater production and use, although flow equalization remains crucial. For this, storage of treated greywater is an important point of attention as varying use (e.g., through toilet flushing) can certainly temporarily exceed the water flow throughout the treatment system. Consequently, water savings depend greatly on the considered storage options, with larger storage basins leading to less overflow and larger buildings benefiting from more equalization. Furthermore, as mentioned earlier, storage systems also have to be supplied with a means of disinfection.

With increasing reuse, another important concern is the increased likelihood of odor, piping blockage, corrosion, and sedimentation in the sewer network due to more concentrated wastewater streams, as the less concentrated streams are the most suited to be reused (e.g., for toilet flushing). Research by Penn et al. [140,141] shows that in terms of the effect of greywater reuse on the water grid, there is little evidence to suggest that there is an increased risk of piping blockage, except in more upstream pipes where the lower flow rates decrease the ability to carry solids along. Greywater reuse has also been shown to flatten diurnal trends in water flows across the grid. Associated lower wastewater flow rates through the sewer system in dense urban areas would also prevent the necessity of increasing sewer pipeline sizes, thus avoiding the large associated costs.

5.2. Energy savings and sustainability

The water sector is known to have a considerable energy consumption and greenhouse gas (GHG) footprint and is also extremely vulnerable to the effects of climate change [142]. The energy cost to transport water in centralized water management systems in the United States is estimated to be, on average, four times the energy required for the actual water treatment and is as high as 20 times in California, with treatment and transport making up 4% of the nation's total electricity consumption [143,144]. An additional energy cost of 2.5 kWh m^{-3} has been estimated for the transport of water over a distance of 100 km with a 250 m height increase [145]. When energy requirements for pumping in centralized water supply systems are high, small-scale greywater reuse especially has the potential to reduce energy consumption for water provision significantly [146], provided the greywater system's pumping costs do not exceed the energy savings.

Due to coming climate change mitigation measures in the water sector, water supply costs are expected to increase globally [147]. This indicates the importance of including a sustainability assessment before the introduction of new approaches in water management. For greywater reuse systems, the question of (long-term) sustainability in terms of energy and material use and GHG emissions is subject to a rapidly growing body of research. Here, life cycle assessments (LCAs) have been frequently used to assess the environmental impact throughout the entire life cycle of the technology and can be used ex-ante to steer system design and policy choices [148,149]. In terms of energy consumption, the principal advantages of decentralized water management are (1) a reduction in energy requirements for the conveyance of water, (2) the possibility of thermal energy recovery as human activities increase the water temperature, and (3) allowing source separation between energy-poor and energy-concentrated water streams.

5.3. Saving energy within buildings

Since tackling the energy use of single buildings forms an important objective in decreasing total energy use, looking into energy recovery solutions at this scale is worthwhile [150]. Of the total household energy consumption in the European Union, 14.8% is used to heat water [151]. Moreover, more effective insulation of buildings could lead to a being used to heat water. In this case, thermal energy recovery of greywater may allow for household energy savings of up to 40% [152]. As a whole, however, when decentralized greywater treatment units are installed, the total household energy consumption is expected to increase [153].

In Table 5, the energy demand, advantages, challenges, and costs of several greywater reuse systems from the literature are presented. For reference, centralized water management, including potable water production and distribution and wastewater collection and treatment, generally has an energy consumption of 0.58−2.11 kWh m^{-3} [154]. For energy savings or production in decentralized greywater treatment, system design must be holistically considered. For instance, for MBRs, many opportunities exist to meet multiple water-quality criteria in greywater treatment, but more than 50% of the energy requirements are for aeration for microbial growth and membrane fouling reduction. Low energy fouling control and its optimization in MBR systems require more study [155].

In terms of energy recovery, organics present in greywater can be maintained at high levels in the concentrated flow when membrane filtration is used, after which it could be treated anaerobically to recover bioenergy in the form of methane. Toward this end, the AFMBR discussed above is a promising technology [80], provided there is a need for methane on-site or at least a means to avoid its emission or to capture it. Here again, though, membrane fouling needs to be controlled effectively and economically. Although the energy produced by the AFMBR may be satisfied by using only a small portion of the gaseous methane energy produced [80], further research is needed to address methane yield per the unit of biodegradable organics in greywater treated by AFMBRs.

Table 5
Energy demand and operational characteristics of greywater treatment systems.

Technology	Scale (m^3 day^{-1})	Energy demand (kWh m^{-3})	Efficiency	Cost (€ m^{-3})	Advantage	Challenges	References
Membrane bio-reactor	3-30	5.6-6.1[a]	BOD_5 = 96-98%, COD = 90-92%, TN = 49-63%, TP = 88-90% [75],[b]	-	Low footprint, good biomass retention for increased organic removal	Energy-intensive. High operating and maintenance costs are required. Frequent fouling problems and chemical cleaning are needed.	[156]
Membrane bio-reactor + Chlorination	1.5	2.9	COD = 90%, BOD_5 = 95%, SS = 98%, Surfactant = 98%, *E.coli* = log4.	5-6	Low footprint, good biomass retention for increased organic removal, extra disinfection to avoid health risks, compliance with water standards	An additional cost of chlorination apart from the challenges mentioned for membrane bioreactors	[155]
Integrated fixed-film activated sludge	0.03	-	COD = 92.52%, LAS = 94.24%, Oil and grease = 90.07%	-	Higher resistance to organic and hydraulic loading than conventional activated sludge	High construction and maintenance cost, expert knowledge required, high energy consumption due to aeration	[157]
Aerobic fluidized bed reactor	0.14	-	COD = 73%, Anionic surfactant = 57%, TN = 42%, TSS = 66%, DOC = 52%	-	Excellent mixing and high mass transfer for good biodegradation, fluidized materials accommodate microbial growth	Expert knowledge is required for maintenance and operation.	[158]
Moving bed biofilm reactor + UV disinfection	1	2.4	COD = 93%, BOD_5 = 97%,	-	Higher biomass concentration, higher organic removal, lower hydraulic residence times, sound mixing and mass transfer, and disinfection ensure microorganisms removal	Manual monitoring is required. Insects are attracted to biofilm reactors. Biocarriers can wash out of the reactor over time.	[159]
Rotating biological contactor	0.0043-0.3000	1.2	COD = 84-89%, BOD_5 = 94%, TSS = 90%, TKN = 75%	0.1	Low operational cost, low technical personnel requirements, good organic removal	Limited removal of pathogens and extra filtration is often needed to filter biofilm particles.	[160]
Gravity-driven membrane bioreactor	0.0014-0.0029	0.02-0.04	TOC = 80-95%	-	No backwashing or chemical and physical cleaning are required, and low energy requirement	Low permeate flux, membrane fouling	[161]
Nano-filtration membrane treatment	52	10	COD = 98.0-99.7%, TOC = 97.7-99.6%, Salinity = 70%, SS = 100%, *E. coli* = 100%	5-6	Higher rejection efficiency, potent for the separation of small organic molecules, used in the desalination process	Prone to membrane fouling, high operating cost involves membrane cleaning, an energy-intensive process	[162]
Moving bed biofilm membrane reactor	0.2	1.26-4.42	COD = 64%, BOD_5 = 95%, TSS = 98%, TN = 79%, PO_4-P = 91%, NH_4-N = 78%	-	Higher biomass concentration, higher organic removal, lower hydraulic residence times, sound mixing and mass transfer, lower membrane fouling	Manual monitoring is required. The choice of bio-carriers is important for fouling reduction and microorganism growth.	[163]
Electrocoagulation	-	6.89-15.5	COD = 31-98%, TP = 80-94%, TN = 47-83%, TSS = 99%	-	No chemicals are needed, and efficient removal of suspended solids	High energy requirement, high operational cost	[164]
Horizontal flow constructed wetland	0.023-0.07	-	COD >89%, BOD_5 > 88%, TSS >85%, TP = 50.7-54.6%, TN = 42.5-77.6%	-	Good organics removal, low energy requirement, low operating cost, serve aesthetic purposes.	High HRT, limited removal of pathogens, and a high amount of space is required	[103]

[a] Highest energy consumption is associated with the smallest scale (increasing economies of scale).
[b] Data are derived from a separate study but for a similar type of treatment setup.

5.4. General sustainability assessment

In terms of direct and long-term environmental impacts, greywater reuse systems are a double-edged sword. Masmoudi Jabri et al. [159] compared the direct reuse of greywater to discharge into the environment followed by the same treatment on the scale of a residential building through LCA and found that reuse significantly decreased toxicity effects in the environment (by 1.6–16.2%) and eutrophication potential (by 17%). However, GHG emissions (by 2%) and human toxicity effects (by 51.8%) increased with greywater reuse. The latter was mainly due to the footprint of polyvinyl chloride piping, which was necessary to transport the treated greywater throughout the building. In another study, Kobayashi et al. [165] found that local greywater reuse could reduce GHG emissions, eutrophication potential, and human health risks for community water provision compared to a centralized water supply, with positive effects increasing with scale (5–3500 people served). They also emphasized that the construction phase was found to be the major contributor (40–90%) to all assessed impact categories.

In terms of environmental impacts, nature-based solutions in greywater reuse have generally been deemed to be the least impactful [6], but they evidently require the largest land footprint. Furthermore, when considering decentralized reuse options, the local energy source used is a major contributor to the total environmental impact of the system [148,166], highlighting the importance of connecting clean energy sources to decentralized water management. Finally, future research may address the impact and resource requirements of greywater reuse systems and compare them to centralized alternatives, as the sustainability of such decentralized systems has been shown to be heavily context-specific.

6. Conclusions

In light of global challenges, such as climate change and rapid urbanization, improving the robustness and sustainability of water management is of critical importance. For this reason, the available knowledge on greywater, its reuse potential, and state-of-the-art of greywater reuse technologies was collected and discussed in this review. The main arguments in favor of considering local greywater reuse can be categorized as follows: (1) high availability of greywater quantities, e.g., matching the presence of users in buildings; (2) a generally lower degree of pollution, entailing lower treatment needs than general domestic wastewaters; and (3) advantages related to high energy content and sustainability.

The key obstacles to reuse were found to be (1) the presence of challenging greywater quality characteristics, which may entail human and environmental health risks; (2) a lack of a legal framework for greywater management; (3) the assurance of good monitoring practices to guarantee consumer safety; and (4) negative consumer perspectives on such reuse practices. A particular focus was provided on the energy consumption of greywater treatment systems and the potential for energy savings, showing a high potential for energy efficiency, even at small scales. Furthermore, we showed that a shift of responsibility from centralized (e.g., government) to decentralized (e.g., individual households) control could lead to increased monitoring and control of the necessary treatment and a greater focus on the importance of consumer perspectives. Overall, we have a positive outlook on integrating extensive greywater reuse in water management. A holistic view of local management needs and context-specific implementations of reuse solutions may allow for a more robust water system as a whole.

CRediT authorship contribution statement

Arjen Van de Walle: Investigation, Writing-original draft. **Minseok Kim:** Investigation, Writing-original draft. **Md Kawser Alam:** Investigation, Writing-original draft. **Xiaofei Wang:** Investigation, Writing-Review & Editing. **Di Wu:** Investigation, Writing-Review & Editing. **Smruti Ranjan Dash:** Investigation, Writing-Review & Editing. **Korneel Rabaey:** Conceptualization, Investigation, Writing-Review & Editing. **Jeonghwan Kim:** Conceptualization, Investigation, Writing-Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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A Critical Analysis of Feasibility of Mixing Waste Water in Cement Mortar and Concrete

Suma. Yarlagadda, SS. Asadi, Ch. Nithin Kumar Reddy

Abstract: ***The aim of this paper is to find the probability of using wastewater obtained from water plants situated in private structures. For the purpose of case study water treatment plants are selected in the region of Kankipaduof Krishna District of Andhra Pradesh. Each plant produces about 3600 to 4100 L/day water is being sold to the consumers of the area. Each plant is producing about 67% of wastewater in this process. Hence 91,500 lts/day is generating as waste water in the municipality region. All plants extract ground water for production and then treat them through Reverse Osmosis Process. The waste water so generated is drained off. Physical and chemical investigation were carried out on 14 water treatment plants. Out of which 10 typical plants were selected namely ChaitanyaJunior College (CC), Punadipadu (PC) area, Near Shivalayam (SC) and Bank colony (BC),in view of the convergences of constituent's in wastewater investigated by chemical and physical examinations. Performance of chose wastewater plants on the properties for example setting times, flexural strength, and compressive strength of OPC were performed in lab and contrasted them with test specimens using Distilled Water as blending water. No noteworthy changes were seen in the initial setting time yet considerable change has seen in the final setting time. Concrete properties like Slump & Density had notinfluenced by mixing water [2]. No major change has observed in compressive strengths (90 days) in four selected plants contrastedwith that of test specimens. The XRD was carried out to observe the main compounds in the hydration process.***

Index Terms**: *Water Crisis, Waste water, Chemical analysis. Use of recycled water in OPC.***

I. INTRODUCTION

Water is life that is why it is called " Jeevan " in Sanskrit. Water sustain all life, ecosystems and human activities. Although water seems to be a common commodity, it is scarcely available on earth and has no substitute [1]. Globally, concrete industry consumes 100crore tons of water every year for blending. Notwithstanding that huge amount of water is used in construction for washing of mixers, curing, for concrete pumps & equipment and for ready mix concrete [4], [5]. In perspective of the issuelooked in tendingto the expanded interestthe accessibility of usable nature of water is again deteriorating step by step all through the previous years and proceeding.This situation is being watched everywhere throughout the country and furthermore careful the world, for the most part if there should arise an occurrence of creating nations, by virtue of release of waste water from the treatment plants to the earth, which are contaminating both the surface and subsurface water bodies. According to Central Statistical Organization, there are nearly 32 lakhs industries in India (1988-1999 decade) of which 1,35,55 are registered as manufacturing industries., else are the industries, of small scale and other like Automobile parking, food industries and suppliers, Fabric industries etc. As per the latest inventory of Central Pollution Control Board, at about 8432 huge and moderate polluting industries are existing in India. In addition, lot many very small scale industries are established in inadvertent areas in a disorganized manner. Besides. such industries are located in residential areas. Over this most of these industries are unregistered. Endeavors for wastewater recycle have gradually increased overall consideration in both the mechanical and horticultural fields. With every one of these results, reuse of waste-water that is created in the water treatment plants must be drilled broadly to monitor valuable water assets and to get economic advancement. Partially treated water contains dissolved solids that affect the water. Even if the water stored unused causes major pollution [3]. In this connection, the present experimental studies are intended to use of waste-water as blending water in Ordinary Portland Cement.The constraints considered are setting times, normal consistency and compressive strength, flexural strength. Setting times &Normal consistency of OPC evaluated. Compressive and flexural strength of OPC evaluated at different ages (3days, 7days, and 28 days, and 90 days).

Table 1: Adequate Limits of polluting influences for solid blending water (all qualities in mg/L, with the exception of PH)

S.No	Constituent	Acceptable Limits
1	Inorganic solids	3000
2	Organic solids	200
3	Suspended solids	2000
4	Total solids	4000
5	Total Alkalinity as $CaCO_3$	1000

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***** Correspondence Author
Suma. Yarlagadda*, **Asst. Professor,** Department of Civil Engineering, VR Siddhartha College of Engineering, Vijayawada.
SS. Asadi,Assoc.Professor Department of Civil Engineering, Vignan's Foundations for Science, Technology and Research, Deemed to be university, Vadlamudi, A.P, India.
Ch. Nithin Kumar Reddy,Asst. Professor,Department of Civil Engineering, Chalapathi Institute of Engineering & Technology, Guntur

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6	Sulphates	1000
7	pH	6-8
8	Sodium Carbonates & Bicarbonates	2000
9	Dissolved solids	2000
10	Carbonate & Bicarbonates	1000
11	Chlorides for PCC	2000
12	Chlorides RCC	3000

Subsequently, everywhere throughout the nation, numerous obscure small scale water-treatment plants are being running because of it, enormous volume of waste-water is produced. Subsequentlythe point of the present work is to observe the practical implication of waste-water from small scale water treatment plants located in the residential areas as blendingwater in cement,which is an ingredient in concrete and other cementations works.

A. Use of Waste water in Cement Mortar

Since from the invention of concrete, potable water has been used for mixing. The present study revealed that the waste-water from the human consumption can also be used in concrete. Water from the sources like rivers that are not polluted by humans and cattle, and that don't have any saline taste, has been found fit for concrete mix [9]. It's also been found that the local water bodies in the villages, like ponds and lakes have very low concentrations of organic matter, silt or other impurities that has a very little or even no adversative effect on properties exhibited by concrete [10]. Potable water resources are endless. For the developing countries and cities with limited resources paired with vast commercial growth, and increase in construction activities, that need to preserve the potable water becomes more urgent each and every year. Thereby the efforts laid for the recycling of the used/waste water have gained prominence all over the world and concentration in both construction/ Industrial and agricultural sectors. In recent time, more attention has been drawn towards the different parts of waste-water reuse, albeitnumerous researches has been conducted on the utilization of rejected water that are created from the treatment plants for creation of concrete. The appositeness of utilizing treated waste-water for blending of concrete was tentatively assessed in Kuwait. Concrete cubes were casted using consumable water, essential treated wastewater, auxiliary treated wastewater and tertiary treated wastewater got from the Raqqa (neighborhood) squander water treatment plant. This sort of water did not influence the concrete properties for example slump and density. Nevertheless, the setting time of concrete were seen to be increment with disintegrating waste-water quality. Preliminary treated wastewater and secondary treated wastewater were observedto have the most impact on retarding setting time and further showed slower strength development for very long time up to 1 year. At initial age of concrete up to 7 days, the strength of concrete with tertiary treated wastewater ismore than that of concrete with tap water. There is a probability of corrosionwith an increase in the usage of preliminary treated wastewater and secondary treated wastewater, specificallyprovided with less cover. In abstract, tertiary treated waste-water from waste-water in Kuwait is observed to be suitable for blending concrete with no unfavorable impacts [2].

II. OBJECTIVES

1. Collection of waste water data
2. Conducting the physical and chemical analysis of collected waste water samples
3. Examine the feasibility of wastewater mixing water in OPC

III. METHODOLOGY

The Physio-chemical properties of cement, sand and wastewater used in the investigation and also the standard experimental procedures laid down in IS codes, which were adopted for the determination of initial and final setting times and normal consistency, compressive strength of cement and mortar cubes are presented in this chapter. Compressive strength is the capacity of the material to oppose the load. It is referred as compressive stress at the point where the material fails [6].

A. *Materials*

The materials used for the studyare:

I. 53-Grade OPC
II. Fine Aggregate (sand)
III. Wastewater from four water treatment plants and Distilled water (DW)

a. Sand

The sand, which was used all through the experimental work, was obtained from the Ennore, near Chennai (Ennore sand IS 650:1991). The sand was obtained from Tamilnadu minerals limited, Chennai. It is the only organization in India, approved by Indian Standard Institution to manufacture and supply of sand conforming to IS 650:1991. The sand used in the experimental work has the following particle size distribution.

a) Passing through 2mm & retained on 1mm

b) Passing through 1mm & retained on 0.5mm

c) Passing through 0.5mm & retained on 0.09mm

Table 2: EnnoreSand Properties

S.No	Properties	Results
1	Shape of grains	Sub Angular
2	Grading	In Percentage
2a	Retained on 2mm sieve	100%
2b	Passing in 2mm sieve	100%
2c	Particle size less than 500µ to 90 µ	33.34%
2c	Particle size 2mm to 1mm	33.32%
2d	Particle size less than 1mm to 500µ	33.33%
3	Fineness Modulus	2.73

4	Specific Gravity	2.66
5	Absorption	0.80%
6	Bulk density, KN/m^3	15.89

b. Distilled water and waste water

The physical properties as well as chemical properties of distilled and Waste-water used as mixing water in OPC are presented in Table 3. The characteristics of wastewater opted for the present study (CC, PC, SC and BC) is provided in Table 4.

Table 4: Characteristics of wastewaters opted for present study

Table 3: Physical and Chemical Properties of Distilled & Waste-water Samples

Name of the plant	pH	Alkalinity $CaCO_3$(mg/L)			Acidity $CaCO_3$ (mg/L)		Solidsin mg/L			chlorides in mg/L	Sulphates in mg/L
		OH^-	CO_3^{-2}	HCO_3^-	Mineral acidity	CO_2acidity	Total solids	Organicsolids	Inorganic solids		
DW	7	0	0	0	0	0	0	0	0	0	0
CC WW	7.12	0	0	559	0	79.0	501.13	17.3	484	174.5	21.5
SCWW	6.92	0	0	463.5	0	80.0	320.91	16.3	302	139.0	20
PC WW	7.15	0	0	543.5	0	79.0	437.12	17.1	420	158.0	23.5
BC WW	7.05	0	0	519	0	82.1	401.85	17.5	384	144	27.6
CMCWW	6.81	0	0	300.2	0	91.1	219.2	19.7	201	150.7	16.7
RC WW	6.01	0	0	410.4	0	92.2	270.10	20.2	248	130.8	15.8
YCWW	6.59	0	0	425.25	0	90.6	225	32.0	194	160.35	08
MSC WW	6.52	0	0	300.13	0	95.79	228	24	203	170.7	4.5
KYC WW	6.79	0	0	423.15	0	95.1	243	23	219	172.3	10.8
PNC WW	6.43	0	0	416.44	0	97.0	280.5	30	249	144.7	12.7
IBCWW	6.62	0	0	413.44	0	96.86	247.4	27.4	219	140.8	10.5
ASCWW	6.35	0	0	400.29	0	98.5	236	20	216	139.2	9.4
NKCWW	6.34	0	0	355.91	0	54.84	241	19	221	152.1	11.5
KKC WW	6.51	0	0	419.17	0	46.26	170	20	149	148.9	12.2

S. No	Waste Waters	pH	Alkalinity as $CaCO_3$(mg/L)			Acidity as $CaCO_3$(mg/L)		Solids in mg/L			Chlorides in mg/L	Sulphates in mg/L
			OH^-	-2 CO_3	$-$ HCO_3	Mineral acidity	CO_2 acidity	Total solids	Organic	Inorganic		
1.	DW	7	0	0	0	0	0	0	0	0	0	0
2.	CCWW	7.12	0	0	559	0	79.0	501.13	17.03	484	174.5	21.5
3.	SC WW	6.92	0	0	463.5	0	80.0	320.91	16.93	302	139.60	20
4.	PCWW	7.15	0	0	543.5	0	79.0	437.12	17.11	420	158.90	23.5
5.	BCWW	7.05	0	0	519	0	82.1	401.85	17.05	384	144	27.6

IV. RESULT AND DISCUSSIONS

The purpose of the investigationis to examine the applicability of waste-water obtained from the small scale plants in Kankipadu as water in OPC. Hence, in laboratory, setting time, normal consistency& compressive strength tests and Flexural strengths on OPC were performed. The results are presented and discussed in subsequent sections.

A. *Normal consistency of Ordinary Portland Cement*

Effect of DW, CC, SC, PC and BC on normal consistency of OPC shown inFig. 1 shows the values of Normal consistency of the selected samples are presented in Table 5.

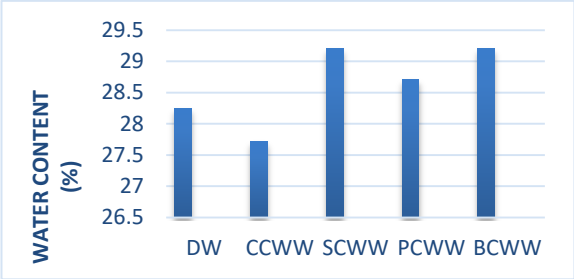


Fig. 1: Waste-water effect on normalconsistency of OPC

The effect of DW, CC, SC, PC and BC on normal consistency of OPC differs marginally compared to that of DW. Normal consistency of CC, SC, PC and BC are 28.5, 27.72, 29.21, 28.71, and 29.21% respectively.

Table 5: Effect of waste-water on physical properties of OPC

S. No	Sample Name	Normal consistency in %	Setting times in mins		Compressive strength in MPa				Flexural strength in MPa			
			Initial setting time	Final setting time	3 days	7days	28days	90 days	3 days	7 days	28 days	90 days
1.	DW	28.25	221	311	33.22	42.17	58.85	61.66	4.06	5.60	6.39	6.54
2.	CCWW	27.72	226	364	34.55	44.71	56.28	59.50	4.11	5.79	6.29	6.48
3.	SC WW	29.21	236	352	32.23	41.78	56.48	60.28	4.04	5.59	6.40	6.44
4.	PCWW	28.71	203	384	33.99	42.27	56.75	59.93	4.08	5.65	6.38	6.43
5.	BCWW	29.21	199	309	33.09	40.97	55.94	59.20	4.08	5.52	6.33	6.29

Table 6: Percentage Change in strengths of OPC

S. No	Waste waters	Percentage change in Compressive strength (MPa)				Percentage change in Flexural strength (MPa)			
		3 Days	7 Days	28 Days	90 Days	3 Days	7 Days	28 Days	90 Days
1	DW	0	0	0	0	0	0	0	0
2	CCWW	+3.98	+5.94	-4.31	-3.46	+1.206	+3.323	-1.53	-0.898
3	SC WW	-2.92	-0.92	-3.98	-2.21	-0.483	-0.175	+0.153	-1.497
4	PCWW	+2.30	+0.227	-3.52	-2.766	+0.483	+0.875	-0.153	-1.796
5	BCWW	-0.346	-2.83	-4.87	-3.94	+0.483	-1.398	-0.92	-3.89

B. *Setting times of OPC*

Initial setting time of concrete: The below shown table 5 and Fig 2 represents the effect of CC, SC, PC and BC on initial setting time of OPC.

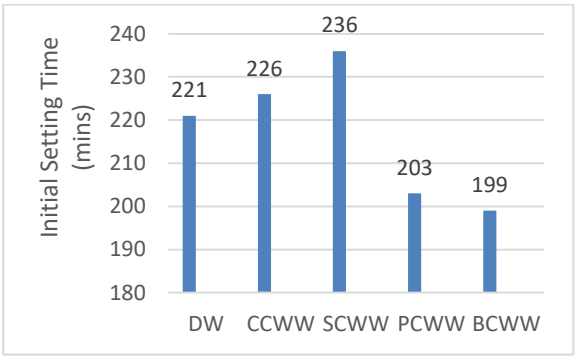


Fig. 2: Different wastewaters on initial setting time of OPC

The selected plants does not shows any significant change compared to that of DW. Initial setting time ofdifferent plants are shown in table 5 as 221, 226, 236, 203&199 minutes respectively. Change of initial setting time of different plants with Distilled Water is+5, +15, -18, -22 mins respectively.

Finial setting time:Table 5 represents the effect of CC, SC, PC and BC on finalsetting time of OPC. Final setting time of different plantsare shown in table 5 as 311, 364, 352, 384 and 309 minutes respectively. Change offinal setting time of different plants with distilled wateris+53 mins, +41 mins, +73mins, and -2 minutes. Subsequently, it is seen that, there is a substantial increase in CC, SC, PC and insignificant decrease in BC when compared to that of DW.

C. *Compression strength of OPC*

Three specimens of 150mm standard cubes are tested for compressive strength as per IS516:1959 [7]. Effect of CC, SC, PC and BCon compressive strength of Ordinary Portland Cement is displayed in Table 5. Percentage change in the Compressive Strength of OPC is mentioned in Table 6. Impact of DW, CC, SC, PC and BC on 3 days compressive strength is shown in Fig. 4.

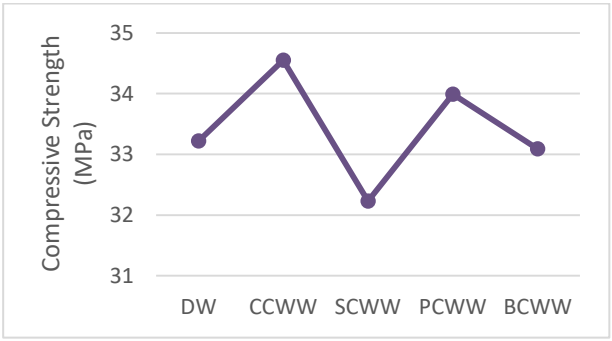


Fig. 4: Wastewater on 3days compressive strength of OPC

Compressive strength obtained for 3 days by using different water plants is shown as 33.22N/mm^2, 34.55N/mm^2, 32.23N/mm^2, 34.99N/mm^2, 33.09 N/mm^2 respectively. Difference in compressive strength is minor when contrasted to that of DW. Change in percentage is shown as (+3.98), (-2.92), (+2.30), (-0.346) respectively when contrasted to that of DW.

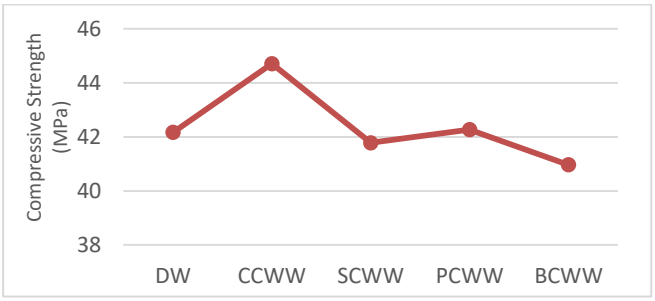


Fig. 5: Wastewater on 7days compressive strength of OPC

Impact of DW, CC, SC, PC and BC on 7days compressive strength is shown in Fig. 5. Compressive strength obtained for 7 days by using different water plants is shown as 42.17, 44.71, 41.78, 42.27, 40.97 N/mm^2 respectively. Difference in compressive strength is irrelevant compared to that of Distilled Water. Change in percentageis (+5.94), (-0.92), (+0.227), (-2.83) respectively contrasted to that of DW. Impact of DW, CC, SC, PC and BC on28days compressive strength of OPC is shown in Fig. 6. Compressive strength obtained for 28 days by using different water plants is shown as58.85, 56.28, 56.48, 56.75, 55.94 N/mm^2 respectively. Difference in the compressive strength is irrelevant compared to Distilled Water. The change in percentage is (-4.31), (-3.98), (-3.76), (-4.92) respectively contrasted to that of DW.

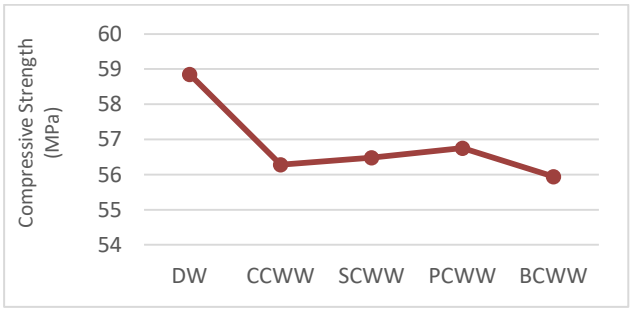


Fig. 6:Effect of different wastewaters on 28days compressive strength of OPC

Impact of DW, CC, SC, PC and BCon 90 days compressive strength of is shown in Fig. 7.

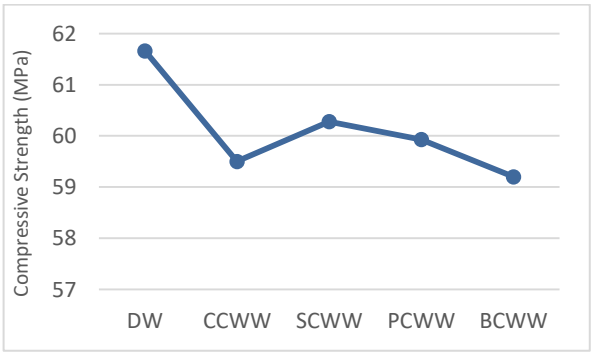


Fig. 7: Impact of wastewater on 90days compressive strength of OPC

Compressive strength obtained for 90 days by using different water plants is shown as61.66, 59.50, 60.28, 59.93, 59.20 N/mm^2 respectively.

Difference in compressive strength is irrelevantcontrastedto DW. Change in percentage is (-3.46), (-2.21), (-2.766), (-3.94) respectively contrasted to DW. However, the proportionate change in compressive strength for 3days, 7days, 28 days and 90 days is (+3.98), (+5.94), (-4.31), (-3.46) for SC (-2.92), (-0.92), (-3.98), (-2.21) forPC (+2.30), (+0.227), (-3.52), (-2.766) for BC (-0.346), (-2.83), (-4.87), (-3.94) respectively when compared to DW.

D. *Flexural Strength of OPC*

Impact of DW, CC, SC, PC and BC on Flexural strength ispresented in Table 5. Percentage change in Flexural Strength is mentioned in Table 6. Fig 8 shows the effect of DW, CC, SC, PC and BC on Flexural strength for 3days. It showsthe 3daysFlexural strength as 4.06, 4.11, 4.04, 4.08, 4.08 N/mm^2 respectively. Difference in Flexural strength is irrelevantcontrasted to DW. The percentage change is (+1.206), (-0.483), (+0.483), (+0.483) respectively contrasted to DW.

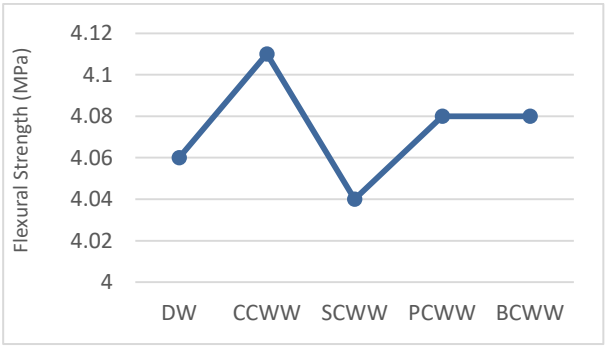


Fig. 8: Effect of different wastewaters on 3days flexural strength

Impact of DW, CC, SC, PC and BC on 7 days Flexural strength is shown in Fig. 9.

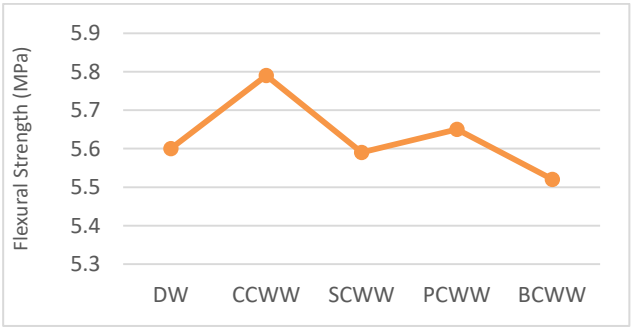


Fig. 9: Impact of wastewater on7days flexural strength of OPC

It shows the 7 days Flexural strength as 5.60, 5.79, 5.59, 5.65, 5.52 N/mm^2 respectively. Difference in the Flexural strength is irrelevant when contrasted to Distilled Water. The percentage change is (+3.323), (-0.175), (+0.875), (-1.398) respectively contrasted to DW.

Effect of Distilled Water, CC, SC, PC and BCon 28 days Flexural strength is shown in Fig. 10.

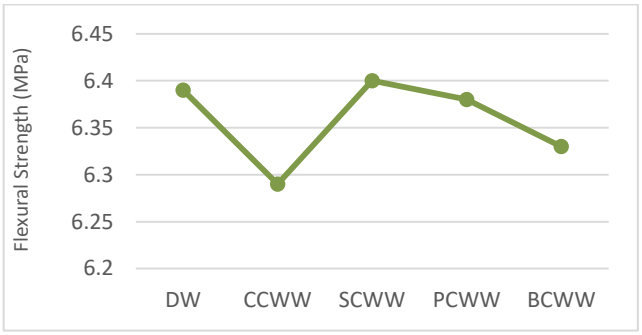


Fig. 10: Effect of waste waters on 28 days flexural strength of OPC

It shows the 28days Flexural strength as 6.39, 6.29, 6.40, 6.38, 6.33 N/mm^2 respectively. Difference in the Flexural strength is irrelevant contrasted to DW. Change in percentage is (-1.53), (+0.153), (-0.153), (-0.92) respectively contrasted to DW.

Impact of DW, CC, SC, PC and BC on 90 days Flexural strength is shown in Fig. 11.

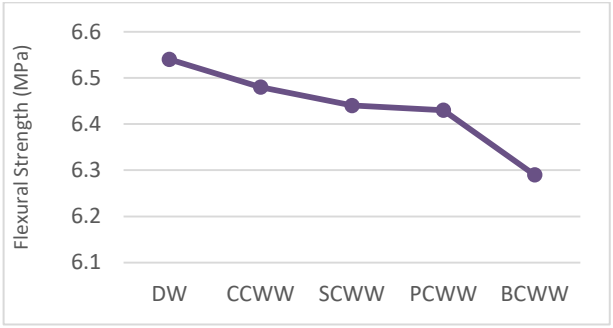


Fig. 11: Impact of wastewater on 90days flexural strength

It shows the 90 days Flexural strength as 6.54, 6.48, 6.44, 6.43, 6.29 N/mm^2 respectively. Difference in the Flexural strength is irrelevant when contrasted to Distilled Water. Percentage change is (- 0.898), (-1.497), (-1.796), (-3.89) respectively compared to DW. However, Compressive &Flexural Strength values of DW, CC, SC, PC and BCare not exceeding 10% of results when compared with Distilled Water.

E. *X-Ray Diffraction ANALYSIS*

XRD analysis for 28 days cured reference samples and test samples are shown in Fig. 3.10 and 3.11. It seems that in samples XRD pattern is same. The crystalline compounds found in the reference sample are C_2S, C_3S, Calcium Hydroxide $\{Ca(OH)_2\}$ at 29.5^0, 18^0, ($34.2^0$and 47.1^0) whereas in test sample are C_2S, C_3S, $Ca(OH)_2$, Calcium Carbonate$\{CaCO_3\}$, Calcium Chloride$\{CaCl_2\}$ at 29.5^0, 18^0, 34.2^0, 47.3^0, 50.9^0. Due to presence of chlorides and bicarbonates in test sample the new compounds i,e., $Cacl_2$& $CaCO_3$areformed.

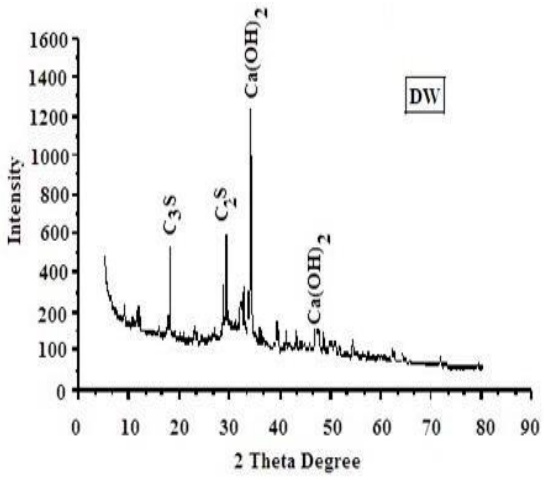


Fig. 12: XRD for 28 days hydrated reference sample

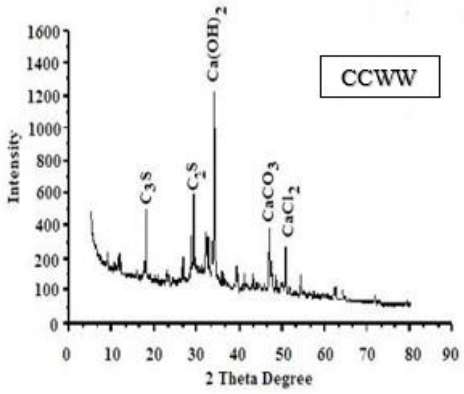


Fig. 13: XRD for 28 days hydrated of test sample

The following are the conclusions drawn from the test results obtained

1) Test samples shows less flexural & compressive strength contrasted to the reference samples, but within the permissible limits as per IS: 456-2000, and BS: 3148-1980. However, longterm strength development and durability studies are to be investigated.
2) Wastewater from the selected plants may be prescribedin cement mortar.
3) In X-ray diffraction analysis, CaCO3 and CaCl2 areobserved in hydrate cement.
4) Wastewaters of CC, SC, PC and BCmay be used as mixing water in OPC.

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AUTHORS PROFILE



Suma. Yarlagadda, **Asst. Professor,** Department of Civil Engineering, VR Siddhartha College of Engineering, Vijayawada.



Dr. SS. Asadi, Department of Civil Engineering, Vignan's Foundation for Science, Technology and Research, Deemed to be University, A.P, India.He received his Ph.D in Environmental Technology and M.Tech in Remote sensing & GIS from Jawaharlal Nehru Technological University (JNTU) Hyderabad. He has more than 22 years of teaching and Research experience in Remote sensing & GIS and Environmental Technology. He has published more than 245 Research Papers in many International and National journals besides undertaking various National projects sponsored by different Government departments and organizations. presented Research work in USA, Sweden and Japan. Presented and participated more than 100 International and national conferences, seminars, workshops. He guided research work of 5 students leading to award of Ph.D. authored 4 books. He is the life member of various international and national professional bodies.



Ch. Nithin Kumar Reddy, Asst. Professor, Department of Civil Engineering, Chalapathi Institute of Engineering & Technology, Guntur

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Grey Water Treatment Using Sand Filtration

Hassane, M. K.[1*]; Hegazy, M. H.[1]; Hussein, H. M.[2]; Sabry, T. I.[2]
[1]Department of Civil Engineering, Faculty of Engineering, The British University in Egypt, Cairo, Egypt
[2]Department of Civil Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt
[*]Corresponding author email: mohamed.khaled@bue.edu.eg

Abstract— *Conventional sand filtration is a clean, green and renowned technology that can be applied for the treatment of grey water. It requires a small footprint area, cost effective for both construction and operation with no skilled manpower. The current research work was conducted at The British University in Egypt to determine the efficiency of sand filtration in treating grey water using the model CE 579 pilot plant. The pilot plant was operated using grey water produced from administrative buildings and students hostels in the University at a fixed water head of 80 cms and effective sand size of 2.38 mm. Three different flux rates and sand media depths were experimented. The optimum removal efficiency was recorded for flux rate of 555 lit/m^2/hrs and sand depth of 80 cms; values recorded were 80.03 % and 78.65 % for TSS and COD respectively.*

Keywords— *Grey water, treatment system, sand filtration, total suspended solids, chemical oxygen demand.*

I. INTRODUCTION

Egypt depends mainly on the River Nile as a source of raw fresh water for different uses; domestic, agricultural, commercial and industrial. Due to the growth of population, agricultural expansion, industrialization and urbanization coupled with the fixed flow of raw water from the River Nile which is estimated to be 55.50 billion cubic meters (bcm) per year. Thus; it is very important to find other secondary sources of raw water. Separation of domestic sewage into grey/black and further reuse of the treated grey water provides a promising potential source of water as it represents about (65-75) % of the total domestic sewage (1).

Grey water separation and characterization has been thoroughly documented in literature (2, 3, 4). The flow rates and composition depends mainly on in-house life style, attitudes, social habits, economic status and usage with high discrepancy reported in the values documented in literature (5, 6, 7). Average values recorded for some parameters include a pH range of (7.2-8.0), total suspended solids (TSS) value of (88-100) mg/lit, biological oxygen demand (BOD) value of (155-411) mg/lit and, finally, chemical oxygen demand (COD) value of (370-806) mg/lit (6, 7).

Filtration is the removal of suspended particles from wastewater by allowing the wastewater to pass through a porous, inactive and clean media. This porous media can be naturally made, such as sand, gravel, crashed stone, and clay, or it can be a membrane synthetically made of various materials (8). In some cases, if raw wastewater is used, large particles and solids are settled prior to filtration in settling basins; to reduce the solids in the influent wastewater. Size of particles retained during filtration depends on the pore size of the filter media used. Figure 1 below gives a summary of the filtration spectrum according to pore size from which we deduce that sand filtration is the first step in the filtration train (9).

Sand filtration removes particles of size bigger than 10 microns and removes some portion of the algae and bacteria. The efficiency of sand filtration for the removal of dissolved particles in wastewater is practically nil as they pass within the sand media pores (10). Grey water treated using a slow sand filter using sand with effective size of 0.3 mm and depth of 400 mm attained removal efficiencies of 89 % and 71.85% for BOD and COD respectively and by using slate waste as media the percentage removal dropped to 51% and 60% for both parameters respectively; and by further changing the media to volcanic turf the removal rates raised to 73% and 65% respectively (10). Using gravel, sand and carbon filter grey water was treated and the removal efficiencies obtained for the parameters under study were 95 %, 52 %, 88 %, 100 % and 100 % for colour, TDS, turbidity, total coliform and E. coli, respectively (11).

Sedimentation followed by filtration and then adsorption was tested for treating grey water and the parameters monitored were TSS, BOD and COD and they gained removal efficiencies of 70.74 %, 85.65 %, and 57.09 % respectively (12). In another study in Egypt, a plain sedimentation tank followed by four sand gravity filters was tested to determine the extent of grey water treatment. The operational range was from 86.5 m^3/m^2/day to 173 m^3/m^2/day and the removal efficiencies obtained were in the range of (40-80) %, (45-82) % and (50-93) % for COD, BOD and TSS respectively (13). Grey water from students hostels in a University in Iran was treated using horizontal filters in series consisting of different types of media starting with sand and ending with granular activated carbon and the elements tested include COD, BOD_5, TSS and turbidity. The set-up was operated at a flux rate of 2.94 m^3/m^2/day. Results from the filtration tests showed that the best filtration performance for the removal of COD, BOD_5, TSS and turbidity with efficiencies obtained reaching 90.42 %, 91.43 %, 82.95 %, and 90.27 %, respectively (14). A filter using nonwoven textile media was used for treating grey water with an average capacity of (1.0-1.4) cm/day. The overall removal efficiencies of COD, BOD_5 and TSS were in the range of (58.80-71.60) %, (56.70-79.80) and (67.00-88.40) %, respectively (15). Sand filter media both alone and mixed with other media was used in the treatment of agriculture drain water and COD removal efficiency was in the range between (77.74-89.00) % (16).

Conventional sand filtration has a main advantage of its low cost and easy operational requirements and can be easily fixed and operated on-site thus reducing the sewage collection works and returning back the treated grey water for reuse for non-

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potable purposes. Its main drawback is its clogging and in some cases the quality of the output effluent treated grey water doesn't meet the required standards (17).

Research Significance

The separation of domestic sewage into grey and black water on the household level and further treatment of the grey water on-site for reuse is gradually becoming a necessity and gaining grounds in many parts of the world.

Consequently, the main objectives of this research study is to determine the efficiency of conventional sand filtration for the treatment of grey water. Optimum operating conditions were also obtained by operating a standard pilot sand filtration plant.

II. Materials and Methods

The experimental work was conducted on model pilot plant CE 579 filtration unit in the Sanitary Engineering laboratories, Faculty of Engineering, The British University in Egypt. The grey water was collected from the administrative buildings and the students hostels in the university; table 1 shows the average influent values to the pilot plant during the operation of the pilot plant.

The CE 579 pilot plant is a standard physical treatment system using sand filtration. The plant consists of a series of tanks and valves and a transparent Plexiglas filter unit and the plant operation is controlled by a special software via a computer connected to the system, figure 2. The plant was operated at three different flux rates 555 lit/m^2/hrs, 1390 lit/m^2/hrs and 2780 lit/m^2/hrs with varying the sand media depth at 40 cms, 60 cms and 80 cms. The sand filter was operated at a constant water head of 80 cms while effective size of the sand media was 2.38 mm. A number of nine runs were conducted for each flux rate for each of the sand media depths mentioned above; the duration of each run was 8 hours.

The filter passage ratio was calculated during the duration of each run to determine the filter clogging percentage. The last run with flux rate of 2780 lit/m^2/hrs and sand media depth of 80 cms was terminated after 6 hrs of operation only as the filter passage dropped to below 50 % recording a value of 39.60 %.

One extra tenth run was conducted for the run with optimum effluent values. This run was a continuous extended run for a period of 18 hours with backwashing every 6 hours after reaching a filter passage ratio of about 57.33 % in average. Backwashing time was 20 minutes at a rate 5 times the flux rate using filtered grey water.

TABLE 1. Values of the collected grey water for the parameters monitored

Parameter	Minimum value	Maximum value	Average value
pH	6.0	8.5	7.25
Total Suspended Solids (TSS) (mg/lit)	121	215	185
Total Chemical Oxygen Demand (CODt) (mg/lit)	194	429	325
Soluble Chemical Oxygen Demand (CODs) (mg/lit)	46	143	105

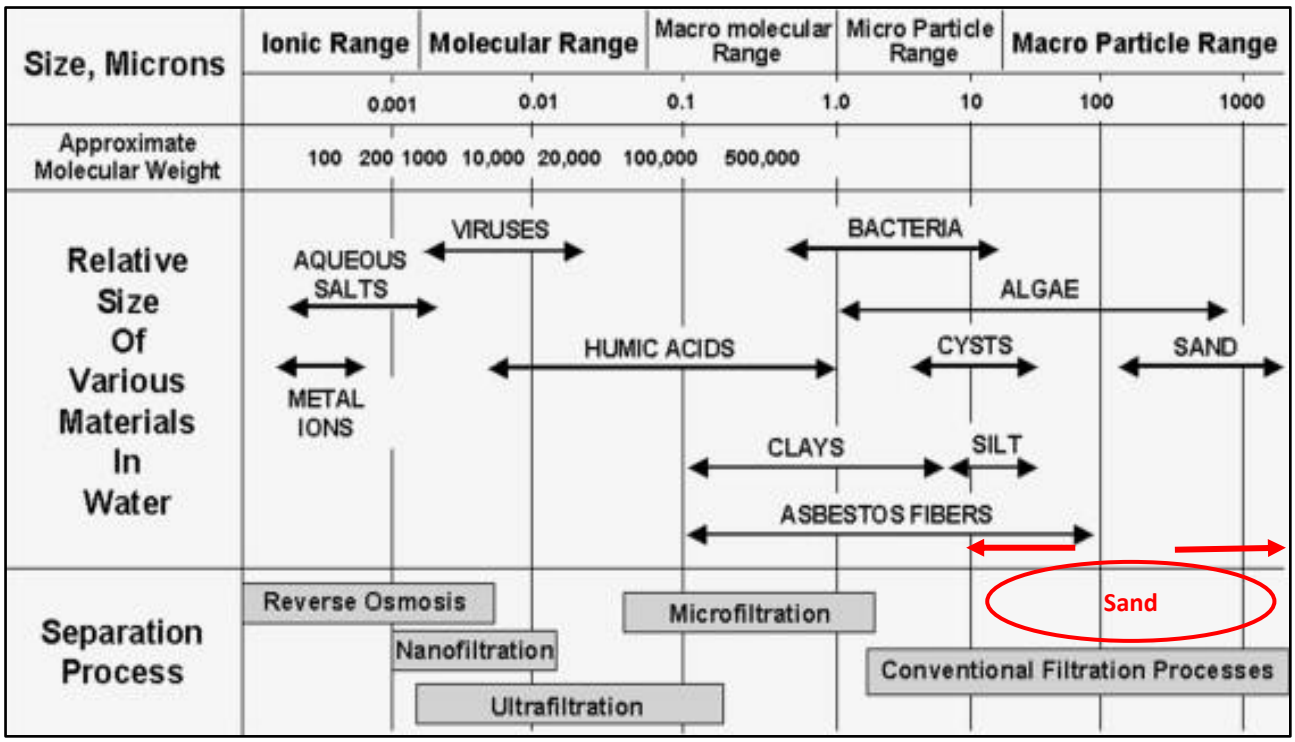


Fig. 1. Filtration spectrum for different separation processes (9)

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No.	Name
1	Raw water pump (P1)
2	Raw water tank (B1)
3	Switch board cabinet
4	Backwash pump (P2)
5	Flow rate sensor (FIR)
6	Temperature sensor (TIR)

No.	Name
7	Valves (V1-V4)
8	Differential pressure sensor (PDIR)
9	Sand filter (F)
10	Pressure relief valve (V5)
11	Bleeder
12	Treated water tank (B2)

Fig. 2. CE 579 pilot plant general view and filter close view

The parameters monitored during the experimental phase of this research work include pH, Total Suspended Solids (TSS), Total Chemical Oxygen Demand (CODt) and Soluble Chemical Oxygen Demand (CODs). All the parameters analyses were done as per Standard Methods (18).

III. Results

Results obtained from the operation of the pilot unit indicated that lower flux rates and deeper sand media gave better removal. The increase in flux rates and media depth accelerated the filter clogging. Figures 3 to 8 show the output results from the operation of the pilot plant. Influent and effluent pH values were almost constant and no any removal was recorded for COD soluble.

The best TSS and COD total removal was recorded at a flux rate of 555 lit/m^2/hrs and sand depth of 80 cms. The removal efficiencies recorded were 81.08 % and 78.75 % for TSS and COD total respectively. This values were for influent TSS and COD total of 202 mg/lit and 410 mg/lit and average effluent of 39.25 mg/lit and 92.25 mg/lit respectively. The run was operated for 8 hrs and the filter passage dropped to 51.80 % at the end of the run. Initial effluent values were above the requirements of the Egyptian Standards; for TSS the effluent values dropped below the standard value of 50 mg/lit after the first hour of operation coinciding with a filter passage of 80.40 % while for COD total it dropped below the standard value of 80 mg/lit after the fourth hour of operation coinciding with a filter passage of 59.20 %. Other flux rates gave moderate removal rates rapid filter clogging especially for deeper sand media depth.

For the extended run for 18 hours with backwashing, the average effluent TSS value was about 39.75 mg/lit and that of COD total was 90.06 mg/lit. This reflects removal efficiencies of 80.03 % and 78.65 % for TSS and COD total respectively. From the figures it can be noticed that the effluent values are high at the beginning of the run and drop as the filtration progresses.

From figure 8 we can deduce that the filter operated at a net flux of 72.30 % of the initial flux rate of 555 lit/m^2/hrs. Thus

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the system net flux is 401.25 lit/m^2/hrs and this reflects on the filter production as it drops due to clogging.

IV. Conclusion

The separation of grey water and treating it on-site and then reusing it for non-potable purposes (toilet flushing, landscape irrigation. etc.) provides a good potential source of raw water that will alleviate the current stress and demand on the natural raw water sources; it represents about (65-75) % of the total household wastewater.

Conventional sand filtration is one of the good options that can be adopted for the treatment of grey water both on large scale and on-site. It is a clean, green and renowned technology that is cost-effective both in construction and operation.

Sand filtration doesn't require skilled manpower for its operation compared with other treatment technologies and it can be operated intermittently. This intermittent operation option is a viable technical and economical asset that makes it easy to operate and maintain locally on-site without the need of high skilled manpower.

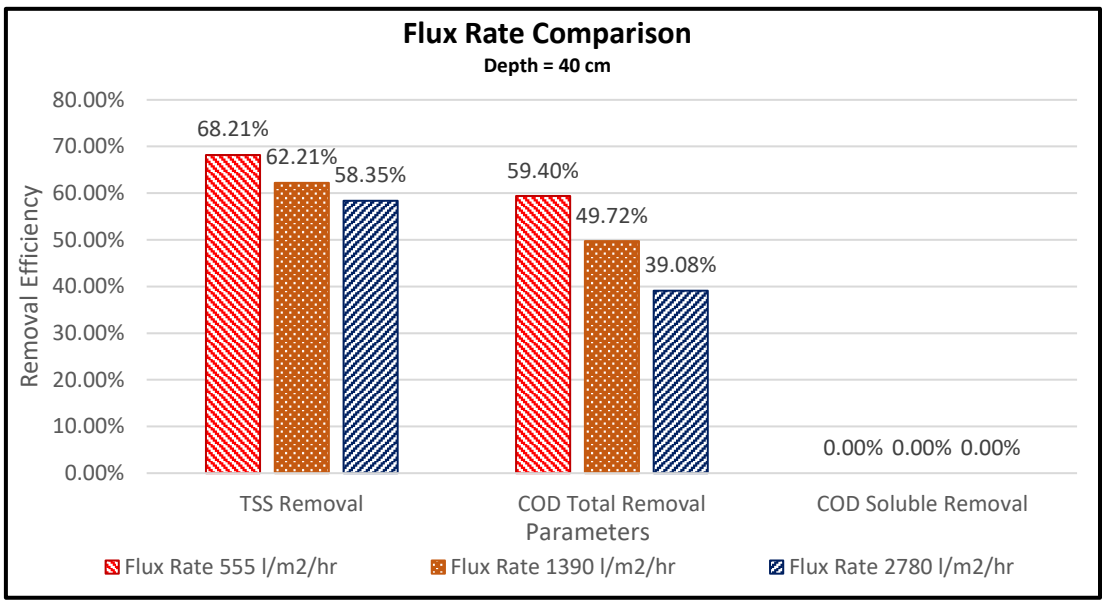


Fig. 3. Flux rate comparison for 40 cms sand depth

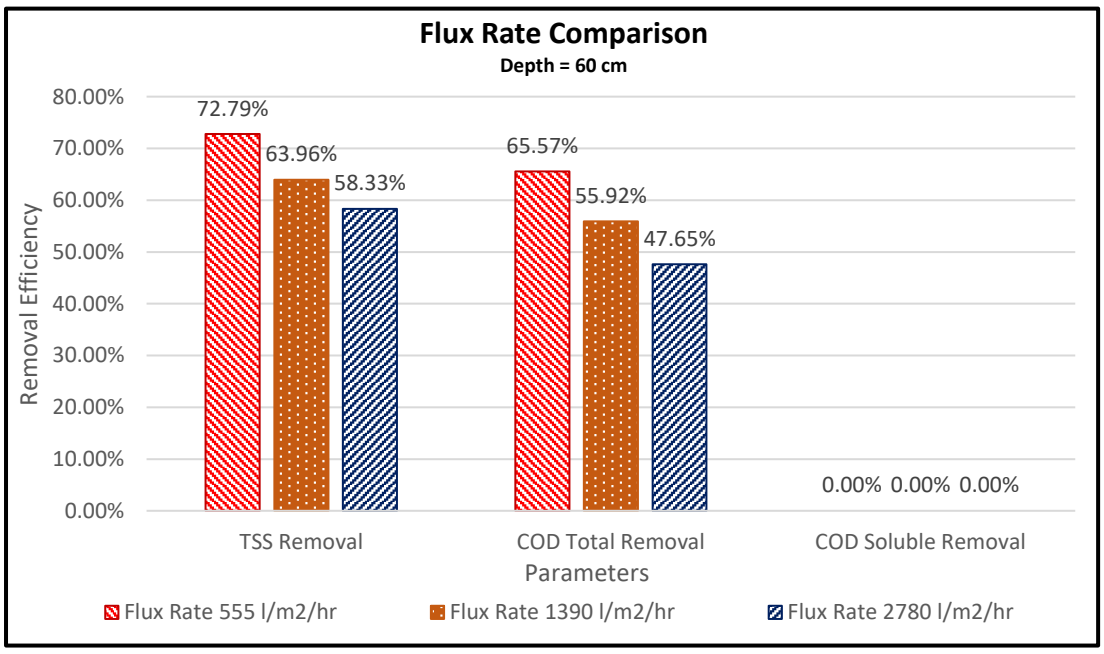


Fig. 4. Flux rate comparison for 60 cms sand depth

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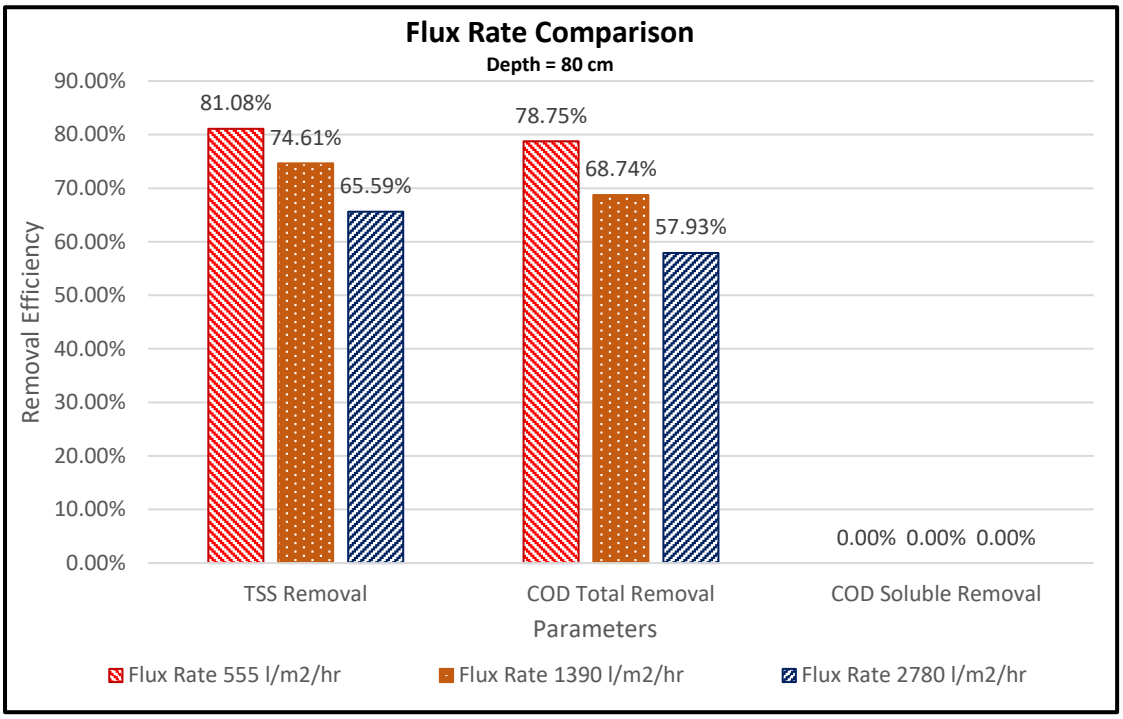


Fig. 5. Flux rate comparison for 80 cms sand depth

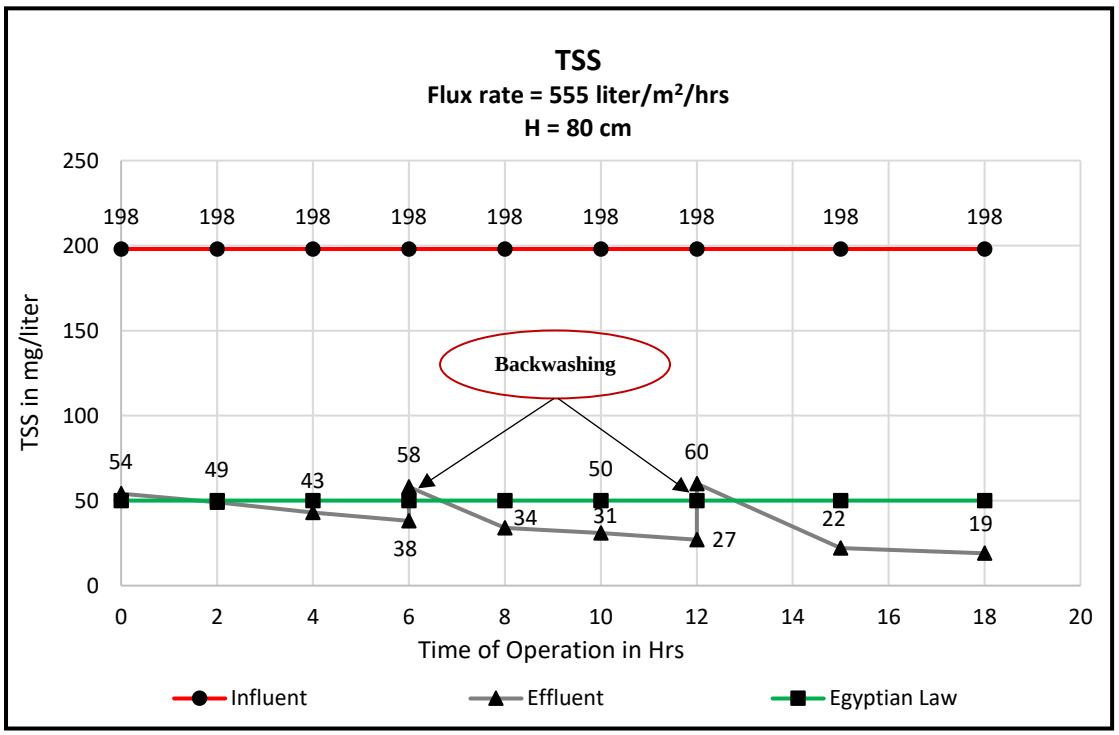


Fig. 6. TSS effluent values for the extended run

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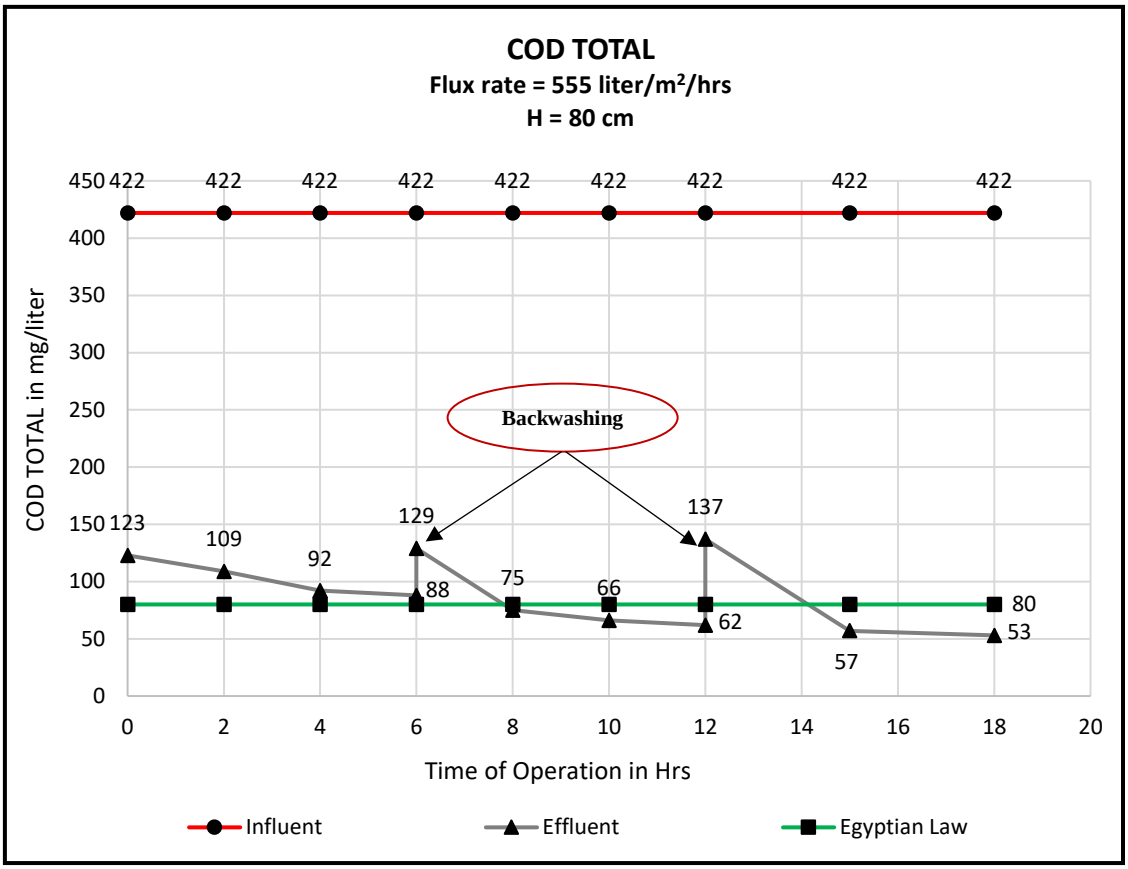


Fig. 7. COD total effluent values for the extended run

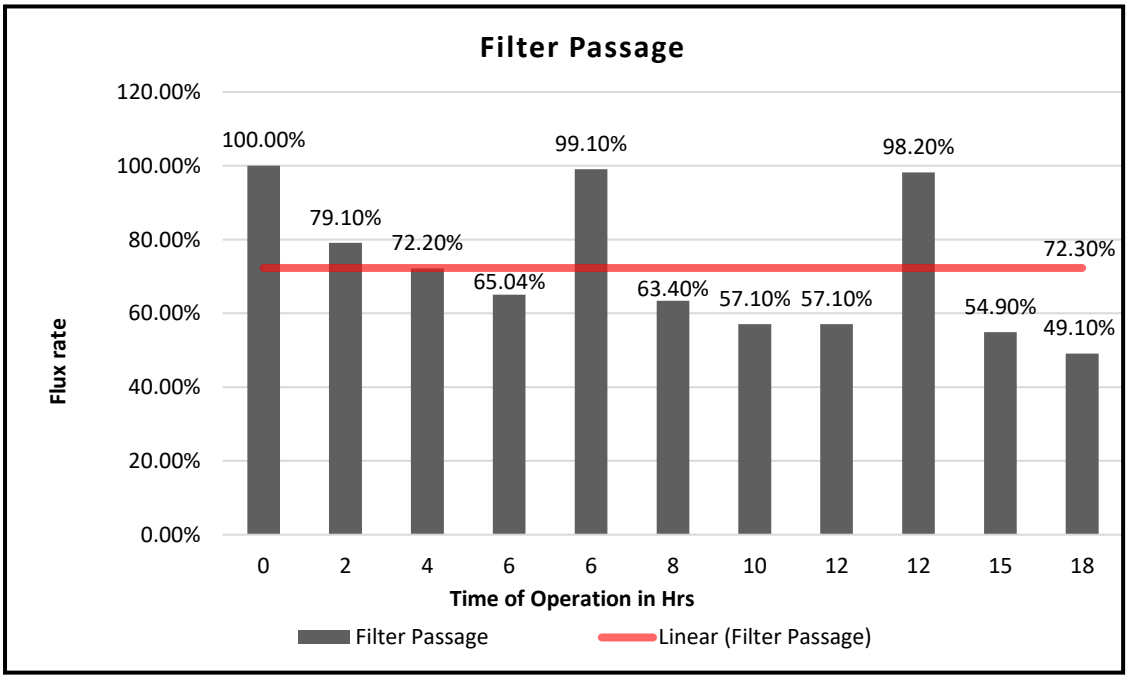


Fig. 8. Filter passage for the extended run

Consequently, from the results shown above, it can be deduced that the best effluent values for the treated grey water are obtained at low flux rates and deep sand filters. Of the three flux rates monitored in this research work, the lowest value of 555 lit/m^2/hrs gave the most efficient removal efficiencies at a sand media depth of 80 cms. Removal percentages of 81.08 %

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and 78.75 % were achieved for TSS and COD total respectively reflecting average effluent values of 39.25 mg/lit and 92.25 mg/lit. TSS effluent values abided with the Egyptian Standards stated in Law 48 for the year 1982 regarding the disposal of wastewater into agricultural drains (COD ≤ 80 mg/lit, TSS ≤ 50 mg/lit) while the COD values were slightly higher in average but as the filtration progressed the values dropped below the standards. As with regards reuse in agricultural irrigation, the TSS effluent values fall within Grade B according to the requirements of code 501/2015.

The main disadvantage of conventional sand filtration in the treatment of grey water is the rapid clogging of the sand media; although the water passage rate within the filter drops due to clogging but the removal efficiency increases. Also sand filtration gave very poor results for the removal of soluble COD.

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"Gheorghe Asachi" Technical University of Iasi, Romania

LOW-COST TREATMENT OF GREY WATER AND REUSE FOR IRRIGATION OF HOME GARDEN PLANTS

Jehad Y. Al-Zou'by[1], Kamel K. Al-Zboon[1]*, Jalal A. Al-Tabbal[2]

[1]Al-Huson University College, Al-Balqa' Applied University, Department of Environmental Engineering, Irbid, Jordan
[2]Al-Huson University College, Al-Balqa' Applied University, Department of Applied Science, Irbid, Jordan

Abstract

Reuse of grey water is an attractive option when available water supplies are limited, and can reduce demand on water supplies and provide additional water resource. This comparative research was conducted to assess the suitability and effects of reusing grey water, treated and untreated, as irrigation water for vegetables, compared with tap water. Tomato (*Lycopersicon esculentum*) and green bean (*Phaseolus vulgaris*) plants were selected as examples. The collected grey water samples were treated through simple filtration processes using natural volcanic tuff, sand, and zeolite as filtration media. Initial characteristics and the efficiency of treatment in terms of physical, chemical, and biological parameters were determined and high removal efficiency was obtained for COD (82%-87.4%), PO_4^- (85%-100%), NO_3^- (75%-64%), and Turbidity (58%-89%). Raw grey water, treated grey water, and tap water were used as irrigation water for tomato and green bean plants under a controlled temperature and humidity environment. Growth patterns and rates, and soil properties for each plant were monitored at assigned time intervals. The results indicated better fruit yields, biological yields, and circumference of green beans plants irrigated with tap and treated grey water than untreated grey water. Except number of leaves no significant difference was found in any measurement for tomato plants. In conclusion, the effects of reusing grey water for irrigation depend on the type of plant irrigated and the quality of treatment. The results also suggest that long-term application of grey water can lead to increased soil alkalinity and salinity.

Key words: grey water, green bean, irrigation, reuse, tomato, volcanic tuff, zeolite

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1. Introduction

Efficient integrated water resource management methods require the implementation of all possible alternatives for water supply and demand-management methods (Al-Beiruti, 2003). In Jordan, water supply is limited and the lack of new water resources and competition between different water uses domestic, industrial, and agricultural is expected to increase in the near future. The available water resources are continuously decreasing due to the growing population, need for food, industrialization, and urbanization, and it is expected that the per capita share will drop to less than 91 m^3/c.y by the year of 2025 (Al Smadi et al., 2010; Ionete et al., 2015). Water shortage has forced Jordan to consider all available water resources to bridge the gap between demand and the available resources (Karpiscak et al., 1990; Stumm and Morgan, 1981; Tsertou et al., 2015). These resources include water reuse, saline, and brackish water. Wastewater reuse and reclamation are often considered viable options for increased water resource availability. Grey water reuse is an option for water demand management and contributes to reducing use of fresh water for irrigation, decreasing both environmental pollution and overall supply costs (Al-Hamaiedeh and Bino, 2010; Al-Jayyousi, 2003; Bodnar et al., 2014).

Grey water is commonly defined as wastewater generated from the bathroom, laundry, and kitchen. That is, except for toilet waste, all water draining from a household is grey water. Due to rapid

* Author to whom all correspondence should be addressed: e-mail: alzboon@bau.edu.jo; Phone: +962-2-7010400; Fax: +962-2-7010379

industrialization and development, there is an increased opportunity for grey water reuse in developing countries, such as Jordan. The most common application for grey water reuse in urban areas is toilet flushing (Dixon et al., 1999; Karpiscak et al., 1990) and irrigation of green areas in parks, school yards, cemeteries, golf courses, car washes, and fire protection are also common (Lu and Leung, 2003). Many Mediterranean countries are investing in wastewater reclamation and reuse due to high evaporation and evapotranspiration, low rainfall, and increased demand for water for irrigation and tourism (Angelakis and Bontoux, 2001).

Water quality restricts the type of crop because water and nutrient requirements differ among crops. Grey water may be harmful to some crops but suitable for others. Use of irrigation water of unsuitable quality will reduce crop yield and worsen the physical properties of the soil (Shahalam et al., 1998). Water with high solids causes clogging to the drip emitters, similarly high nutrient level enhances growth of bacteria inside the irrigation pipes and might clog it (Shatanawi and Fayyad, 1996). Untreated grey water can be highly polluted and thus may pose health and esthetic risks and may significantly change soil properties, which can impact the movement of water in soil and the transport of contaminants in the vadose zone. For example Escherichia coli concentrates in kitchen wastewater were observed in the range $1{:}3x10^5$ – $2{:}5x10^8$ per 100 ml, while the thermo-tolerant coli were found in the range $9{:}4\ x10^4$ –$3{:}8\ x10^8$ per 100 ml and the faecal streptococci between 5150 and $5{:}5\ x10^8$ per 100 ml (Eriksson et al., 2002; Friedler, 2004; Gross et al., 2007; Lado and Ben-Hur, 2009; Misra and Sivongxay, 2009; Travis et al., 2008; Wiel-Shafran et al., 2006).

To avoid the negative impacts of untreated grey water, many treatment technologies have been evaluated, such as sand filtration (Friedler et al., 2005; Halalsheh et al., 2008), volcanic tuff beds (Houshia et al., 2012), natural zeolites (Widiastuti et al., 2008), wetland beds (Halalsheh et al., 2008; Houshia et al., 2012), reedbeds (Dallas et al., 2004), membrane bioreactors (MBR) (Merze et al., 2007), RBC (Friedler et al., 2005), UASB-hybrid reactors (Halalsheh et al., 2008), and disinfection (Friedler et al., 2005). Review of the efficiency of these treatment methods indicated that the currently preferred treatments for grey water use physical and biological/natural systems. Recently, chemical systems, such as coagulation, adsorption and advanced oxidation processes (AOPs), have been shown to be effective for low-to-moderate strength grey water (Boyjoo et al., 2013). These chemical processes can effectively remove suspended solids, organic materials, and surfactants from low-strength grey water.

The combination of an aerobic biological process with physical filtration and disinfection is considered to be the most economical and feasible solution for grey water recycling. The MBR appears to be an attractive solution in urban residential buildings (Li et al., 2009).

Much effort has focused on exploring the application of natural zeolites and modified natural zeolites in water and wastewater treatment, especially for reducing or removing contaminants in grey water (Widiastuti et al., 2008). This is due to its advantages of low cost, ion-exchange, adsorption capability, high microelement contents, micro porosity, and acido-basic or redox properties of the surfaces of natural zeolites (Kocaoba et al., 2007; Nurul et al., 2008).

Tomatoes and green beans are popular plants in the home garden, are fairly easy to grow, and produce a good yield for the amount of garden space required. They also showed no marked yield reduction under irrigation with saline or grey water (Al-Hamaiedeh and Bino, 2010; Misara et al., 2010; Mitchell et al., 1991).

In this work, reuse of grey water as a potential source of water to irrigate garden plants (tomato and green bean) was examined. This will increase the availability of water resources, reduce water bills, increase family productivity, and improve the economic situation, especially for low-income families. To improve water quality, three low-cost materials were assessed: natural volcanic tuff, silica sand, and zeolite. The impacts of water type (raw grey water, treated grey water, and tap water) on plants and soil properties were investigated.

2. Experimental

Two experiments were carried out to determine the effect of grey water treatment on yield and agronomic traits of tomato (*Lycopersicon esculentum*) and green bean (*Phaseolus vulgaris*) grown under controlled environments. Seedlings of tomato were obtained from Zhran nursery, Al-Baqa, Jordan. Green bean seeds were obtained from Migdady Agricultural Company.

2.1. Sampling sites

Grey water samples were collected from two sites (Fig. 1). Site A was in Al Adasyah city, in the north-west of Jordan, where no municipal sewage system exists. Composite wastewater is collected in a primitive system of earth excavations, while grey water is collected in concrete-lined ditches, and used for irrigation at the site. This grey water is a composite of sink, laundry, kitchen, and floor cleaning water (composite samples). Site B was in Irbid city, in the north of Jordan, where a municipal sewage system exists that collects both waste water and grey waters. Samples of grey water were collected from site A directly from ditches repeatedly for 6 months. These ditches were thoroughly mixed before sampling (composite samples), and samples of 40-60L volume were obtained daily. For site B, divergence of the grey water plumbing system was used for collection; grey water samples were collected in buckets from sinks, the laundry, and

kitchens. Grey water collected from both sites (A and B) was mixed.

2.2. Grey water characterization and treatment

The mixture of grey water samples was analyzed for chemical, physical, and biological composition (Table 1). High concentrations of NO_3 were detected (383 mg/L); this could be attributed to the use of nitrogen in surfactants. The COD level in the collected samples was less than that in wastewater in Jordan (Al-zboon and Al-Ananzeh, 2008). K, Na, Cl, N-NO_3, and PO_4^- in wastewater come from a variety of household items used in the kitchen, bathroom, and laundry, and human waste. According to Tchobanoglous et al. (2003), typical fluid contributions from a house to a septic system are 26.7% from toilets, 21.8% from clothes washing, 16% from showers, 15.7% from faucets, 13.7% from leakage, 1.7% from baths, 1.4% from dishwashing, and 2.2% from other sources. Treatment of grey water was based on simple physical treatment, mainly filtration, using various media: natural silica sand (Jordan desert sand), volcanic tuff sand (red tuff, Jabal Artin, Jordan), and zeolitic tuff. These materials are widely available in Jordan at low cost; indeed, they can be taken freely from various sites. A simple treatment method, especially a filtration process, can be installed in the home garden where no energy source or maintenance is required, beyond periodic replacement of the filtration media. The availability of these materials and a simple treatment process make them an attractive low-cost option for the treatment of grey water in the home.

The physical and chemical compositions of these media are shown in Table 2. All media were sieved, washed with distilled water, and oven-dried. Effective sizes of all media were 0.45-0.55 mm, with uniformity coefficients of 1.7. A batch treatment process was considered using a column of 10-cm diameter and with a 30-cm bed depth. A minimum hydraulic loading of 1.5 mL/cm^2.min was used to achieve a flow rate of 120 mL/min with a contact period of 25-50 min.



Fig. 1. Locations of grey water and tuff samples (G1, G2: grey water samples, T1, T2 tuff samples)

Table 1. Effect of media type on grey water treatment efficiency

	Initial conc. (mg/L)	*Tuff*		*Sand*		*Zeolite*	
		Final Conc. (mg/L)	*Removal efficiency %*	*Final Conc. (mg/L)*	*Removal efficiency %*	*Final Conc. (mg/L)*	*Removal efficiency %*
COD	502	90	82	63.50	87.40	72.40	85.50
PO_4^-	5.20	0.0	100	0.79	85	0.0	100
NO_3	383	135	64	150	61	165	57
Turbidity	110	46	58	12	89	25	77
pH*	7.30	7.20	--	7.20	---	7.40	--
Na+	361.50	80.56	77.70	65.53	82	200	45
K+	19.29	3.84	80	8.96	53.60	10.20	47
Fe	0.46	0	100	0	100	0	100
Mn	0	0	0	0	0	0	0
Cu	0.28	0.17	39	0.16	40	0.14	49
Zn	0.25	0.06	76	0.18	28	0.12	52

2.3. Column construction

A column study was conducted to address the question whether breakthrough of potential contaminants would occur. The columns were filled with a 30cm depth of media, and covered with a 2.5cm layer of the stone to prevent swirling and crusting of the media upon addition of grey water. The columns were fastened and housed in a temperature-controlled room, set at 17°C to represent average field conditions. Columns were loaded with the media manually.

All treatments were conducted in triplicate. Leachate from the columns was collected and analyzed chemically. Testing parameters included COD, nitrate, pH, orthophosphate, turbidity, iron, manganese, copper, zinc, and oil, and grease (Table 2). Analytical procedures were as in grey water characterization.

Table 2. Chemical and physical properties of volcanic tuff, silica sand and zeolite (XRD And XRF analysis)

Chemical composition	***Volcanic tuff %***	***Silica sand %***	***Zeolite %***
SiO_2	41.69	99.50	69.31
CaO	12.83	0.03	2.07
Al_2O_3	10.60	0.3	13.11
Fe_2O_3	8.87	0.03	1.31
MgO	6.24	<0.005	1.13
TiO_2	2.30	0.04	N.A
K_2O	1.41	N.A	2.83
Na_2O	1.06	N.A	0.52
P_2O_5	0.36	N.A	N.A
MnO	0.12	N.A	N.A
Dry specific gravity	1.96	2.7	1.32
Porosity	38.20	30	41.5
Water absorbance (%wt)	12.74	<0.65	15.07

2.4. Preparation of pots

Pots of 30-cm diameter and 45-cm depth were filled with soil obtained from the Al-huson University College campus field. Sufficient soil was collected from the top 10 cm and brought to the laboratory for drying and sieving to reduce aggregate size to < 4 mm. Samples of the soil (< 2 mm fraction) were analyzed for a range of properties. The soil contained 27.2% sand, 32% silt, and 40.8% clay. The pots were filled with 8 kg of this soil and completely blocked to prevent water loss.

2.5. Irrigation treatments

Fifteen pots were placed on the greenhouse bench using a randomized block design to allocate three irrigation treatments randomly to each of five blocks (replicates). The pots were divided into three groups: The first group was irrigated with raw grey water (T1), the second with treated grey water (T2), and the third with tap water – groundwater source (T3). Soil water potential was maintained by frequently weighing the pots; an amount of water equal to the weight loss was added. Plants were irrigated to the field capacity for 1 week before starting the experiment to improve root development. During irrigation, water was added slowly to the center of the pot to ensure even distribution throughout the pot and to avoid water flow along the soil–pot interface.

2.6. Soil quality measurements

In order to determine the impact of using greywater on soil properties, two soil samples were taken from each pot; one before planting and the other one after harvesting. After drying, undesirable materials such as plastic and wood were eliminated from the soil samples, and passed through a sieve with 2mm diameter. The properties measured included pH, SAR, electrical conductivity, organic matter content, Ca, Mg, Na, K, Cl, NO_3, N, P, Cu, Zn, and Mn. All analyses were conducted according to standard methods (AOAC, 1989).

2.7. Plant yields and components measurements

Plants were harvested at maturity. Shoots were separated from roots at the soil surface. Yield and yield components were measured. The plants were harvested during the growing season by cutting and the following vegetative growth parameters were recorded: plant height (cm), number of branches/plant, fresh weight (g/plant), number of leaves/plant, number of fruits per plant, weight of fruits per plant, circumference of fruit for tomato and green bean, and length for green bean.

2.8. Statistical analysis

Statistical analyses used one –way analyses by ANOVA and the least significant deference test (LSD) with regard to the effects of different irrigation treatments. The SAS software was used (SAS, 2004).

3. Results and discussion

3.1. Effect of media type on grey water treatment efficiency

The mean values of the various testing parameters are shown in Table 1. COD values for the column samples showed ~80% removal efficiency, which averaged 502 mg/L for raw grey water. Data in Table 1 show mean COD values of 90 mg/L for the tuff media, 63.5 mg/L for the sand media, and 72.4 mg/L for the zeolite media. The data indicate that all media (tuff, sand, and zeolite) had high removal efficiency (80%). This is so because there is little space between the media grain particles and the organic compounds are easily trapped. Most of the COD is removed at the top of the column; efficiency

is reduced towards the bottom because of the absence of oxygen.

Achak et al. (2009) explained the removal of COD through physical and biological phenomena. The particulate matter is filtered; sedimentation takes place and adheres to sand particles. Biological degradation then takes place under oxygenated conditions. Hua et al. (2003) reports that about 75-80% of COD is removed in the first 25-30 cm of sand. The efficiency decreases due to clogging, which reduces the filtration rate and the availability of the oxygen. Orthophosphates were completely retained in tuff and zeolite columns where the effluents throughout had PO_4^{3-} contents below the detection limit. Due to their high levels of iron, calcium, and aluminum, PO_4^{3-} tend to react with them and precipitate, while sand has a lower content of such metals, which affected the removal efficiency (84%). Raw grey water contained 5.2 mg/L PO_4^{3-} which was precipitated within the columns, likely by iron. Achak et al. (2009) explains that phosphorous is removed by adsorption, precipitation, and ionic exchange.

Stumm and Morgan (1981) and Reddy and D'Angelo (1994) explained the processes of adsorption and precipitation that, in acidic soils, are dominated by iron oxides and aluminum. Phosphorous is adsorbed and precipitated, and thus becomes immobilized by ferric oxyhydroxide, forming ferric and aluminum phosphates. In alkaline soils, phosphorous retention or precipitation is dominated by calcium and magnesium (Weber-Shirk and Dick, 1997). The adsorption and precipitation process is highest under acidic conditions which are close to neutral. However, some phosphorous is adsorbed with iron under alkaline conditions like pH 10 (Lind, 1998). Turbidity in column effluent showed a different trend than raw grey water (Table 1). The tuff media had a mean turbidity value of 46 NTU, sand media, 12 NTU, and zeolite, 25 NTU, while raw grey water averaged 110 NTU. The media effect was significant because sand, which has the lowest porosity, resulted in 89% removal efficiency, zeolite 77%, and tuff 58%.

Nitrate values in column effluents showed trends similar to the COD, with an average removal efficiency of 60%. Raw grey water contained ~383 mg NO_3^-/L (86.4 mg/L as N). The mean value for the tuff media was 135 mg/L, sand media, 150 mg/L, and zeolite media, 165 mg/L. The effect of media type was statistically non-significant. Removal of nitrate by the various media is attributable to ion exchange, and adsorption rather than denitrification, because the activities of nitrifying bacteria require a longer time scale (Tchobanoglous et al., 2003).

Other parameters, with final concentrations and removal efficiencies, are shown in Table 1.

3.2. Plant growth

The results of the first experiment, which examined the benefits and risks associated with domestic grey water reuse for the purpose of tomato irrigation, indicated no significant differences among the water treatments for any measurement (Table 3 and Fig. 2). All plants appeared healthy from all soils, indicating that grey water can be used for irrigation, like tap water, with no adverse effect on the growth or yield of the plant (except N. of leaves). This result is likely explained by the low nutrient content of the grey waters, and their low heavy metals and therefore non-inhibitory levels of heavy metals. These results are similar to those reported by Pinto et al. (2010) for grey water irrigation of silver beet and those of Misra et al. (2010) for grey water-irrigated tomato plants. These results reinforce the potential of domestic grey water as an alternative irrigation source. However, these results are also in contrast with some previous reports of detrimental effects of grey water on plant growth (Bubenheim et al., 1997; Wiel-Shafran et al., 2006). For example, a study of lettuce plants grown using soil medium indicated 'chlorosis' within a 30-day period (Wiel-Shafran et al., 2006). In another study, which used liquid medium and Igepon-42, showed toxicity symptoms after 4-6 h, with 'browning' of lettuce roots and suppression of root dry mass within 24 h (Bubenheim et al., 1997).

In contrast, there were significant differences among water treatments for green bean yield, biological yield, and the circumference of green beans (Table 4 and Figs. 3, 4, 5). Treated grey water-irrigated *Phaseolus* plants exhibited a biological yield, fruit yield, and green bean circumference similar to tap water-irrigated and greater than grey water-irrigated plants (Table 4). This demonstrated the importance of prior treatment of grey water before use for irrigation of *Phaseolus vulgaris*.

The effect of grey water and treated grey water reuse on soil properties was assessed after harvesting of the crops. Irrigating plants with raw grey water (treatment T1) resulted in a significant ($p < 0.05$) increase in soil pH when compared with the control treatment (T3) (Table 5). These results suggest that the long-term application of grey water could increase soil alkalinity. Soil pH affects the availability of a range of soil nutrients, such as phosphorus, copper, iron, manganese, molybdenum and zinc for plant growth. A pH value between 6 and 7.5 is usually considered optimal for growth of many plants and the microbial health of the soil. Thus, extra care must be taken when soil pH falls below 6 or rises above 8.2 (De Clerck et al., 2003).

Therefore, regular pH monitoring of soil irrigated with grey water may be necessary, and any increase in soil pH above 7.5 should be corrected by adding gypsum. The results also showed an increase in salinity with grey water compared to tap water (Table 5). This may be due to the high concentration of salt in the untreated samples. However, salt accumulation might differ in the context of garden beds compared with pot experiments because surface runoff and leaching may occur in garden beds due to rainfall.

Table 3. Effect of the type of water on the yield of tomato (*Leucopersicon esculentum)*

Type of water (T)	***Mean square***					
	NF	***WF***	***CF***	***L***	***PH***	***BY***
T1	2.25 A	19.42 A	13.52 A	38.25 A	30.52 A	43.71 A
T2	3 A	20.63 A	11.51 A	24.51 B	30 A	45.21 A
T3	3 A	33.12 A	13.52 A	29.75 AB	29.53 A	69.93 A
LSD (p≤0.05)	1.25	13.84	2.66	11.78	12.68	28.51
F value	1.23	3.08	1.92	0.99	0.02	2.73
Pr value	0.34	0.09	0.2	0.39	0.98	0.12

Number of fruit per pot (NF), weight of fruit (g) (WF), circumference of fruit (CF), number of leaves (L), plant height (PH) and biological yield (BY).

Table 4. Effect of the type of water on the yield of the green bean (*Phaseous vulgaris*) plant

Type of water (T)	***Mean square***							
	NF	***WF***	***CF***	***B***	***L***	***PH***	***LF***	***BY***
T1	3.5 A	06.16 B	1.64 A	3.33 A	14.83 A	8.83 AB	8.25 A	15.68 B
T2	5 A	15.00 A	2.76 A	3.83 A	13.0 A	7.73 B	7.88 A	34.35 A
T3	5.16 A	11.3 AB	2.48 A	3.50 A	10.51 A	12 A	9.68 A	25.9 AB
LSD (p≤0.05)	1.86	6.26	0.59	1.25	6.59	3.49	1.80	14.45
F value	2.21	4.57	8.72	0.37	0.99	3.75	2.97	3.8
Pr value	0.14	0.03	0.03	0.69	0.39	0.048	0.57	0.04

Number of fruit per pot (NF) , weight of fruit (WF), circumference of fruit (CF), number of branches per plant (B), number of leaves (L), plant height (PH) , length of fruit (LF), and biological yield (BY), Same letter in the column means insignificant difference at the 0.05 probability using LSD test.

Table 5. Effect of grey water irrigation on soil properties

Type of water	***W1 (Grey Water)***	***W2 (Treated Water)***	***W3 (Tap Water)***
pH	8.31 A	8.18 AB	7.88 B
EC(ds/m)	2.52 A	1.65 B	1.32 B
Ca (meq/l)	7.58 A	6.72 B	6.45 B
Mg(meq/l)	3.52 A	3.55 A	2.35 A
Na(meq/l)	6.90 A	5.19 AB	4.50 B
K(meq/l)	0.29 A	0.22 AB	0.20 B
Cl(meq/l)	7.74 A	5.26 A	4.72 A
NO_3_N(ppm)	74.52 A	26.11 B	7.36 B
P(ppm)	621 A	501 B	447 B
Cu(ppm)	0.42 A	0.35 A	0.20 A
Zn(ppm)	6.44 A	4.92 A	4.18 A
Mn(ppm)	12.31 A	4.27 B	3.08 B
SAR	2.92 A	2.30 A B	2.14 B
Organic Matter(w/w)%	1.79 A	0.47 B	1.68 A

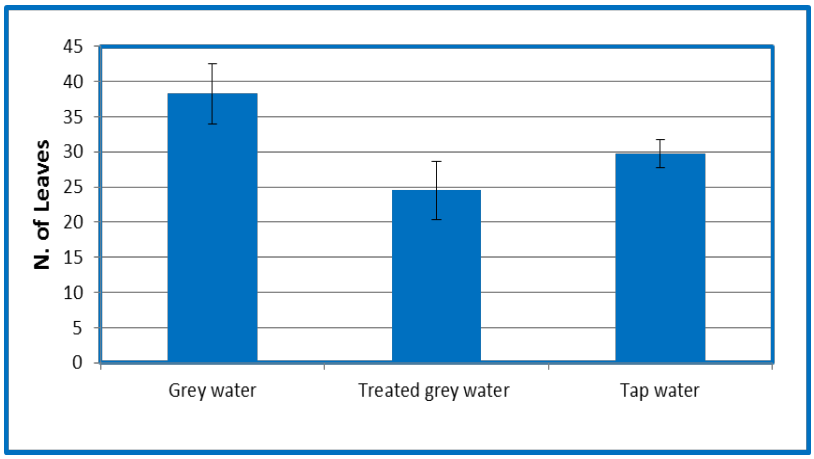


Fig. 2. Mean number of leaves of tomato under three type of water (error bars show standard error)

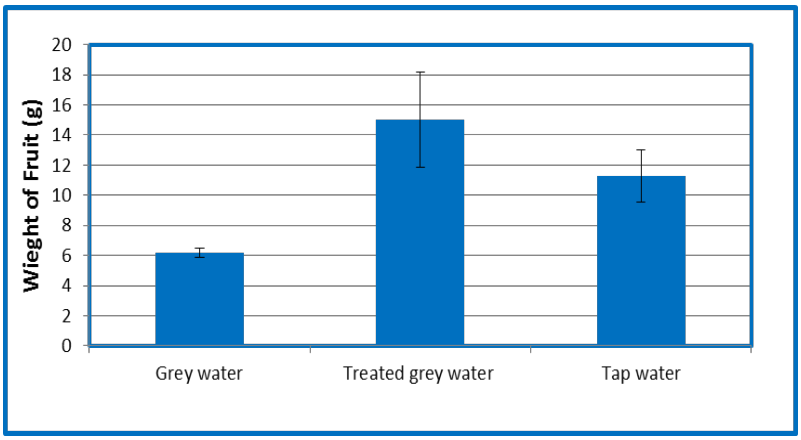


Fig. 3. Mean fruit wieght of green bean under three type of water (error bars show standards error)

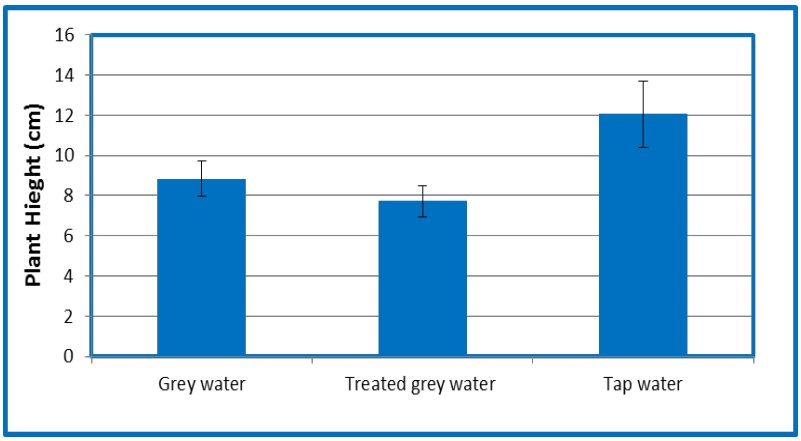


Fig. 4. Mean Plant hieght of green bean under three type of water (error bars show standard error)

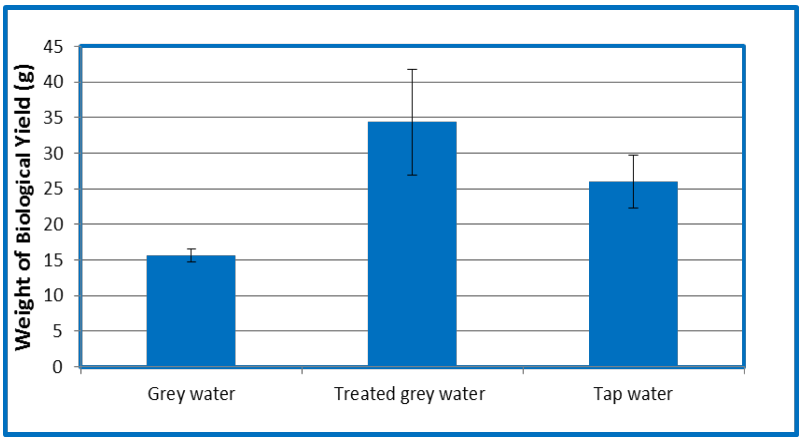


Fig. 5. Mean of WY of green bean under three type of water (error bars show standard error)

4. Conclusions

The study revealed that tomato (*Lycopersicon esculentum*) plants irrigated with grey water or treated grey water showed no significant differences in any parameter assessed.

Also, irrigation of green bean (*Phaseolus vulgaris*) with grey water or treated grey water had non-significant effects on the number of beans, number of leaves, and number of branches.

However, green beans irrigated with treated grey water showed fruit weight and circumference, and biological weight, similar to those of plants irrigated with tap water.

The availability of natural low-cost materials (silica, volcanic tuff, zeolite) and the simplicity of the treatment method (filtration) make it an attractive low-cost option for the treatment of grey water in the home. The use in plant production of grey water treated with natural materials represents a beneficial alternative to fresh water. Irrigating plants with grey water without treatment will result in increased soil pH, EC, SAR and other parameters compared with treated grey water.

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