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Enhancing Greywater Treatment for Sustainable Irrigation: Utilizing Natural Filtration Materials and SMBR Technology

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ABSTRACT

The investigation of natural filtration materials such as bentonite, perlite, and date seeds is part of the research program we are conducting aimed at resolving the urgent problem of sustainable water management in arid areas, for example, Egypt, by studying the effectiveness of these materials at treating greywater for irrigation usages. Utilizing the filtration method in conjunction with submerged membrane bioreactor (SMBR) technology, the research evaluates how effectively greywater can be cleaned of organic matter, heavy metals, and contaminants. The data shows that perlite provides better solid and organics reduction than SMBR, eliminating more pollutants from the water body. The purified greywater fulfills directives of the water authorities regarding reuse for irrigation, thus demonstrating the role of ¨natural¨ filtering materials and advanced treatment technologies in maintaining water sustainability. This scientific study, hence, highlights the influence of nature-based variants in water treatment techniques to achieve sustainable water goals as mentioned in Egypt`s Vision 2030.

1. Introduction

The world's freshwater resources are becoming increasingly scarce. Currently, about 54% of all accessible freshwater from rivers, lakes, and underground aquifers is being used by the world's six billion inhabitants [1]. As the population and climate change affects water availability, the global freshwater shortage is expected to worsen. Water scarcity is particularly acute in regions like Egypt, where rainfall is rare and deserts dominate the landscape [2].

One solution to this challenge is reducing freshwater usage in urban areas by implementing greywater systems [3]. Greywater, which comes from sources like sinks, showers, and laundry, can be reused for various non-potable purposes such as toilet flushing, town cleaning, car washing, and gardening (including public parks, golf courses, and residential lawns) [4] as shown in Figure (1).

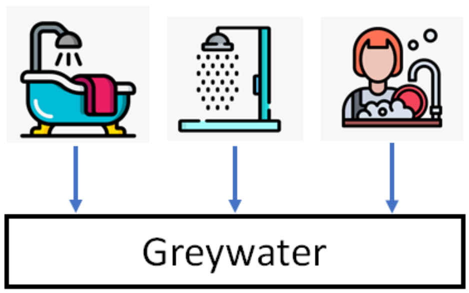

Figure (1) Greywater sources

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In Egypt, residential water usage accounts for about 8% of total potable water consumption. Of this, approximately one-fifth is used for toilet flushing and one-third for landscape irrigation (Ministry of Water Resources and Irrigation, 1997). Greywater comprises a significant portion, ranging from 50% to 80%, of total household and about 75% of total municipal wastewater. Utilizing greywater systems can help alleviate pressure on freshwater resources and contribute to sustainable water management in urban areas [5].

Managing urban water resources by treating and reusing greywater presents an appealing solution. Greywater contains many pollutants that vary according to its source as reported in Table (1).

Table 1: Greywater contaminations [6]

Greywater Source	Characteristics
Washing Machine	- Contains bleach, foam, grease, oil, nitrate, phosphate, soaps, sodium, and suspended solids. - Exhibits high pH, salinity, and turbidity.
Dishwasher	- Contains bacteria, foam, food particles, oil, grease, organic matter, soaps, and suspended solids.
	- Exhibits high pH, turbidity, salinity, and high oxygen demand.
Bath and Shower	- Contains bacteria, oil, grease, soaps, suspended solids, hair, and hot water.
	- Exhibits odor, turbidity, and high oxygen demand.
Sinks (Washroom, and Kitchen)	- Contains bacteria, food particles, oil, grease, organic matter, soaps, and suspended solids.

This method effectively decreases the demand for potable water in urban areas, alleviates the strain on sewage treatment facilities, and reduces associated costs [7]. Greywater, sourced from activities like bathing, showering, handwashing, and laundry, constitutes a significant portion, ranging from 50% to 80%, of the overall water demand as shown in Figure (2) [8].

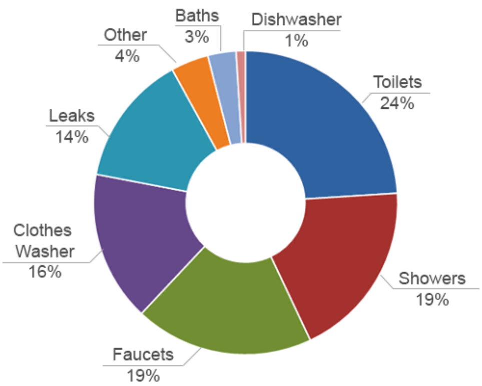


Figure (2) greywater components [8]

2. Literature review

Greywater is a promising element in achieving water sustainability, particularly in dry and semi-arid areas. Depending on its source, duration of storage, and degree of contamination, greywater may harbor various pathogens. Numerous studies have explored technologies for treating greywater. However, employing greywater for irrigation poses a potential risk of introducing organic pollutants into groundwater, surface water, aquatic habitats, and soil [9]. Global reviews have examined several case studies of greywater recycling initiatives [10].

Physical greywater treatment systems involve both filtration and sedimentation processes. Filtration serves as either a preliminary or subsequent treatment step, with the effectiveness of the treatment influenced by the filter's porosity and the size of contaminants as shown in Figure (3). Pre-treatment filtration methods encompass screen meshes, sand bed filtration, nylon sock-type filtration, metal strainers, gravel filtration, and mulch tower systems.

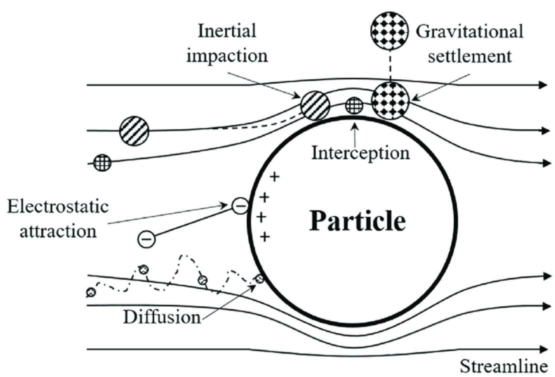


Figure (3) Filtration Mechanism [10]

[11] demonstrated a mean removal rate of 30% for COD through sand filtration in treating greywater derived from bathrooms. Similarly, [12] achieved a mean removal rate of 26% for COD and 52% for TSS by employing a mulch tower system comprising mulch, coarse sand, fine gravel, and coarse gravel. Membrane filtration techniques such as microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF) consistently yield high-quality effluents, with quality directly linked to the molecular mass cut-off (MWCO) of the membrane [13]. Notably, Ramona et al. (2004) achieved a mean removal rate of 93% for COD, 84% for TOC, and 50% for soluble ionic elements through NF treatment of greywater from showers, resulting in effluent of exceptional quality suitable for unrestricted irrigation.

Table 2: Materials used in greywater treatment

Type of Material	Target Pollutant	Removal Mechanism
Activated Carbon	BOD_5, COD, TN, TP	Adsorption
Activated Charcoal	EC, BOD_5	Adsorption
Peat moss and lime pebbles	COD, BOD5, E.coli	Filtration
Pine Bark	BOD5, COD, TN, TP	Adsorption
Moringa oleifera	COD, Turbidity, Conductivity, BOD5	Coagulation
Sawdust	TSS, TDS, O&G, COD	Filtration

When compared to physical and chemical treatments, submerged membrane bioreactor system (SMBR) technology stands out as the sole method capable of attaining satisfactory removal efficiencies for organic substances, surfactants [14], and microbial contaminants without requiring additional post-filtration or disinfection steps. In essence, SMBR technology has demonstrated itself as the most effective approach for treating and reusing greywater by integrating the physical separation of colloidal substances, including pathogenic bacteria, with aerobic biological treatment of dissolved organic matter.

So, this research study aims to combine the filtration process through a vertical way and biological treatment represented in submerged membrane bioreactor system (SMBR) technology on greywater to achieve the proper degree of treatment to reuse it for irrigation purposes as illustrated in Figure (4).

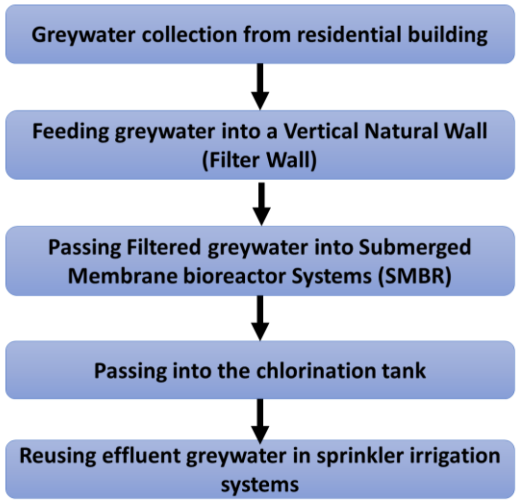


Figure (4) Experimental Frame Work

So, this research study aims to provide a compressive understanding of the performance of combing the filtration performed by various natural-based materials followed by biological treatment represented by submerged membrane biofilm reactor (SMBR) to achieve a proper treatment of greywater collected from residential buildings to reuse it as a renewable source for irrigation.

3. Methodology

3.1. Greywater Sampling Collection

As illustrated in Figure (5), greywater samples were collected from the washing basin in a residential building in El-Sharqia, Egypt. 100 liters of greywater were collected from 5 plastic containers each with 20 liters. To prepare the plastic containers for greywater samples, they were sanitized by rinsing them with diluted water to maintain the original properties of the raw greywater. The samples were then acidified to preserve the levels of COD and BOD before transporting them to the experimental site, where the small-scale model was set up. Table (3) illustrates the

Physiochemical characteristics of collected greywater.

Figure (5) Greywater Collection

Table 3: The Physiochemical characteristics of collected greywater.

Parameter	Average Value	Standard Deviation
pH	7.9	0.2
Total suspended solids, TSS	98	5.6
Biological oxygen demand, BOD	212	12.4
Chemical oxygen demand, COD	374	27.5
Total nitrogen, TKN	27	5.3
Total phosphorous, TP	13.5	1.7

3.2. Filtration media preparation

3.2.1. Bentonite Nano-particles Preparation

- Natural bentonite was obtained from a commercial company called “National Company for Natural Bentonite”.
- The bentonite is dried in an oven at 100°C for 7 days to remove moisture.
- After drying, the bentonite is crushed using a mortar to break it into smaller pieces.
- The crushed bentonite is further milled using a planetary ball mill (PBM) at a ratio of 1:5 for 24 hours (15 rpm).
- The milled bentonite powder is sieved through a 200-mesh screen.
- The sieved powder is diluted with hydrochloric acid (HCl) at a concentration of 32% (10M) and heated to 70°C for 90 minutes while stirring at 300 rpm.
- The solution is washed repeatedly with distilled water until it reaches a normal pH level.
- Finally, the washed solution is dried at 70°C for 5 hours.

3.2.2. Date seeds Preparation

- Date seeds were gathered, cleansed, and air-dried using an oven.
- The dried seeds were moistened with water and covered with a wet cloth, then left at room temperature for 40 days, ensuring the cloth remained damp.
- After germination, seeds with consistent characteristics were rinsed, air-dried using a fan oven, and subsequently crushed into a powdered sample.
- The powdered sample was washed with distilled water and dried at 110°C for 6 hours.

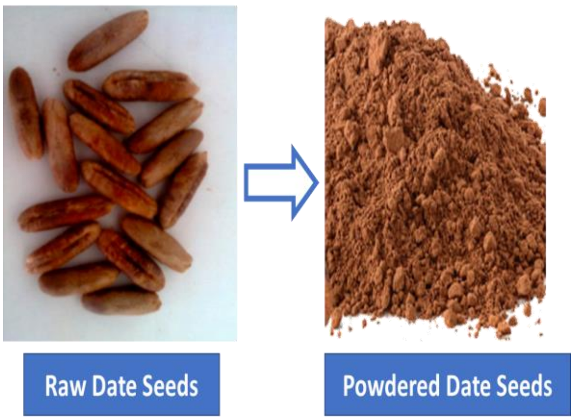


Figure (6) Date Seeds Preparation

3.2.3. Zeolite

This research used natural zeolite (Cp), specifically clinoptilolite from Egypt (obtained commercially from Gamma Company), with a size fraction of 0.2–1 mm. As reported by [15], natural zeolites act as cation exchangers due to their negatively charged surface. Chemical modification with (hexadecyltrimethylammonium bromide) is done to enhance zeolite properties and improve its effectiveness in water treatment. Normally, water molecules fill the large cavities and channels inside the zeolite framework, forming hydration spheres around exchangeable cations. To remove anions from water, the zeolite surface is modified with a solution of inorganic salts resulting in the formation of oxy-hydroxides that bind with anions in solution. This modification led to the creation of an adsorption layer on the zeolite surface and a change in surface charge from negative to positive. The modification is summarized as follows:

- 1 gram of CP was placed into a beaker containing 100 milliliters of redistilled water.
- The mixture was stirred using a magnetic stirrer and heated to 80°C for 3 hours.
- Following this, 1 gram of HDTMA-Br dissolved in redistilled water was added to the Cp mixture.
- The Cp mixture with HDTMA-Br was stirred at 80°C for 24 hours.
- Subsequently, another portion of 1 gram of HDTMA-Br solution was added to the Cp mixture and stirred for an additional 5 hours.
- The modified material was then subjected to centrifugation at 4500 rpm for 5 minutes.
- It was washed with hot redistilled water until the test for bromides (Br-) using AgNO3 indicated negative.
- Finally, the modified material was washed with hot ethanol and dried at 105°C for 24 hours.

3.3. Experimental model setup

3.3.1. Vertical Wall Configuration

The vertical wall is a Multi- Vertical Filter packed with several materials. The wall consists of 4 vertical filters each with a 20 cm width separated by a gravel column with a 10 cm width to provide stability for the systems and the raw greywater is fed into the wall through a pump at the rate of 10 L/ h from the top of the vertical wall. To stabilize the flow entering the filter, and convert it into homogenous, isotropic without forming a vortex that hurts the filter efficiency, a layer of medium gravel is layered on the top of the filter where flow is entered to enable the uniformity of the greywater flow. Figure (7) shows a full description of the vertical filter.

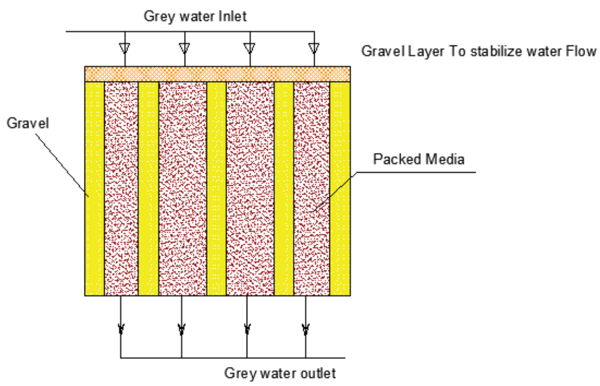


Figure (7) Vertical Filter Wall

3.3.2. Submerged Membrane Bioreactor System (SMBR)

The submerged membrane bioreactor system (SMBR) utilized a bioreactor with a working volume of 45 L with a dimension of 60 cm × 30 cm × 30 cm. The system included a hollow fiber ultrafiltration (UF) membrane module, specifically from BituNil Membrane Solutions, Egypt, submerged within the bioreactor as shown in Figure (8). This membrane module comprised 80 fiber units, each measuring 0.2 meters in length, with a pore size of 0.04 mm and a total surface area of 0.047 m^2. Effluent from the membrane module was extracted using a peristaltic pump, maintaining a constant transmembrane pressure (TMP).

To ensure adequate dissolved oxygen levels for microorganisms within the bioreactors, compressed air was supplied via a perforated tube located at the membrane module's bottom, at a flow rate of 3.4 L/min. Additionally, the compressed air served to induce shear stress for effective scouring of the membrane surfaces and facilitate thorough mixing of the sludge suspension within the bioreactors.

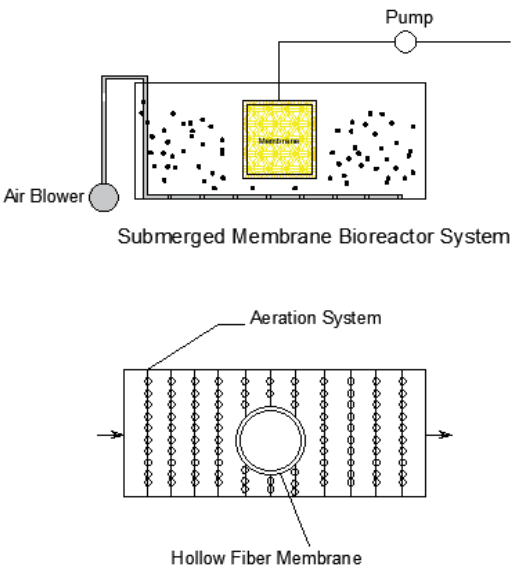


Figure (8) Submerged membrane bioreactor system (SMBR)

3.4. Steps of Experimental Work

Greywater samples were collected from a building, and fed into a feed tank to prepare it for experimental work. Greywater was fed under pressure through a centrifugal pump with rate of 10 L/hr. into the vertical wall which is packed with different materials (Zeolite–bentonite-date seeds). Each material was used separately. Then, Filtered greywater was passed into SMBR where biological treatment took place for a hydraulic retention time (HRT) of 8 hours. The dissolved oxygen in the aeration tank was adjusted to 3 mg/l. After an HRT of 8 hours, the effluent was pumped through a pump at a rate of 10 L/hr. into a chlorination tank to eliminate the microorganisms grown in the aeration tank. The chlorine dose of 0.5 mg/l was added to the greywater to be collected into a reservoir to be used as a feed tank for sprinkler irrigation systems. Figure (9) illustrates the full scheme of the laboratory pilot.

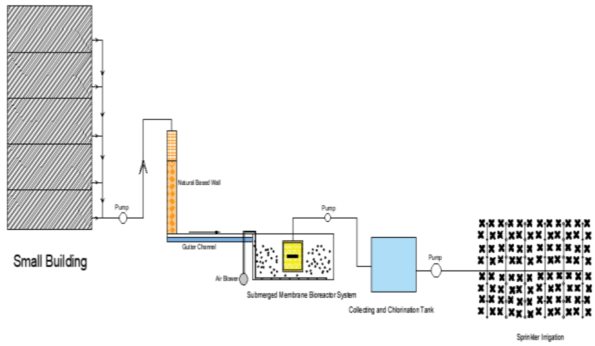
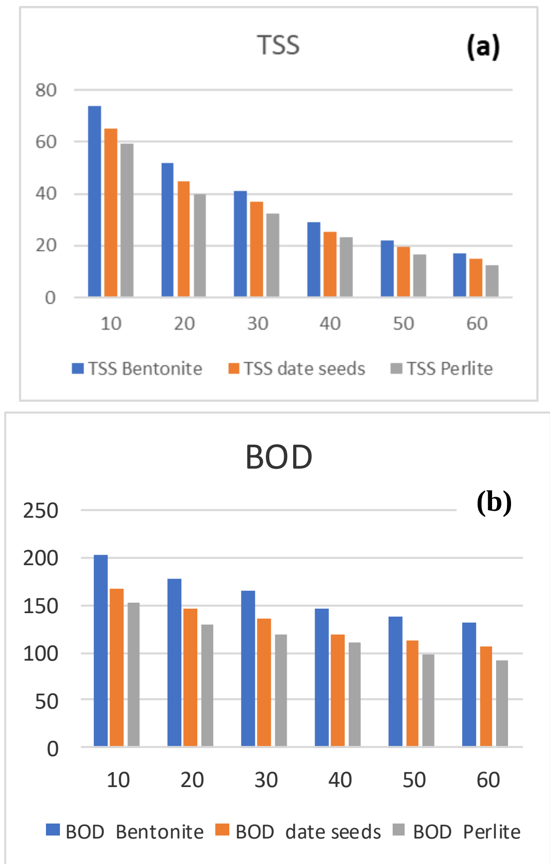


Figure (9) a scheme of the laboratory pilot

4. Results and Discussion

4.1. Performance of filtration media for Pollutants Contaminations removal

As illustrated in Figure (10), perlite shows remarkable performance in removing organic matter, suspended solids, and nutrients from greywater, and is better than both date seeds and bentonite, respectively.



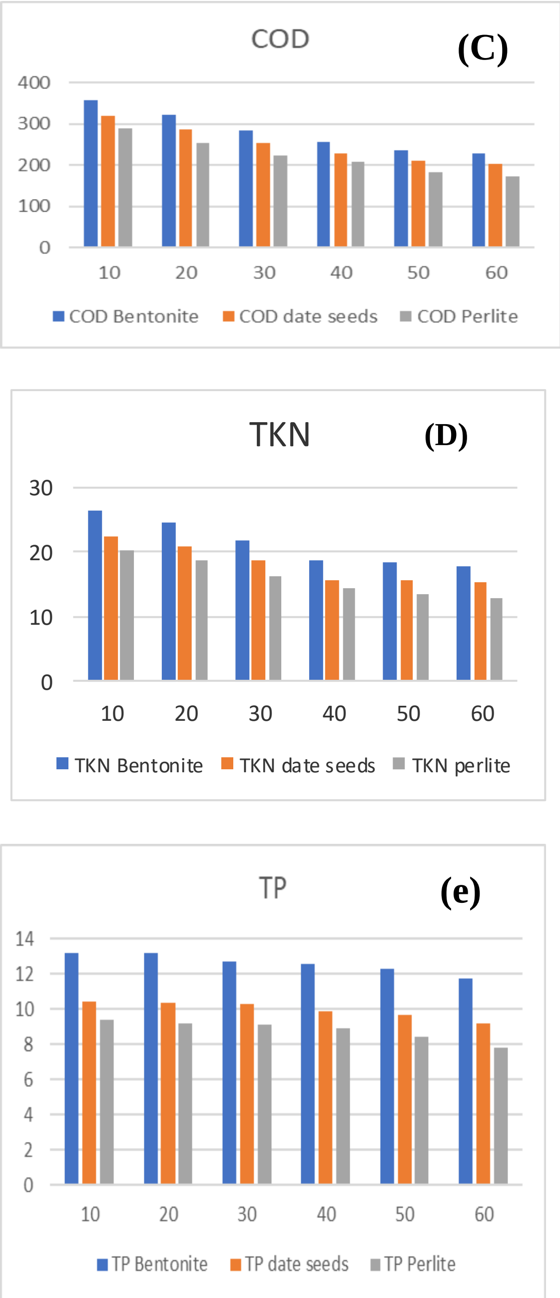


Figure (10) Performance of each Filter media at various sampling times (a) TSS, (b) BOD, (C) COD, (D) TKN, and (e) TP

4.2. Removal of Total Suspended Solids (TSS)

As proven in Figure (11), the TSS removal efficiency of perlite was 39.59%, 59.49%, 67.04%, 76.43%, 82.86%, and 87.14%, respectively over sampling times of 10, 20, 30, 40, 50, and 60 minutes. It cannot be overemphasized that Perlite is the best product when there is a need to efficiently get rid of suspended particles. It has been recognized for that capacity and has been used extensively in water treatment Although Bentonite and Date seeds can sometimes have some effects in particular cases or special environments, among other factors, the wide-reaching application of Perlite makes it the preferred option. Many types of suspended particles have negative impacts on greywater quality due to overloading it with absorbance of nutrients or toxic elements. As greywater flows past or through perlite filter beds or encounters perlite filter aids, these particles may end up being physically captured by the microscopic pores and voids within perlite. With this granulated filtration process, not only does the suspension flow get separated, but organics are also removed, leaving the water cleaner before discharge [16].

The high removal efficiency of TSS over bentonite and date seeds may be due to the usage of nanoparticles of perlite. Nanoparticles of perlite greatly enhance the removal of suspended solids from greywater by maximizing surface area and adsorption properties [17]. Their smaller size allows for deeper penetration into the water, leading to stronger interactions with suspended solids. This results in more efficient particle capture and retention, improving overall filtration performance. Ultimately, nanoparticle-sized perlite significantly boosts the effectiveness of greywater treatment, leading to higher-quality water and more sustainable wastewater management practices [18].

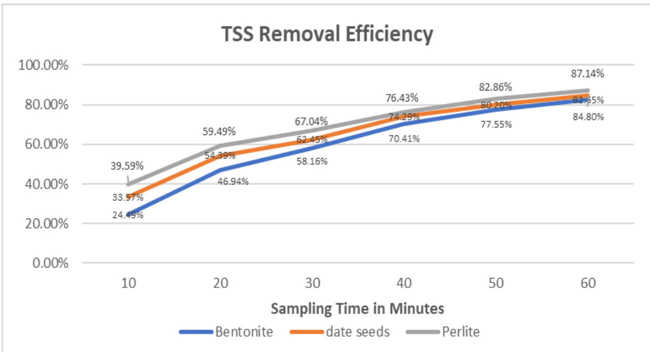


Figure (11) TSS removal efficiency

4.3. Removal of organic matter and nutrients

Perlite nanoparticles also achieve a better COD, and BOD performance than the two other media by achieving a removal efficiency up to 56.95% for BOD, and 53.66% for COD.

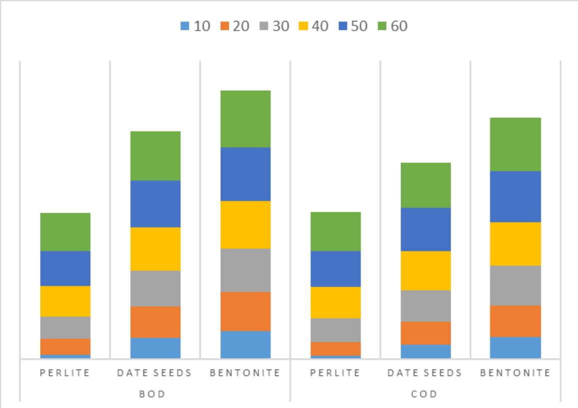


Figure (12) COD and BOD removal efficiency

Perlite has three mechanisms to remove COD and BOD from greywater via the multistage process. The porous structure in perlite acts like a trap of suspended solids and organic matter in the greywater by preventing them from passing through. The solids represent the main component of the biological load in the water, which is expressed in COD and BOD indicators.

Furthermore, perlite's surface properties implicate some degree of adsorption wherein organic compounds adhere to its surface. This sorption too further diminishes the amount of organic pollutants in the water resulting in reduced COD and BOD concentrations [19]. Moreover, perlite can facilitate microbial activity, though not as much as the dedicated biofiltration media. Microorganisms that naturally exist on perlite surfaces can eat natural organic materials leading to their further decomposition and decrease of COD and BOD [20]. Perlite's filtration, adsorption, and microbial activity together form vital functions in removing organic contamination as well as reducing the COD and BOD levels of greywater which could make the efficiency of wastewater treatment more effective [21].

4.4. Performance of Submerged Membrane Bioreactor System (SMBR)

Table 4: The concentrations of COD, BOD, TSS, TKN, and TP in mg/l after each treatment stage

	Parameters	Raw greywater	Filtration Stage	SMBR (HRT=8 HR)	Cl_2 Tank
Perlite	TSS	98.00	12.60	5.04	5.00
	BOD	212.00	91.20	14.59	11.30
	COD	374.00	172.40	20.69	16.90
	TKN	27.00	12.90	2.71	2.62
	TP	13.50	7.80	4.68	4.65
Date Seeds	TSS	98.00	14.90	6.54	6.32
	BOD	212.00	107.40	18.24	15.70
	COD	374.00	202.90	25.86	21.90
	TKN	27.00	15.20	3.79	2.86
	TP	13.50	9.20	6.85	5.40
Bentonite	TSS	98.00	17.00	5.81	5.81
	BOD	212.00	131.00	19.70	16.90
	COD	374.00	228.00	27.93	24.30
	TKN	27.00	17.90	4.09	3.60
	TP	13.50	11.73	7.40	6.30

The efficiency of the SMBR system in removing COD, TKN, and TP, as factors to measure, was assessed. For COD, the average removal efficiency during the first phase was 72 % and became 88 % during the last stages, as the microbial population growth was significant. For the course of the experiment, SMBR has managed to achieve a removal efficiency of 88%. As for the TKN extracted, things went well after the first period and the system efficiency reached an average of 79 %. The removal rate of TP in the sample was seen to fluctuate from 21 %, before increasing further back to 42 %. Generally speaking, during the entire SMBR operation, COD and TKN expectations were achieved, with some fluctuation in TP removal throughout the cycle.

Based on previous studies [22], The SMBR system is noted by a synergy of biological processes and physical filtration generated by the membrane technology thus leading to the rejection of organic matter from the wastewater. SMBR Procedure comprises the flow of the greywater into a reactor containing microorganisms, for instance, bacteria and fungi, which destroy the organic wastes in the greywater. For nutrition, these microorganisms use organic material as the food source that further gets converted to simpler forms such as carbon dioxide and water which are more stabilized. Out of this biological digester process, the concentrations of the organic contaminants found in the greywater are decreased considerably [23].

The membrane acts as a physical filter, separating only the water from the silt, bacteria, and other large molecules, thus allowing the clean water to pass while keeping the contaminated particles. Consequently, the membrane adequately evacuates fit clean water from the treated gray water resulting in a high-quality effluent with low levels of organic compounds. In addition, the membrane immersed in the water in the bioreactor intensifies and retains biomass which consequently improves the efficiency of the treatment processes based on biology. Through the sustainment of a high microbial population in the bioreactor, the system is well-built to provide continuous organic matter degradation that ultimately leads to improved treatment performance and better organic pollutant removal in the greywater [24].

4.5. Availability of Treated Greywater for irrigation

It was proposed that the treated wastewater generated by the pilot project be directed into a collection tank designated as the feed tank for a sprinkler irrigation network. According to Figure 13, the concentrations of TSS in the effluent greywater range from 5 mg/l to 6.30 mg/l, BOD ranges from 11.30 mg/l to 16.90 mg/l, and COD ranges from 16.90 mg/l to 24.30 mg/l. These recorded concentrations were found to be below the specified limits for COD, BOD, TSS, TN, and TP as outlined in the Egyptian regulations for agricultural reuse purposes. [25]

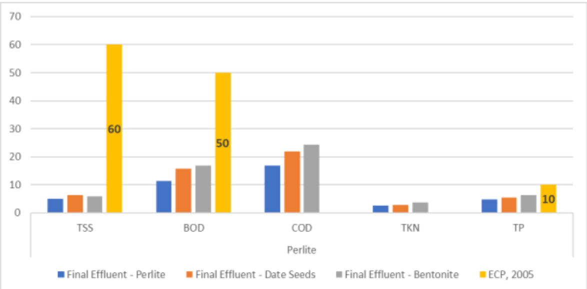


Figure (13) Comparison between Final Effluent and ECP for 2005

4.6. Applicability of reused greywater on sustainability

The integration of nature-based materials in the process of treated greywater recycling for irrigation as an alternative will be the major contributor to achieving sustainability targeted in Egypt's Vision 2030. There are thus several sustainability targets that we can address through the application of agro-waste in the treatment process. First of all, filtered natural filtration substances promote the fast and intensive removal of contaminants from greywater, making it more suitable for irrigation while putting less pressure on freshwater resources. Furthermore, converting agricultural by-products to water treatment utilizes the capacity of a circular economy and application of resource efficiency which could reduce waste and environmental conservation. Also, incorporating natural filtering materials into water treatment systems harmonizes with agriculture sustainability by providing eco-friendly alternatives for irrigation water reuse that increase crop productivity and help achieve food security issues targeted for Egypt's vision for 2030. Fundamentally, bentonite clay, perlite, and date seeds are amongst the natural adsorption materials used in water treatment for irrigation purposes, which have significant contributions to the accomplishment of the aforementioned goals.

5. Conclusion

Accordingly, this research offers the primary importance of natural filtration components, like clay bentonite, perlite, and date seeds, in the water discharge process involving the irrigation sector, which in turn supports the objectives of the Sustainable Water Resource Management in Egypt's Vision 2030 document. The study exerts waste materials from agriculture for the organic matters as well as contaminants removal from this greywater into a stream that is approved according to the regulation of agriculture reuse. The paper indicates the usefulness of the SMBR-based integrated technology for wastewater treatment in which the organic filtering materials symbolize the improvement of water quality and encourage water reuse. Thus, in addition to overcoming water scarcity problems, the utilization of these materials as well is of great importance for circular economy concepts and agricultural sustainability if Egypt aims to make environmental sustainability one of its main priorities.

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Conflict of interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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