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ORIGINAL RESEARCH PAPER

Development of a sustainable, green, and solar-powered filtration system for E. coli removal and greywater treatment

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ABSTRACT

BACKGROUND AND OBJECTIVES: Jordan's limited water resources have reduced daily water consumption, leading to a highly concentrated greywater production rate of 54 million cubic meters per year. The presence of nitrate ions, total dissolved solids, total suspended solids, chemical oxygen demand, and biological oxygen demand in greywater poses excellent environmental and health risks when disposed untreated. Water scarcity directly impacts water and food security and is expected to intensify at the current resources management practices. The significance of the current and predictable water shortage in the context of sustainable development and the presence of new technologies brought further attention to utilizing non-conventional water sources. Reclamation of treated wastewater, greywater, brackish, and seawater desalination is Jordan's water budget's only non-conventional water resource. This study aims to address Jordan's water scarcity crisis by developing a low-energy, solar-powered greywater filtration system using natural materials while ensuring compliance with Jordanian standards for safe agricultural applications.

METHODS: Several treatment methods have been proposed; however, most of these systems require high to medium energy levels for treatment purposes. Hence, the running cost of the system is relatively high. To address this issue, a four-stage, low-energy, green, and decentralized solar filtration system for greywater treatment has been developed, which uses natural materials available in Jordan and activated carbon to reduce organic and solids content and remove pathogens. The system also uses hot water generated by a Photovoltaic solar system to sanitize the greywater, a novel concept of approach for sanitization. This innovative system is powered entirely by solar energy and can be installed in individual homes.

FINDINGS: The results of the developed solar filtration system were very efficient in reducing turbidity, chemical oxygen demand, and Escherichia coli removal: 92, 95, and 100 percent, respectively. Furthermore, the system showed a high potential for total coliforms and Escherichia coli inactivation, reaching 4.64 and 3.15 log units, respectively. Product water meets Jordan standards, ensuring safe reuse for irrigation applications. The findings of this study highlight the satisfactory performance of the developed greywater solar filtration setup. The economic feasibility analysis demonstrates that the proposed system is economically viable and financially sound. The system's reliance on solar energy and the absence of consumables contribute to its sustainability. They are addressing sustainable practices in greywater treatment in addition to water scarcity concerns.

CONCLUSION: The treated greywater, obtained through the series of treatment steps, including solar disinfection, successfully met the Jordanian standards for safe reuse. The substantial reduction of Escherichia coli and total coliforms to acceptable levels demonstrates the treatment system's effectiveness in generating pathogen-free greywater, suitable for a wide range of applications. The study concludes that the solar filtration setup consistently delivers high-quality, pathogen-free greywater, meeting stringent regulatory requirements. This innovative, sustainable system offers a viable solution to Jordan's water scarcity, introducing a new non-conventional water resource that requires no consumables (non-chemical, non-hazardous materials), thereby addressing sustainability concerns in greywater treatment.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
41	9	7

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INTRODUCTION

Almost 94 percent of people in Jordan have access to fresh water through the public network, and 93 percent (%) have access to clean sanitation services (63% via the public sewer network and 30% via other safe means) (MWI, 2023). As a leader in the reuse of treated wastewater, 90% of wastewater produced in Jordan around 178.2 million cubic meters (m^3) annually- is treated at 32 wastewater treatment plants to ensure compliance with Jordanian irrigation and industrial reuse standards and is reused directly or indirectly in agriculture (Bdour and Hadadin, 2005). According to the most recent water budget report from the Ministry of Water and Irrigation (MWI, 2023), the available water from all resources in 2022 was 1104.8 million m^3 distributed as 30.8% surface water, 54.4% groundwater, 14.5% treated wastewater, and 0.3% sea desalinated water (Fig. 1.). Around 96% of available water are mainly used for domestic and agricultural purposes, where the municipal uses about 47.5%, irrigation uses 48.6%, and the industrial sector uses only 3.3% (WMI, 2023). The domestic water demands represent one of the most significant challenges faced by the water sector in Jordan. Water Authority of Jordan (WAJ) claimed that as the drinking water deficit remains an alarming problem due to water shortage, the exponential population growth intensifies the domestic water needs, creating inflation in the domestic water tariffs (MWI, 2023). Over the last decade, WAJ decided to increase the water charges for domestic and industrial uses to compensate for the prolonged increase in water demands accompanied by the intense water shortage. The domestic and industrial water tariffs have almost doubled over the last decade. As such, although the most significant freshwater sources are allocated to the agricultural sector (about 51-60% of the groundwater), the irrigation water tariffs also increased, at least by more than 20% (MWI, 2023; Van Den Berg and Agha Al Nimer, 2016).

Overview of the promising role of greywater

For countries with limited water resources, every droplet is very important. Jordan is considered one of the poorest countries in water availability rates according to the population-resource equation (Fig. 2). This water challenge has increased in the last few decades as a result of natural expansion as well as the influx of refugees. Hence creating a burden on the limited water resources. In other words, the water used is higher than the renewable supply (Halalsheh *et al.*, 2008). This water shortage leads to the production of large amounts of concentrated greywater. Finding alternative water resources and recycling methods is important since greywater can be collected, treated, and later used in agricultural fields (Chowdhury and Abaya, 2018). Greywater is generally defined as wastewater resulting from used water except for toilet use (fecal contamination) (Hadadin *et al.*, 2010). The composition and

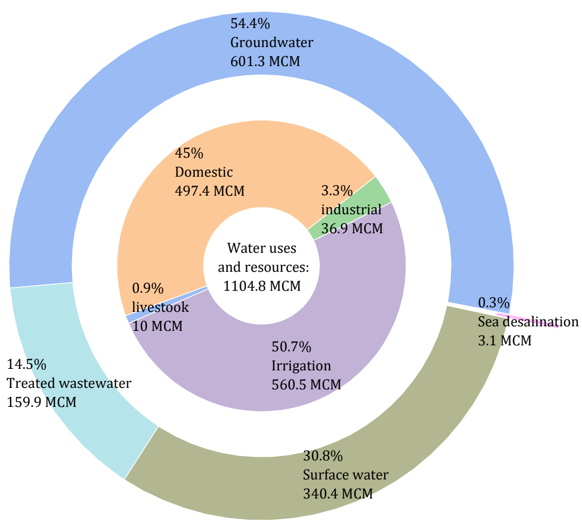

Fig. 1: Water uses and resources for 2022 (MWI, 2023)

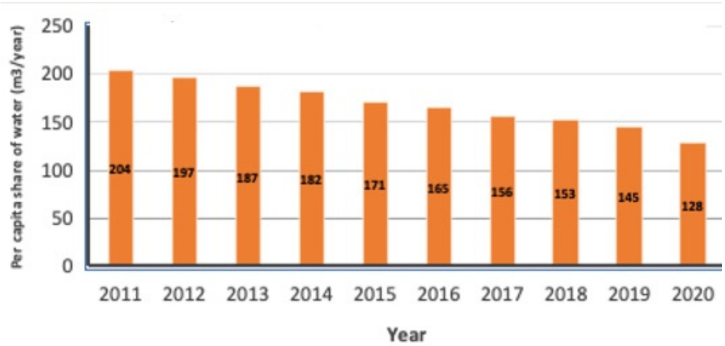

Fig. 2. Per capita share of water in (m^3/year) in Jordan for the last decade (MWI, 2023)

characteristics of greywater vary and reflect the nature of lifestyle and the variations in used water compared to discharged waste. It is acidic and has a potential of hydrogen (pH) value of 5.44 (Chowdhury and Abaya, 2018; Balasubramanya *et al.*, 2022). It is estimated that 50-80% of greywater is produced from household wastewater (Balasubramanya *et al.*, 2022; Albalawneh and Chang, 2015). In 2018, the amount of greywater produced in Jordan at the household level typically ranged from 51 to 63 Liter per person per day (L/person/day) and about 54 million m^3/ year (Al Arni *et al.*, 2022). Few studies investigated the characteristics of greywater. Ammari *et al.* (2014) reported the average values of nitrates (NO^3), total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), and biological oxygen demand (BOD) to be 104.7, 2022, 508, 1688, and 1155 parts per million (ppm), respectively. The reported characteristics were higher than the Jordanian standards (JS 893/2006) of chemical and biological characteristics for recycled greywater, indicating the need for treatment before use. Various technologies are being studied and developed for greywater treatment. Some technologies focus on biological treatment systems, including upflow anaerobic sludge blanket (UASB), membrane bioreactors (MBR), constructed wetlands (CW), and sequencing batch reactors (SBR). For example, by adding seed sludge from an anaerobic digester processing primary and secondary sludge, UASB achieved 76% biodegradability and 84% COD removal (Leong *et al.*, 2017). However, the specific conditions affecting their performance, such as greywater fractions and loading rates, need more detailed exploration to optimize their efficiency (Bani-Melhem *et al.*, 2023). Hybrid membrane bioreactors (HMBR) removal of COD, BOD_5, and total phosphorus (TP) was identical to conventional bioreactors except for ammonia (NH_3), which was slightly higher in the modified bioreactor (Palmarin and Young, 2019). Using a multistage CW showed that the system performance depends on different greywater fractions and hydraulic and organic loading rates (Magalhães Filho *et al.*, 2021). The coupling between SBR and solar photocatalytic reactor (SPCR) as a potential method to remove contaminants from greywater (organics, nutrients, and emerging contaminants (ECs)) reached 100% efficiency for the net total organic carbon (TOC) removal, and 93 % for total nitrogen (TN) removal (Priyanka *et al.*, 2022). While HMBR demonstrated similar performance to conventional bioreactors, understanding the implications of higher ammonia levels in modified bioreactors is essential for evaluating its overall effectiveness (Blanky *et al.*, 2017).

Other technologies looked into chemical treatment systems, such as granular activated carbon, coagulation (GAC), ion exchange, and photocatalytic oxidation. The study of biologically active GAC (BAC) as a recommended media for biofilters found that the Freundlich isotherm was the best fit for the equilibrium adsorption data; the adsorption kinetics were found to be best fit by the pseudo-second-order and intraparticle diffusion models. Also, intraparticle pore diffusion was rate-limited, with some mass transfer resistance due to external film diffusion at lower COD gradients (Sharaf and Liu, 2021). The assessment performance of intermittently operated saturated filters of different grain sizes using natural greywater coagulated with polyaluminium chloride (PACl) based on physicochemical and microbial parameters showed a significant reduction in turbidity, BOD, and COD

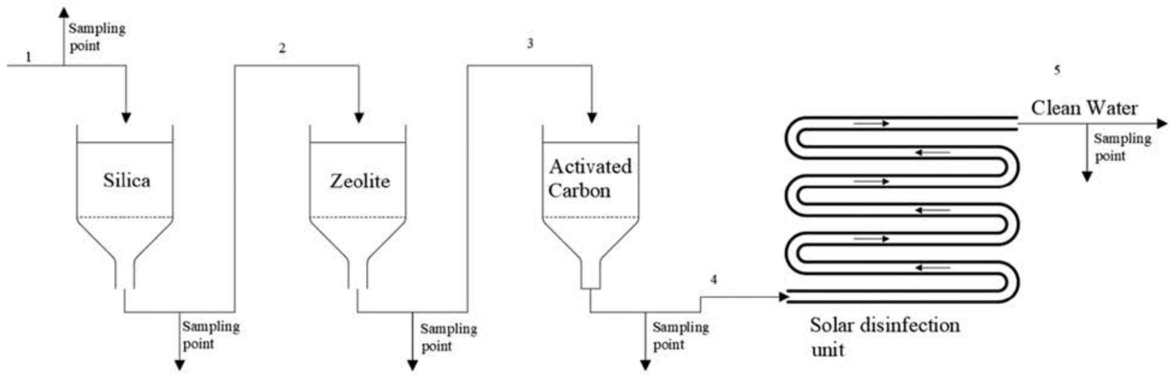

Fig. 3: Flow chart of the proposed solar filtration system (SFS)

by 94, 76, and 80%, respectively when using sand filtration after coagulation (Singh *et al.*, 2021). Spent green tea was evaluated as a potential adsorbent to remove toxic materials from greywater, such as mercury (Hg^{2+}), lead (Pb^{2+}), and cadmium (Cd^{2+}), which found the highest adsorption capacity for Hg^{2+} and Pb^{2+} ranged from 10 to 100 milligram/gram (mg/g). The adsorption efficiency at various concentrations in mono systems by the adsorbent from tea waste ranged from 99.99% to 100% for Hg^{2+} and Pb^{2+} and also from 11.11% to 18.28% for Cd^{2+} (Gameli *et al.*, 2022). Also, a submerged spiral-wound ultrafiltration (UF) membrane module for a greywater treatment system was investigated. It found that the UF membrane filtration system could maintain a permeate flux of 6 to 10 Liter per square meter per hour (L/m^2/h). TOC in the permeate can be reduced from 161 milligrams per liter (mg/L) in the influent to 28.6 mg/L, resulting in an average elimination rate of 83.4 (Li *et al.*, 2009a). It needs a discussion on the long-term performance, fouling issues, and practical considerations for large-scale implementation (Khalil and Liu, 2021). Physical treatment systems are also being studied, including membrane filtration and coarse sand and soil filtration, which was mostly followed by a disinfection step (Li *et al.*, 2009b). The effectiveness and performance of a horizontal series filter (HSF) containing different efficient adsorbents such as GAC, natural zeolite, and pumice in single and combined forms for the removal of COD, BOD5, TDS, pH, and turbidity from greywater showed that GAC outperformed zeolite as the best adsorbent for removing COD, BOD5, and TDS from greywater. However, pumice is preferable for removing turbidity (Bahrami *et al.*, 2020). It reported that the biodegradability of greywater is badly affected due to the existence of surfactants and nutrients. The standard greywater treatment methods only removed some of the amount of surfactants and nutrients. These nutrients are the best food to be consumed by bacteria such as Escherichia Coli (*E. coli*), found in greywater. Despite the efficiency of these proposed systems, these treatment systems suffer from a significant drawback as they require a high to medium level of energy for treatment purposes; hence, the system's running cost is relatively high (Waris and Ghaith, 2022). The primary aim of the current study is to design a decentralized, low-cost, and green greywater treatment system that can recycle treated water for toilet flushing, garden irrigation, and car washing purposes rather than disposing of it into the sewer.

Moreover, hot water using a photovoltaic (PV) solar system will be utilized to sanitize the greywater by elevating water temperature to a level that can kill most pathogens and microorganisms in greywater. These objectives collectively aim to advance the understanding of greywater treatment technologies, offer a practical solution with environmental and economic benefits, and provide valuable non-conventional water resources in regions facing water scarcity challenges. This study was conducted at Jordan University of Science and Technology (JUST) in 2022-2023. By addressing the aforementioned knowledge gaps, this study can ensure that the proposed greywater treatment system is innovative, sustainable, and precisely tailored to the challenges presented by Jordan's water shortage dilemma.

MATERIALS AND METHODS

The greywater treatment system designed and developed in this study is to be decentralized and standalone, allowing it to be installed at individual households, buildings, or properties. This approach provides building owners, whether residential or commercial, the flexibility to install a system tailored to their needs and reuse the treated water for different purposes. Also, the system has a low energy consumption and is driven by solar energy.

System design and development

In recent years, various natural minerals, including clay, silt, and zeolite, have significantly removed hazardous materials from water and wastewater resources. The developed system treats greywater in four stages, as shown in Fig. 3. Stages 1, 2, and 3 contain silica sand, zeolite, and activated carbon, respectively. The designed system directs water to enter each stage aforementioned from the top and exit to the next stage from the bottom. Then, the treated water is passed through solar collector tubes. The greywater will undergo several filtration stages intended to remove solids that may be present via silica sand, absorb chemicals that may be present by zeolite, and remove any residual detergents and odor that may remain in the greywater using activated carbon. The output of the third tank passed through solar collector tubes, which provide uniform heating to avoid any cold spots where pathogens may survive and overcome microbial and pathogen resistance for chemical treatment.

The solar disinfection step was introduced as thermal disinfection is probably the eldest disinfection technique (Pansonato *et al.*, 2011). The temperature of filtered greywater is increased and optimized to reach about 70 degrees Celsius (°C), which is higher than the optimal temperature for heat pasteurization of 65°C needed to kill existing pathogens in greywater (Al-Gheethi *et al.*, 2013; Khajvand *et al.*, 2022). Moreover, introducing hot air into the first three stages of the system through a specially designed opening was also tested to investigate the effect of hot air in enhancing the treatment results by sanitizing the treatment medium and water. Hot air was introduced through solar units that heated and conducted the ambient air into the tanks. In order to optimize the operating parameters, this study investigated the optimum flow rates of feed water, material characteristics, operating temperature, and contact time. The experimentation was based on the quality of the treated water and incorporated physical and chemical tests required by the Jordanian standards of water (JS 893/2006) (Ammari *et al.*, 2014). Fig. 4 shows the greywater system that has been designed and used in this study, which consists of the three tanks, while Fig. 5 shows the solar panels used for hot air and the disinfection unit.

To determine the optimum contact time for sanitizing greywater, several factors were considered in this study, including initial pathogen concentration, initial water temperature, and desired level of disinfection. Commonly, at higher temperatures, the required contact time is shorter. This study investigated contact time intervals, namely, 2 minutes, 4 minutes, and 6 minutes, to determine the sufficient level needed to achieve the desired reduction in fecal coliform bacteria that meets Jordan Standards for recycling reclaimed domestic wastewater (JS 893/2006). Herein, more than hot water treatment is required for the complete disinfection of all types of pathogens, and other treatment techniques may need to be combined to achieve the desired level of disinfection.

Experimental procedures

One milestone aspect of this study was the optimization of various parameters of the treatment process, such as the size of silica sand particles used in the first stage of treatment. Initially, a 400 micrometer (µm) silica sand was used, but this particle size was unsuitable as it blocked the porosity and clogged the treatment tank due to the small size. Changing the size to around 1 millimeter (mm) showed a better performance of the treatment tank. Table 1 shows the grain size distribution of the various filtration mediums used in this experiment. For silica, most of the medium falls within the range of greater than 600 µm and less than 1.8 mm, accounting for 86% of the total. A tiny portion, only 0.90%, lies within the range of greater than 1.8 mm and less than 2 mm. The remaining 13.10% of the silica medium has a diameter smaller than 600 µm.

A total of 2400 liters (L) of greywater from domestic household showers and bathroom sinks were treated using the proposed system. The water was treated

Fig. 4: Developed greywater filtration system

Fig. 5: Solar panels used for hot air and the disinfection unit

with and without the introduction of hot air. It is worth noting that no synthetic greywater was used in this study. The tests were conducted on different days due to the limited daily greywater collection and unsuitable weather conditions. Greywater from the bathroom sink and showers were mixed in a tank and conveyed to the tanks according to the previous description. Samples of water from the mixture tank and out of each tank were collected to conduct different physical, biological, and chemical tests; locations of sampling points are shown in Fig. 3. A total of 24 greywater samples were collected from the influents and effluents of the SFS stages, and stored at room temperature for a maximum of three days. The collected samples were analyzed for pH, electrical conductivity, turbidity, BOD, COD, TOC, density, E. coli, and total coliforms. The majority of the tests were conducted at the WAJ laboratories.

The greywater system designed in this study operates as a decentralized and standalone unit, providing adaptability for individual installation in wide settings. The four-stage treatment process incorporates silica sand, zeolite, and activated carbon to eliminate solid contaminants effectively, absorb chemicals, and neutralize residual detergents and odor. Solar collector tubes and the introduction of hot air contribute to thermal disinfection, optimizing pathogen elimination (Samimi and Moghadam, 2024). Experimental procedures involved an essential optimization phase, determining factors like silica

Table 1: The grain size distribution of the various filtration mediums used in this experiment.

Silica		Zeolite		Granular activated Carbon	
600 µm -1.8 mm	86%	600 µm -1mm	19%	300 µm - 600 µm	2%
1.8 mm-2 mm	0.90%	300 µm - 600 µm	24%	600 µm - 1mm	98%
<600 µm	13.10%	1 mm -1.4 mm	57		

Table 2: Average measurements for treatment with and without hot air

Measured parameter	With hot air				Without hot air			
	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	Mix tank	Silica sand tank	Zeolite tank	Carbon tank
pH	7.29	7.5	7.6	8.01	7.22	7.3	7.5	7.81
TDS	428	429	442	448	593	436	448	488
Turbidity	62.6	25.8	4.8	4.4	77.2	35.2	7.9	4.5

sand particle size, contact time, and the impact of hot air introduction. Notably, optimizing the treatment process parameters, such as the size of silica sand particles, was undertaken to enhance overall system performance. The experiments used 2400 liters of natural domestic greywater from showers and bathroom sinks. Samples were collected at various stages, and a comprehensive set of physical, chemical, and biological tests were performed to evaluate the system's efficiency. The grain size distribution of filtration media was carefully considered, with adjustments made for optimal performance. The methodology ensured a robust investigation, addressing specific challenges identified in greywater treatment.

RESULTS AND DISCUSSION

Sand filtration media

Basic tests were made on the site where the treatment system is located. Each tank, including the mixture tank, TDS, pH, and turbidity, were measured and recorded for 18 test runs. The readings of the mixture tank were also taken as a reference to investigate the efficiency of the treatment process. Table 2 lists the average measurements for the treatment of 2400 L with and without the introduction of hot air for each filtration stage. The changes in measurements through the treatment process suggest that the medium nature of filtration tanks could cause such changes, such as an increase in pH values throughout the stages and a significant decrease in turbidity. No change was seen in TDS values, suggesting that extra chemical treatment might be needed to decrease these readings. At this stage, no apparent effect of using hot air was seen as the trend of the measurements did not differ; theoretically, there is no role of hot air in these measurements.

According to the Jordanian standards for treated greywater, treated wastewater must have a pH value between 6 and 9, TDS up to 2000 mg/L, turbidity up to 5 nm, and according to the results presented in Table 2, the treated water meets these standards. It can be used for various usages, such as irrigation and toilet flushing. Another set of tests used for qualifying greywater includes measuring concentrations of some heavy metals in the treated water. The same samples were collected and tested on Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) at JUST. Table 3 lists the average results of some heavy metal concentrations versus Jordanian standards. The results are for an average of 2400 L of greywater treatment. The results in Table 3 show that the water in different tanks matches the standard in terms of heavy metal concentration. It is also worth mentioning that the water in the mixture tank meets the standard; the medium-used tanks do not affect the heavy metal concentration. However, some concentrations increased at certain tanks but were still within the limits of the Jordanian standards. Hot air usage does not show a significant effect.

Chemical and biological tests were conducted in the quality laboratories at the Water and Irrigation Ministry. A total of 2400 L were treated, and samples were collected and sent to the laboratories in three batches. Table 4 lists the average results of biological and chemical tests versus the Jordanian standards; the tests include measurements for BOD, COD, E.

Table 3: The average results of some heavy metals concentration versus Jordanian standards

	With hot air (mg/L)				Without hot air (mg/L)				JS 893/2006
Heavy metals	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	Standard value (mg/L)
Li	0	0	0	0	0	0	0	0	2.5
Al	0.45	0.4	0.72	0.51	0.52	4	0.46	0.36	5
V	0	0	0	0	0	0.01	0	0	0.1
Cr	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.1
Fe	0.28	0.12	0.44	0.49	0.21	2.75	0.23	0.37	5
Mn	0	0	0.01	0.01	0	0.06	0	0	0.2
Co	0	0	0	0	0	0	0	0	0.05
Ni	0.01	0.01	0.03	0.01	0.01	0.04	0.01	0.01	0.2
Cu	0.01	0.01	0.02	0.07	0.01	0.03	0.01	0.03	0.2
Zn	1.21	1.55	1.49	2	1.54	1.63	1.48	1.68	2
Cd	0	0	0	0	0	0	0	0	0.01
Pb	0.03	0.01	0.15	0.23	0.02	0.05	0.03	0.07	5

coli, and acrylonitrile-butadiene-styrene (ABS). The results in Table 4 show that the treated water from the system can be used for irrigation but not for toilet flushing. Also, using hot air does not improve the result of treated water. In fact, hot air has a negative effect on *E. coli* results as this type of bacteria is an aerobic bacterium, so it will reproduce in a medium that contains air and high temperature. However, the treated water using hot air can still be used for irrigation. This summarized all tests that have been conducted for the greywater treatment system. All results confirm the standards, so the system that has been used can be efficient in treating greywater to save the waste of water that can be used for other purposes, especially for irrigation.

Solar disinfection

The results presented in Table 5 demonstrate the effect of each treatment phase on COD, BOD, total coliform, and *E. coli levels* in the treated greywater. The treatment process involved passing the filtered greywater through a series of treatment phases, including silica sand, zeolite, carbon, and solar tubes. The initial concentration of Escherichia coli was 49,000, the most probable number per 100 milliliters (MPN/100mL). No effect was seen on E. coli concentration in the first two stages of filtration (Silica sand and Zeolite tanks), which remained consistent at a concentration of 49,000 MPN/100mL. However, a significant reduction to 1400 MPN/100mL was measured after passing through the Carbon tank, reaching a 0.54 log units *E. coli* inactivation. This indicates that the carbon filtration process effectively removed a substantial portion of the E. coli present in the greywater. The solar disinfection treatment unit remarkably impacted the E. coli content, reducing it to 0 MPN/100mL. Results indicate that the solar disinfection unit was highly effective in removing E. coli from the greywater, reaching a 3.15 log unit E. coli inactivation, comparing the results of the microbial removal of SFS with other systems investigated in previous studies, such as stand-alone sand filtration, rotating biological contactor followed by sand filtration, and a membrane bioreactor equipped with ultrafiltration membranes (Friedler *et al.,* 2006). Both rotating biological contactors, followed by sand filtration and membrane bioreactor, exhibited substantial microbial removal, with 2.1 and 3.6 logs removal (Friedler et al., 2006), while the SFS system achieved a 3.15 log units E. coli inactivation.

Similarly, the initial concentration of total coliforms was 16,000,000 MPN/100 *mL*. The subsequent treatment steps in the silica sand and zeolite tanks decreased total coliform concentration to 5,400,000 MPN/100mL (0.47 log units' total coliforms inactivation). The value was significantly reduced to 79,000 MPN/100mL (1.83 log units' total coliforms inactivation) after passing through the carbon tank, as illustrated in Fig. 6.

Remarkably, the solar treatment unit brought the total coliform count to a level lower than 1.8 MPN/100 *mL,* reaching 4.64 log units' total coliform inactivation. This indicates that the solar disinfection process reduced the total coliform concentration and met the specified limit, suggesting that the greywater was effectively treated to remove coliform bacteria. In terms of organic pollutants, the levels of BOD and

Table 4: The average results of biological and chemical tests versus the Jordanian standards

Test	With hot air (mg/L)				Without hot air (mg/L)				JS 893/2006 Standard value
	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	Mix tank	Silica sand tank	Zeolite tank	Carbon tank	
BOD (mg/L)	26	28	30	14	27	29	29	13	60 (mg/L) (Irrigation) 10 (mg/L) (Toilet flushing)
COD (mg/L)	456	416	137	22	330	262	124	14	120 (mg/L) (Irrigation) 20 (mg/L) (Toilet flushing)
E-coli (MPN/100mL)	22,000	110,000	17,000	4,900	14,000	1,100	700	700	10^4 (MPN/100mL) (Irrigation)10 ((MPN/100mL) (Toilet flushing)
ABS (mg/L)	1.1	1.2	1.3	0.5	1.2	1.3	1.3	1	25 (mg/L)

Table 5: Effect of each treatment step on COD, BOD, total coliform, and Escherichia Coli

Measured parameter	Silica sand tank	Zeolite tank	Carbon tank	Solar tube	Unit
Escherichia coli	49,000	49,000	1400	0	MPN/100mL
Total Coliforms	16,000,000	5,400,000	79,000	<1.8	MPN/100mL
BOD	24	22	11	12	mg/L
COD	545	56	29	19	mg/L

COD were progressively reduced throughout the treatment process. The BOD concentration decreased from 24 mg/L in the untreated greywater to 11 mg/L after passing through the carbon tank, and the COD concentration decreased from 545 mg/L to 29 mg/L in the same treatment step. The solar tube treatment resulted in a slight increase in BOD (12 mg/L) and a further decrease in COD (19 mg/L), as shown in Fig. 7.

A one-way analysis of variance (ANOVA) (Samimi *et al.,* 2023) was conducted to assess the statistical differences among the means of each treatment step for the parameters of interest, including E. coli, Total coliform, BOD, and COD. The results revealed statistically significant mean differences for all analyzed parameters ($p < 0.05$) (Samimi and Nouri, 2023). These results indicate that the overall efficiency of greywater SFS was sufficient. Treated greywater obtained after the various treatment steps, including the solar disinfection process, met the Jordanian standards for safe reuse. Reducing E. coli and total coliforms to acceptable levels demonstrates the treatment system's effectiveness in providing pathogen-free greywater suitable for various applications. The solar-equipped filtration unit succeeded in greywater treatment, particularly in turbidity, chemical oxygen demand (COD), and Escherichia coli (E. coli) removal. A comparative analysis of treatment efficiency with and without the solar system provides valuable insights into the benefits of solar disinfection. Table 5 presents the effect of each treatment step on COD, BOD, total coliform, and E. coli in the treated greywater. Solar disinfection was highly effective, reducing E. coli concentration to 0 MPN/100mL, demonstrating a 3.15 log units E. coli inactivation. The solar treatment unit also brought the total coliform count to a level lower than 1.8 MPN/100 mL, reaching a 4.64 log unit total coliform inactivation. These results underscore the success of the solar disinfection process in achieving pathogen-free greywater, making it suitable for various applications. The solar-equipped filtration unit meets water quality standards and demonstrates enhanced efficiency in pathogen removal, affirming its suitability for safe water reuse in various contexts.

SFS lifecycle cost analysis (LCCA)

The LCCA of the SFS includes four major items as illustrated in Table 6: Initial investment 1) which include storage tanks, pumps, solar panels, drainpipes, pipe fittings, filter media, and electrical control devices; 2) Operating and maintenance costs (OMC) which includes costs of filer medium replacement every ten months and cost of regular

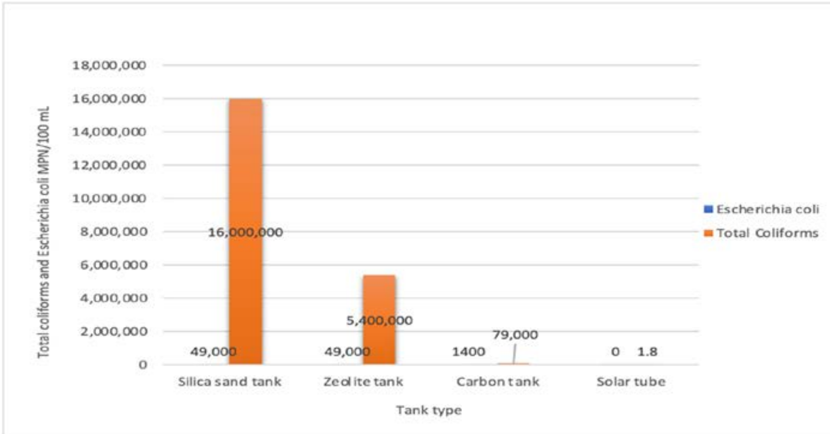

Fig. 6: Total coliforms and Escherichia coli removal efficiencies across different tanks

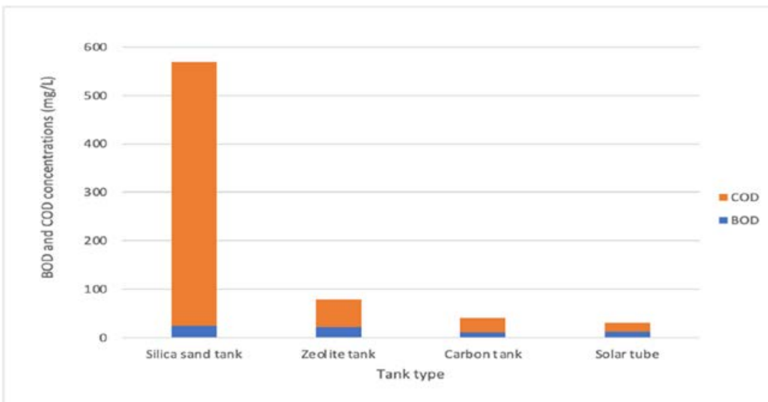

Fig. 7: BOD and COD removal efficiencies across different tanks

cleaning of the solar panel, and fittings and parts replacements; 3) Assuming the revenues and savings (RS) of using SFS water will approximately save 40% of the water utility bill which is 17.5 US Dollars (USD) per month (210 USD) yearly per dwelling unit; 4) Resale or Salvage value; assuming that SFS needs replacements approximately every 15 years and costs 340 USD. To perform financial calculations and evaluate the economic viability of the proposed system over its entire lifespan, Table 6 shows the values used in the economic feasibility calculations.

In this study, the net present value (NPV) has been calculated to investigate the LCCA with a minimum acceptable rate of return (MARR) of a minimum of 3% (Juan *et al.*, 2016). This analysis used three leading investments using Eq. 1 (Bdour *et al.*, 2023).

With Net Present Value (NPV)

$$NPV = \sum\left(\frac{RS - OMC}{(1+DR)^2}) - \text{II} + \frac{SV}{(1+DR)^2}\right) \quad (1)$$

With Payback Period (PP), using Eq. 2 (Bdour *et al.*, 2023).

$$PP = \frac{II}{\sum(RS - OMC)} \quad (2)$$

With Benefit Cost Ratio (BCR), using Eq. 3 (Bdour *et al.*, 2023).

$$BCR = \frac{\sum RS}{II + \sum OMC} \quad (3)$$

Where; II: Initial investment of SFS system

Table 6: SFS Lifecycle cost analysis parameters

Parameter	Value
Initial Investment (II)	USD 850
Operating and Maintenance Costs (OMC) per year	USD 120
Revenues and Savings (RS) per year	USD 210
Lifecycle Duration (LD)	15 years
Discount Rate (DR)	10%
Resale Value (SV)	USD 340

OMC: Operating and Maintenance cost of SFS per year.

RS: Revenues and Savings per year, representing the difference between water bills with and without the SFS system.

LD: Lifecycle Duration, which indicates the expected operational lifespan of the setup.

DR: Discount Rate, which accounts for the time value of money.

SV: Resale Value or Salvage Value represents the potential value that can be recovered if the system is sold.

In this study, OMCs were considered part of the LCCA, as outlined in Table 6. The OMC includes the cost of filter medium replacement every ten months, regular solar panel cleaning, fittings, and parts replacements. The frequency of maintenance is designed to ensure optimal and sustained system performance. The 10-month interval for filter medium replacement is based on empirical observations and aims to address any potential decrease in filtration efficiency over time. Regular cleaning of the solar panel is essential to maintain its effectiveness in harnessing solar energy for disinfection. Table 7 shows the economic feasibility analysis of the developed SFS. These results demonstrate that the SFS system is economically viable and financially sound. The positive NPV, high initial rate of return (IRR), relatively short PP, and a BCR greater than one suggest that investment in the developed system is favorable. Furthermore, this system will be attractive to owners and households of dwelling units due to its profitability; buying it will allow them to treat and reuse a good portion of the water used for showers and toilets. This treated greywater can be used safely for irrigation without threatening their health and environment. Although the system's revenue is vital, applying this system will ultimately help lessen the water shortage in Jordan by introducing a new non-conventional water resource. Also, bearing in mind that the developed system entails no consumables (non-chemical, non-hazardous materials) that work as a standalone system to address the sustainability of greywater treatment.

According to a study by Tabieh *et al*. (2022), it was estimated that the average value to produce one cubic meter of domestic water in Jordan is 2.4 USD. However, in 2023, the government recently increased the water tariff for the domestic sector, which showed the highest water unit prices. It has been assessed that water bills for household consumers will rise by 10 USD for consumption over 73 cubic meters (MWI, 2023). Comparing this cost with other countries worldwide, the cost in the United States is 0.75 USD, Japan 1.5 USD, and Germany 3.05 USD (Varady *et al*., 2022). Previous studies have shown that water scarcity directly impacts water and food security and is expected to intensify at the current resources management practices. Jordan's resources are being unsustainably utilized to compensate for the population needs in the supply-demand chain (Belda González, 2018). As illustrated in Figs. 8 and 9, the intensifying pressure on the country's resources, accompanied by a drastic increase in the water and food demands, is also threatening the sustainability of the energy sector in Jordan since it imports about 94% of its fossil fuel resources. This has indirectly contributed to the high electricity tariffs in Jordan.

The significance of the current and predictable water shortage in the context of sustainable development and the presence of new technologies brought further attention to utilizing non-conventional water sources (Aznar-Sánchez *et al*., 2018; Moghadam and Samimi, 2022). Significant non-conventional resources include treated wastewater and brackish water desalination. The reclamation of the treated wastewater, brackish, and seawater desalination is the only non-conventional water resource in Jordan's water budget. Treated wastewater is primarily used for irrigation (98.4%), with a tiny amount used in the industry (1.6%). Most treated wastewater comes

Table 7: Results of SFS economic feasibility investigations

Parameter	Value
NPV	1,947 $US
IRR (NPV=0)	22.97%
PP	≈ 3.18 years
BCR	≈ 2.07

Fig. 8: Demand and supply projections for the domestic sector in Jordan (MWI, 2023)

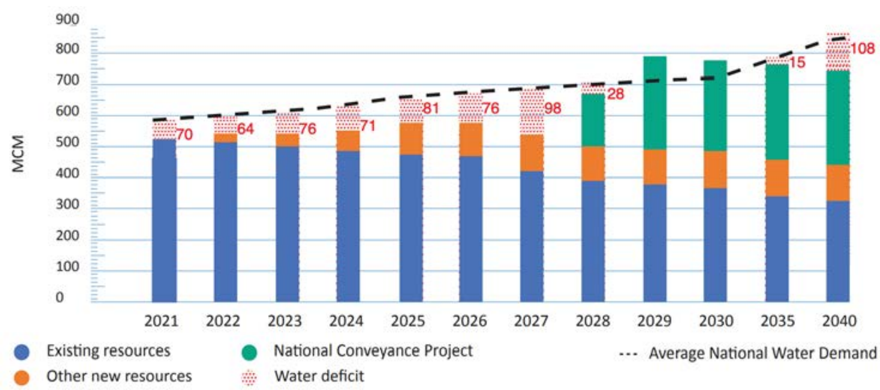

Fig. 9: Agricultural supply and demand projections in Jordan (MWI, 2023)

from wastewater treatment facilities registered in the Jordan Valley (71.3%). Because of the small coastal area in Jordan, seawater desalination has been considered on a limited scale (0.3%) as a source. This indicates that introducing a new non-conventional water resource and reducing the associated costs per cubic meter for domestic water utilization is essential in Jordan. The illustrated claim proves the outstanding economic performance attained with SFS that was primarily implemented to reduce and conserve the domestic demands of individuals. The empirical results obtained from the SFS provide valuable insights into its efficiency in treating greywater and removing contaminants, particularly E. coli. These results can be linked to previous studies, shedding light on the system's performance compared to traditional water treatment methods and its contributions to environmental sustainability. The results of E. coli removal indicate a significant reduction in E. coli concentration throughout treatment. The carbon tank achieved a 0.54 log unit of E. coli inactivation, and the solar disinfection unit further reduced it to 0 MPN/100 mL, indicating a 3.15 log unit of E. coli inactivation. This aligns with the literature emphasizing the importance of effective E. coli removal to ensure safe water reuse (Priyanka *et al.,* 2022). Also, the study monitors various parameters during the greywater treatment, including pH, TDS, turbidity, heavy metal concentrations, BOD, COD, and E. coli. The results demonstrate that the treated water meets Jordanian standards for safe reuse, supporting literature on the necessity of adhering to water quality standards in treated wastewater (Waris and Ghaith, 2022). Moreover, the SFS contributes to environmental sustainability in several ways. The use of solar energy for water treatment aligns with the global push for renewable energy adoption. The system employs natural filtration media, avoiding the need for chemical treatments and reducing the environmental impact associated with traditional water treatment methods. The decentralization of the system further minimizes the reliance on centralized infrastructure. LCCA provides insights into the economic viability of the SFS. The NPV, high IRR, short PP, and a BCR greater than 1 suggest that the SFS investment is favorable and proves a superior performance compared with other treatment technologies (Singh *et al.,* 2021).

CONCLUSION

This study introduces a novel four-stage solar filtration system for treating greywater. The system effectively reduces organic and solid content by utilizing natural materials and activated carbon and removes E. coli pathogens. It introduces a pioneering approach to greywater treatment, integrating natural filtration media and solar disinfection for efficient and sustainable contaminant removal. This novel system contributes a unique combination of renewable energy reliance and eco-friendly design, setting it apart as a groundbreaking solution in the realm of water treatment technologies. The developed system demonstrates impressive efficiency in turbidity, COD, and E. coli removal, achieving 92%, 95%, and 100%, respectively. Additionally, it exhibits substantial potential for inactivating total coliforms and E. coli, making the treated water suitable for safe reuse in irrigation applications. The combination of sand filtration and solar disinfection presents a highly favorable and environmentally conscious approach to greywater treatment. This green decentralized system utilizes natural treatment processes to produce high-quality water that can be effectively utilized in various fields, with a particular emphasis on irrigation purposes. This combination's economical and environmentally friendly nature makes it suitable for implementation by individual homeowners as well as commercial buildings, hotels, universities, and hospitals. Moreover, in regions like Jordan, where water resources are limited, adopting such a green decentralized system can significantly contribute to environmental preservation by conserving precious freshwater resources. The findings of this study highlight the satisfactory performance of the developed greywater SFS. The treated greywater, obtained through the series of treatment steps, including solar disinfection, successfully met the Jordanian standards for safe reuse. The substantial reduction of E. coli and total coliforms to acceptable levels demonstrates the treatment system's effectiveness in generating pathogen-free greywater, suitable for a wide range of applications. These findings affirm the capability of the solar filtration setup to deliver high-quality treated greywater that meets stringent regulatory requirements consistently. Additionally, the economic feasibility analysis underscores the viability and financial soundness of the SFS system. Its reliance on solar energy for operation and the absence of consumables contribute to its sustainability. This addresses water scarcity concerns and aligns with sustainable practices in greywater treatment. The study's findings have significant implications for Jordan's water management. The solar filtration system offers a promising non-conventional water resource by consistently producing high-quality treated greywater that meets regulatory standards. Implementing this system has the potential to alleviate water shortages, providing a valuable contribution to sustainable water use in the region. This study adds scientific value by comprehensively investigating a novel four-stage solar filtration system for greywater treatment. The systematic evaluation of its efficiency in removing contaminants, particularly E. coli, coupled with economic feasibility analysis, contributes valuable insights to sustainable water treatment. Integrating natural materials, activated carbon, and solar disinfection showcases innovative solutions, advancing our understanding of eco-friendly technologies for decentralized water reuse systems.

AUTHOR CONTRIBUTIONS

R. Abdallat performed the research experimentation and interpretation of the results and wrote the manuscript; A. Bdour supervised the work and concept formulation and wrote the manuscript. A. Abuhaifa did the experimental work, sampling, and prototype manufacturing; F. Alrawash interpreted data and prepared all the tables and figures. L. Almakhadmah collected references, prepared the manuscript, and organized the text. S. Hazaimeh did the statistical analysis and paper editing.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

%	percentage
μm	micrometer
ABS	acrylonitrile-butadiene-styrene
ANOVA	Analysis of variance
BAC	Biologically active granular activated carbon
BCR	Benefit Cost Ratio
BOD	Biological oxygen demand
COD	Chemical oxygen demand
CW	Constructed wetland
Cd^{2+}	Cadmium
^{o}C	Degree Celsius
DR	Discount rate
ECs	Emerging contaminants
E. coli	Escherichia Coli
GAC	Granular activated carbon
HSF	Horizontal series filter
Hg^{2+}	Mercury
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
II	Initial investment
IRR	Initial rate of return
L	Liter
LCCA	Lifecycle cost analysis
LD	Lifecycle Duration
L/person/day	Liter per person per day
L/m/h	Liter per meter per hour
MARR	minimum acceptable rate of return
MBR	Membrane bioreactor
mm	millimeter
MPN	Most probable number
m^3	Cubic meter
mg/g	Milligram per gram
mg/L	Milligram per liter
NPV	Net Present Value
NH_3	Ammonia
NO^{-3}	Nitrates
OMC	Operating and maintenance costs
PACl	polyaluminium chloride
pH	Potential of hydrogen
PP	Payback Period
ppm	Parts per million
PV	photovoltaic
Pb^{2+}	Lead
RS	revenues and savings
SBR	sequencing batch reactor
SFS	Solar filtration system
SPCR	solar photocatalytic reactor
SV	Resale Value

TDS	total dissolved solids
TN	Total Nitrogen
TOC	Total Organic Carbon
TSS	Total suspended solids
UASB	upflow anaerobic sludge blanket
USD	US Dollars
IF	ultrafiltration
WAJ	Water Authority of Jordan

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