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PV-RO drinking water filtration system: case of Qala-e-Gulbaz Village, Kabul Province

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ABSTRACT

Pollution and over-exploitation of groundwater aquifers in Kabul Province have led to deteriorated water quality and decreased quantity. In its turn, these have caused elevation of physical, chemical, and biological contaminant concentrations in the province's groundwater beyond national and international drinking water quality standards. The article describes the outcomes of a pilot photovoltaic reverse osmosis (PV-RO) system for drinking water treatment in Qala-e-Gulbaz Village, Kabul Province, Afghanistan. The main system's components include PV solar panels, three dosing pumps, two alternative current pumps, two alternative-to-direct-current inverters, sand and carbon filters, two sediment filters, one ultra-violet filter, two water flow meters, and a complete water supply distribution system. The study was assisted by the Danish Committee for Aid to Afghan Refugees (DACAAR) ground monitoring well (GMW) system; quality analysis of different physical, chemical, and biological parameters of raw and filtered water samples; measuring filtered water and wastewater flow rates; determining associated limitations and pressures; as well as valuating different related expenses during cost per capita calculations. Water quality testing has shown the system's removal efficiency of 97% for salinity, 97% for total dissolved solids, above 90% for other chemicals (anions & cations), 65.52% for turbidity, and 100% for bacteria. The plant's mean quantity efficiency has amounted to 50%. The study highlights certain key challenges including high initial cost, significant wastewater volume, and need for professional operators leading to high operational and maintenance expenditures, with the initial system's cost per capita of USD79.54. Therefore, under the condition of optimizing efficiency, improving wastewater management, reducing original costs, implementing training programs, and developing the necessary policy framework PV-RO water treatment systems represent a viable alternative.

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1. Introduction

Water is a plentiful natural resource covering three-quarters of the Earth's surface. Yet, potable water is found in only 3% of all water sources. Globally, 25% of the world's population lack access to freshwater of sufficient quality or quantity, more than 80 countries have serious water-related issues (Abo Zaid, 2015), and developing countries like Afghanistan face significant challenges in ensuring safe drinking water supply (Omary, 2024). According to Hamdard (2020), Kabul Province suffers from microbial contamination, chemical pollutants, and inadequate infrastructure further complicating public water access. Specifically, in areas like Qala-e-Gulbaz, the lack of reliable water sources necessitates the adoption of innovative solutions to meet the growing demand for clean water. To address these challenges, technologies like the photovoltaic reverse osmosis (PV-RO) drinking water filtration system are emerging as promising solutions. The system combines solar energy with reverse osmosis, making it particularly suitable for regions with abundant sunlight but limited clean water infrastructure (Elfaqih et al., 2024; Maftouh et al., 2023). Recent studies demonstrate the effectiveness of PV-RO systems in providing clean drinking water in resource-constrained areas (Maftouh et al., 2023), confirming their potential for improving water access and public health.

Previous research highlights that RO systems are effective in removing micropollutants (Sudhakaran et al., 2013; Vries et al., 2013)), with the solution-diffusion model playing a key role in water purification (Abraham & Luthra, 2011; Kim et al., 2018). However, limited studies focus on the practical deployment of such systems in socio-economically constrained regions like Kabul, where financial resource, technical capacity, and infrastructure limitations create additional commissioning and sustainability bottlenecks.

The primary objectives of this study were to evaluate the technical efficiency of the PV-RO system in removing physical, bacteriological, and chemical contaminants, as well as ensuring the treated water meets WHO guidelines and Afghanistan's National Drinking Water Quality Standards (ANDWQS). Furthermore, the study assessed the system's quantitative efficiency (liters per hour), measured its operational performance against specifications, and calculated its cost per capita, including operation and maintenance.

This research aligns with ongoing WASH initiatives and contributes to achieving the Sustainable Development Goals (SDGs) associated with clean water and sanitation. By assessing the feasibility of PV-RO systems in rural Afghanistan, this study provides insights into the potency of these technologies to contribute to sustainable water solutions in similar settings. The investigation's findings may be valuable for policymakers, development organizations, and practitioners working to improve water access and quality in Afghanistan and other resource-limited areas.

The study was supported by DACAAR through the construction of deep production water wells, elevated reinforced cement concrete (RCC) storage tanks, and installation of a solar-powered reverse osmosis ultra-filtration system, with the technical support by the Silicon Solar Co. This collaborative approach has ensured both local involvement and technical expertise, critical for long-term system sustainability.

2. Methodology

2.1. Study area

Kabul Province is located 1,800 meters above sea level in the north-eastern part of Afghanistan (Fig. 1).

Only about 20-27% of Kabul’s population have continuous access to centralized water, with the majority relying on shallow hand-pumping groundwater wells for domestic and micro agricultural water consumption due to the lack of a stable central water supply (Omid et al., 2018). In addition, DACAAR confirms that groundwater is the main source of various needs, such as domestic, irrigation, and industry (Omid et al., 2018). As per (Groundwater Natural Resources and Quality Concern in Kabul Basin.Pdf, n.d.), electrical conductivity (EC) concentrations in the Lower Kabul Basin (LKB) aquifer range from 672 to 15,290 μS/cm, with the mean value of 1,428 μS/cm, indicating high spatial variations in salinity (Zaryab et al., 2021). Recent research has identified various sources of salinity in the LKB aquifer, including the dissolution of minerals, anthropogenic effects, and evaporitic lacustrine deposits (Zaryab et al., 2021). Located in Kabul Province, Qala-e-Gulbaz Village faces significant challenges with groundwater salinity and chemical contamination (Zaryab et al., 2021). Fig.2 shows EC contour lines and concentrations (in μS/cm) in all districts of Kabul Province and the study area, with the latter demonstrating salinity exceeding 5,000 μS/cm.

DACAAR’s GMW system was used for locating high salinity groundwater points for piloting the RO water treatment system. The GWMs in Kabul Province are shown in Fig. 1.

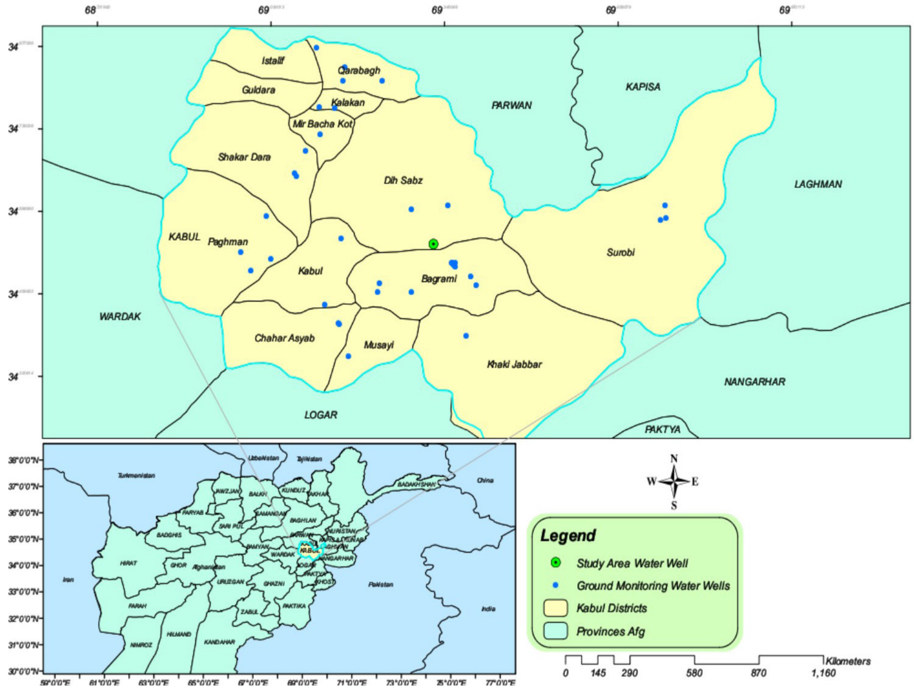

Figure 1. Figure 1. Map of Afghanistan, Kabul Province, study area and Kabul's GMWs.

Note. Created by the author using ArcGIS; data from MapCruzin (n.d.)

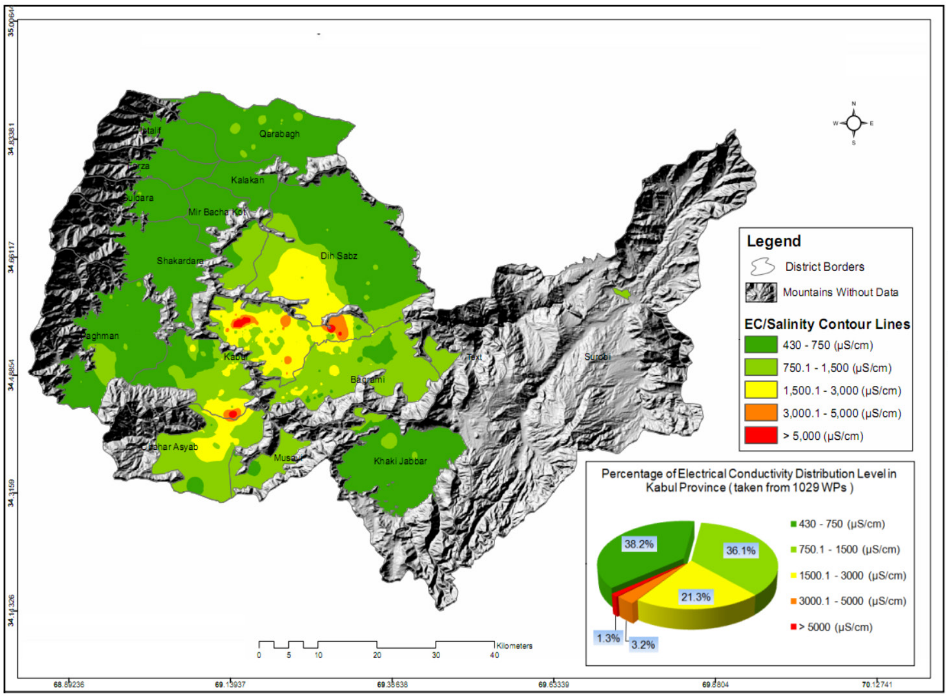

Figure 2. EC Contour Lines for the Groundwater of Kabul Province.

Note. From DACAAR (n.d.)

2.2. Description and operation of the reverse osmosis plant and water supply system

The solar-powered RO filtration system from ROsolution.pk with the capacity of filtering 10,000 gallons per day (GPD) of raw water with required solar array size of 9.5 KW and two inverters (one for pressure pump and one for remaining pumps of 5.5 KW) were installed by the Silicon Solar Company. Fig.3shows the RO plant block diagram, all parts of the facility, and their connections. The water supply system was constructed by DACAAR and consisted of a tube well with a safe yield of 2.9 l/sec, 6 meter elevated RCC water storage tank with 10 m3 capacity for source water, 12 meter elevated RCC water storage tank with 20 m3 capacity for filtered water, and a distribution piped network with 152 water flow metered house connections. Fig.4 Fig. 3 shows all system elements and workflow directions. 2,135 individuals (305 families in 152 homes) were benefitting from the system at the time of the study.

As shown in Fig. 3 Fig. 3, the RO filtration plant receives raw water pumped from the tube well using a PV solar water pump. The water is then pumped by a feeder pump to two sand and carbon pre-RO filters. Before entering the two sediment filters, sodium hydroxide for boron treatment and an antiscalant are added by two dosing pumps (Dosing Pump #1 and #2). The water then passes through the sediment filters.

Next, the water is pumped with a high-pressure booster pump through the RO filter. After the RO process, minerals are added via a third dosing pump (Dosing Pump #3). Next, the water goes through an ultraviolet (UV) filter to remove pathogens. Following that, the water passes through a post-carbon filter and is sent to a 2 m3 plastic surface water storage tank. From there, it is pumped to a 20 m^3 reservoir elevated water storage tank, which delivers water to residential connections by gravity.

The RO membrane is cleaned daily using a backwashing system. All the system's electrical instruments run on solar power, and are manually operated by a trained operator.

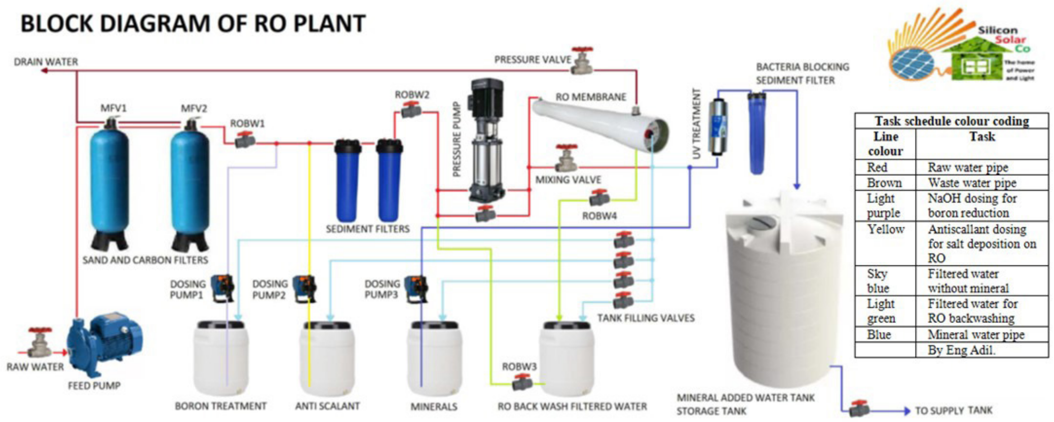

Figure 3. Reverse osmosis plant diagram and working procedure (Eng Adil, personal communication, June 10, 2024).

Note. Used with permission.

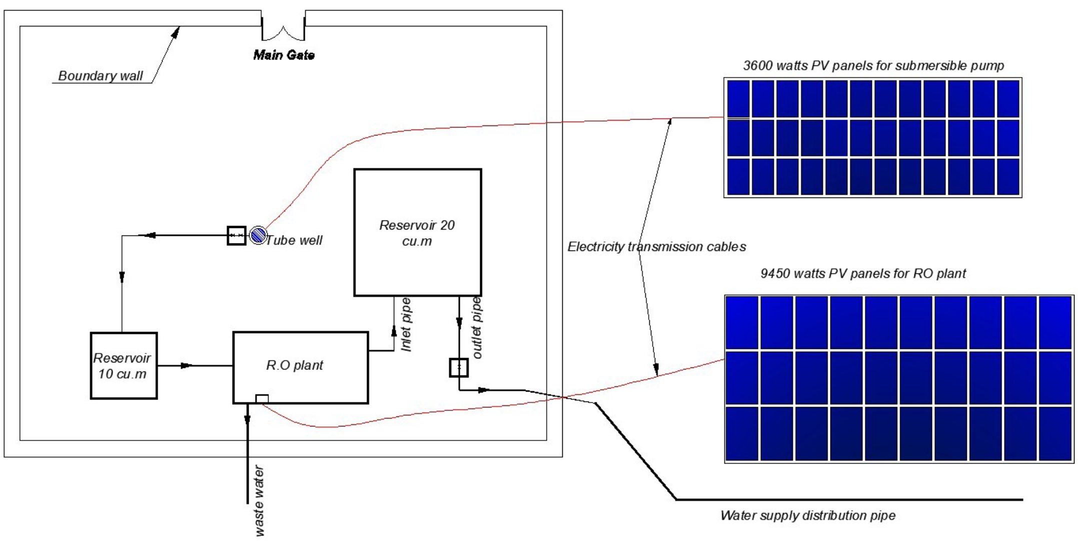

Figure 4. RO plant and water flow diagram.

2.3. Research design

a. Water sample collection and quality analysis

Following the launch of the RO plant, in total 8 source water samples (tube well) and 8 filtered water samples (RO plant) were regularly collected in plastic bottles for 8 months by a lab technician and then analysed in DACAAR's water quality testing laboratory for physical, chemical, and biological parameters (refer to Table III for physical parameters, Table IV for biological parameters, and Table V for chemical parameters).

b. Water flow measurements

Both raw and filtered water flow rates were measured in winter and summer hours with the help of installed water flow meters in both raw and filtered water lines.

c. User perceptions on the system

A questionnaire (Table I) was designed to collect information from the users on the filtered water quality, quantity, and general perception. The data was collected by interviewing 10% randomly selected families by a hygiene & health promotion couple from DACAAR office.

Table I. RO filtration water supply system evaluation questionnaire.

Question	User Feedback
Are you happy because of this project (considering quality, quantity, and access)?	1. Yes 2. No
What are all the purposes you use the RO filtered water for?	1 - Drinking, 2 - Cooking, 3 - Bathing, 4 - Hand washing, 5 - other (specify)
How much water do you use every day from the RO plant?	( ) liters
Is water available all the time or whenever needed?	1. Yes 2. No
How is the taste of the RO plant filtered water?	1. Tasty/fresh 2. Saline 3. Other (specify)
How is the smell of the RO plant filtered water?	1. No smell 2. Smell 3. Other (specify)
How is the appearance of RO plant filtered water?	1. Clean 2. Turbid 3. Other (specify)
Does the RO plant provide enough water for the entire family?	1. Yes 2. No
Since you started using the RO-filtered water, has your family's health improved, stayed the same, or become worse?	1. Better 2. Worse 3. About the same
Do you pay for the water?	1. No (why): 2. If yes, how much per month ( ) AFN

d. Demographics

Around 2,135 individuals (305 families living in 152 households) were benefiting from the system at the time of the investigation.

e. System's implementation costs

To calculate the cost per capita of the entire system, all expenses associated with all its elements, including installation and implementation, were factored in as shown in Table II.

Table II. Cost of solar-powered RO filtration water supply system.

Category	Description	Cost distribution
RO filtration & PV system	Complete RO filter unit with photovoltaic solar panels	17.0%
Electrical accessories	Power cables, electrical fittings, and related components	0.6%
Shelter/protection	Steel canopy construction for RO plant	1.5%
Installation & setup	On-site installation and commissioning of the RO unit	0.2%
Water infrastructure	RCC reservoirs, PE pipe network, and well construction	80.8%
Total		100 %

3. Results and discussion

3.1. Water quality test results

Water quality testing started soon after launching the RO plant. In total, 8 source and 8 filtered water samples were regularly collected and tested. Test results are presented in Tables III, IV, and V below.

Table III. Test results for physical parameters.

Parameter	Raw water mean	Filtered water mean
EC (μS/cm)	5,490	166
TDS (mg/l)	3,776	111
Turbidity (NTU)	1.16	0.4
pH	7.96	7.75

Table IV. Test results for biological parameters.

Statistics	Bacteria in RO-filtered water (CFU*/100 ml)	Bacteria in source water (CFU*/100 ml)
Maximum	0	55
Minimum	0	0
Mean	0	27

* CFU – colony forming unit.

Table V. Test results for chemical parameters (anions & cations).

Parameter (Anions)	Raw water mean (mg/l)	Filtered water mean (mg/l)
Total Alkalinity	310	26.3
Alkalinity P	10	9.6
Alkalinity M	360	42.5
Bicarbonate	340	24.5
Carbonate	20	16.7
Hydroxide	0	0
Chloride	1,125	55
Sulphate	1,317	17.5
Sulphite	2	6.5
Sulphide	0.02	0.003
Fluoride	5.2	0.3
Nitrate	284	7.3
Nitrite	0.322	0.05
Phosphate	0.15	0.03
Boron	6.3	2.8
Bromide	0.38	0.31
Parameter (Cations)	Raw water mean (mg/l)	Filtered water mean (mg/l)
Total Hardness	850	41.3
Calcium Hardness	140	12.6
Sodium	1,267	47.8
Potassium	10	1.3
Calcium	56	5
Chromium	0.02	0.015
Magnesium	155	14
Ammonium	0.28	0
Manganese	0.017	0
Copper	0.22	0.16
Aluminum	0.01	0.01
Total iron	0.14	0.03
Total Arsenic	0.015	0

3.1.1. Removal efficiency for salinity and total dissolved solids

Electrical conductivity – a measurement of total dissolved solids and ionized species in waterways – qualitatively represents the state of inorganic pollution (Kelmendi et al., 2018). Water with low TDS may also taste bland. While TDS is merely a secondary indicator of water quality and does not directly affect health, it can be a sign of overabundance of toxic ions, such as nitrate, copper, lead, aluminium, and arsenic. Pipes and other infrastructures may experience scaling as a result of higher TDS levels (Ahmed et al., 2015).

The salinity (EC) and TDS of the source water were found significantly above the limits of WHO recommendations, and the ANDWQS. The EC and TDS removal efficiency of the RO plant was very high, and the filtered water therefore underwent re-mineralization, with mineral water classified as containing at least 250 parts per million (mg/l) TDS. Fig. 5 and Fig. 6 show the filter removal efficiency for EC and TDS respectively, as compared to the WHO guidelines and ANDWQS ranges.

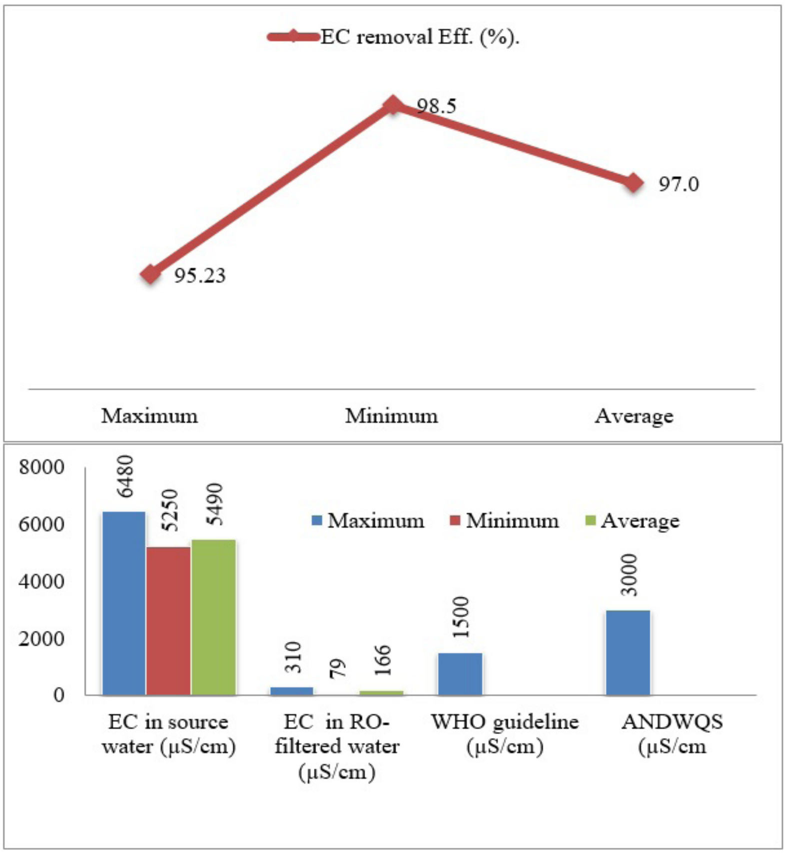

Figure 5. EC concentrations of source water and RO removal efficiency.

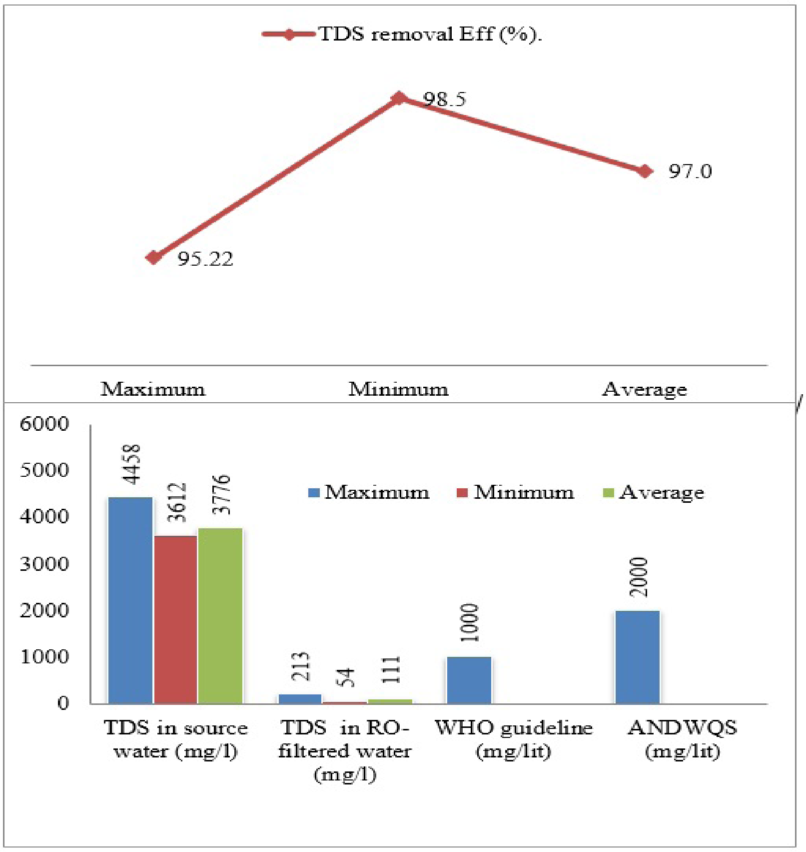

Figure 6. TDS concentrations of source water and RO removal efficiency.

3.1.2. Chemicals removal efficiency

Bacteria, fertilizers, heavy metals, and thousands of hazardous organic chemicals represent the primary constituents of water contaminants (WHO, 1999). Group 3 and 4 metals, as well as Cd, Cr, Cu, Pb, Ni, Fe, Hg, Zn, Al, and Se, are considered heavy metals and harm human physiology (Bacha et al., 2010). Toxic metals - typically found in municipal, urban, and industrial runoff - can be dangerous to both humans and biotic life. The increased concentration of trace metals, particularly heavy ones, in river water is the result of rising urbanization and industrialization (Ahmed et al., 2015).

All chemical elements in the filtered water were within the permissible limits. Table VI shows the chemical (anions and cations) removal efficiency of the RO unit.

Table VI. Chemicals removal efficiency of RO filter.

Parameter (anions)	Source water mean (mg/l)	Filtered water mean (mg/l)	Removal Eff. (%)	WHO guideline (mg/l)	ANDWQS (mg/l)
Total alkalinity	310	26.3	92%	- *	- *
Alkalinity P	10	9.6	4%	-	-
Alkalinity M	360	42.5	88%	-	-
Bicarbonate	340	24.5	93%	-	-
Carbonate	20	16.7	17%	-	-
Hydroxide	0	0	0	-	-
Chloride	1,125	55	95%	250	250
Sulphate	1,317	17.5	99%	250	250
Sulphite	2	6.5	-225%	-	-
Sulphide	0.02	0.003	85%	-	-
Fluoride	5.2	0.3	94%	1.5	1.5
Nitrate	284	7.3	97%	50	50
Nitrite	0.322	0.05	84%	0.2-3.0	3
Phosphate	0.15	0.03	80%	-	-
Boron	6.3	2.8	56%	2.4	2.4
Bromide	0.38	0.31	18%	-	-
Parameter (cations)	Source water mean (mg/l)	Filtered water mean (mg/l)	Removal Eff. (%)	WHO Guideline (mg/l)	ANDWQS (mg/l)
Total hardness	850	41.3	95%	300	500
Calcium hardness	140	12.6	91%	-	-
Sodium	1267	47.8	96%	200	200
Potassium	10	1.3	87%	-	-
Calcium	56	5	91%	-	-
Chromium	0.02	0.015	25%	0.05	0.05
Magnesium	155	14	91%	-	-
Ammonium	0.28	0	100%	1.5-35.0	
Manganese	0.017	0	100%	0.4	
Copper	0.22	0.16	27%	2	2
Aluminum	0.01	0.01	0%	-	0.2
Total iron	0.14	0.03	79%	0.3	0.3
Total Arsenic	0.015	0	100%	0.01	0.05

* No guideline value set.

3.1.3. Turbidity removal efficiency

Turbidity is a factor in determining the kind and intensity of treatment required, and it also hurts disinfection efficiency. Suspended particles, including silt, clay, finely divided organic and inorganic matter, soluble colored organic compounds, plankton, and other microscopic organisms, are the main causes of turbidity in water (Elevli et al., 2016).

Turbidity of the source water was within the allowed limits, and the turbidity of filtered water was below that of the raw water. Normally, the turbidity of drinking water should be lower than 5 nephelometeric turbidity units (NTU), according to the WHO recommendation and ANDWQS. For details, refer to Table VII.

3.1.4. pH (potential hydrogen) removal efficiency

People who have excessive stomach acidity may experience digestive problems as a result of low pH. This explains why drinkable alkaline water has become more popular recently – it helps balancing the acids in the digestive tract and makes people feel comfortable. The body becomes more alkaline with the use of alkaline water, which cures a variety of illnesses, including cancer (Yehia & Said, 2021).

The pH of the raw and treated water were within the recommended limits, but the filtered water had lower pH than the source water, as shown in Table VII.

Table VII. Turbidity & pH removal efficiency of RO filter.

Statistics	Parameter	Source water	Filtered water	Removal eff. (%)	WHO guideline	ANDWQS
Average	Turbidity (NTU)	1.16	0.40	65.52	≤ 5 NTU	≤ 5 NTU
Average	pH	7.96	7.75	2.64%	6.5 - 8	6.5 - 8.5

3.1.5. Bacteria removal efficiency

In developing countries, acute microbial diarrheal conditions pose a severe public health threat – individuals with the lowest financial resources and worst access to hygienic facilities are the ones most afflicted by diarrheal illnesses. Waterborne microbial infections mainly affect children under 5, especially in Asian and African nations (Seas et al., 2000). WHO estimates that over 5 mln people die from water-related disorders each year. Cholera is the most notable of them, accounting for about 50% of microbial intestinal morbidity (Cabral, 2010).

The bacterial removal efficiency of the RO unit amounted to 100% (see Table VIII for the parameter data).

Table VIII. Bacterial removal efficiency of RO filter.

Statistics	Bacteria in RO filtered water (CFU/100 ml)	Bacteria in source water (CFU/100 ml)	Removal Efficiency (%)
Maximum	0	55	100
Minimum	0	0	100
Mean	0	10	100

3.2. Quantitative efficiency of RO filter

The removal of micropollutants from drinking water is limited by conventional treatment methods. As a result, it is highly recommended to develop and implement additional treatment steps, such as activated carbon, ozonation, ultraviolet light, and membrane treatment (Ebrahimzadeh et al., 2021).

The quantitative efficiency of the RO plant examined within the framework of this study was found to be approx. 50%, i.e. 50% of the source water proceeded to filtration, and the remaining 50% was rejected/wasted. The RO plant operates for 6 hours/day in winter and 8 hours/day in summer, producing around 9.81 m3 of filtered water per day in winter and around 12.36 m3 per day in summer. The RO plant can provide around 4.6 l/person in winter and around 5.8 l/person in summer for 2,135 users.

3.3. Cost per capita calculation

The economic feasibility of solar-powered reverse osmosis systems remains a significant challenge, particularly in remote and arid regions. While PV-RO systems offer a sustainable solution for providing clean drinking water, the initial capital costs and maintenance expenses can be prohibitive (Maftouh et al., 2023). This cost disparity highlights the need for innovative financing models and technological advancements to reduce expenses and make PV-RO systems more accessible to communities in need (Maftouh et al., 2023)

To calculate the system's total cost per capita, all the initial expenses associated with the plant were divided by the number of individuals, making it USD79.5 or slightly higher – manifesting the primary limitation of such systems.

3.4. Discussion on limitations

a) High initial cost

One of the primary challenges of implementing PV-RO systems is their high initial cost (Garg, 2015). The expenses associated with purchasing and installing photovoltaic panels, reverse osmosis membranes, and other necessary equipment can be substantial (Garg, 2015). According to a review by Al-Addous et al. (2024), the capital cost of PV-RO systems remains a significant barrier to their widespread adoption, especially in developing countries where financial resources are limited. As mentioned above, the cost per capita of the piloted system in Qala-e-Gulbaz Village amounted to USD79.5, which exceeds the economic capacity of villagers in Afghanistan, necessitating support from governmental and non-governmental organizations to deploy such installations. Additionally, to recommend the PV-RO system for communities in a cost-effective manner, it is crucial to leverage donor funding for initial installation, promote community-based operation and maintenance to reduce long-term costs, as well as optimize the system's sizing and energy consumption to match actual demand.

b) High quantity of disposed water

Another critical issue with PV-RO systems is the high quantity of disposed water – during desalination, a considerable amount of brine or concentrate water is generated, which requires proper handling to avoid environmental harm (O.S. Abd El-Kawi, 2025). According to O.S. Abd El-Kawi (2025), the disposal of this concentrated brine can pose significant environmental challenges, particularly in regions with limited water resources. Effective management strategies are essential to mitigate the potential environmental impacts of disposed water (O.S. Abd El-Kawi, 2025). The quantitative efficiency of the RO plant was found to be approx. 50%, meaning that half of the source water underwent filtration, and the remaining half got rejected as waste, indicating a high amount of water wasted and potential harm to the ecosystem. To address this limitation, the study recommends using the generated brine for agriculture where feasible, or exploring zero liquid discharge (ZLD) technologies. Regular monitoring and responsible disposal practices should also be integrated into the system’s operation and maintenance (O&M) plan to minimize environmental damage.

c) High O&M cost and lack of professional operators

High O&M costs and lack of professional operators likewise represent notable challenges (Prescinto, 2024). Maintaining PV-RO systems requires regular monitoring, cleaning, and repair, which can be costly and labour-intensive (Prescinto, 2024). Additionally, the shortage of skilled professionals to operate and maintain these systems can lead to inefficiencies and increased downtime (Prescinto, 2024). As noted by Prescinto (2024), adopting digital tools and optimizing O&M strategies can help reduce costs and improve system performance. The operator of the system in Qala-e-Gulbaz Village was selected during the initial phase of the system's installation and trained by a technical expert from the Silicon Solar Company on the manual operation and maintenance, including dosing, antiscalant and filter washing protocols. Furthermore, to reduce O&M costs, the study recommends implementing regular preventive maintenance, training local operators, optimizing energy-efficient components, and periodically upgrading key components to enhance system performance as well as minimize the need for costly repairs and external expertise.

3.5. Observation of water storage in households

The households in the study area store their drinking water in containers (mostly, in jerry cans). Since recontamination of treated water is a common issue, household water storage containers underwent examination. As the result, it was revealed that the majority (56%) of the target households used narrow-mouthed containers, 19% had wide-mouthed and 25% had both types of containers. The openings of all the containers were covered in 100% of the cases. The research teams judged the water storage containers to be clean in 100% of the households.

3.6. User perceptions on the system

After running the RO filtration plant for 8 months, DACAAR's health and hygiene promoter couple interviewed 16 households using the questionnaire (Table VIII), with the following user feedback:

a. 100% of the interviewed households liked the filtered water because it was tasty, fresh, clean, and without smell;

b. All households used the treated water only for drinking and cooking;

c. All households received on average 50 liters of water (minimum 30 liters, maximum 60 liters) every day;

d. All the water meters at the households were functional, and readings were recorded every month by the operator of the water management committee (WMC);

e. 100% of the interviewed households stated that since they had started using the filtered water from the RO plant (8 months ago), their health has improved (they noticed a decrease in waterborne diseases).

3.7. Wider policy design of the national system

The design and implementation of PV-RO systems nationwide require a strategic approach that integrates technical and socio-economic factors. Based on the Qala-e-Gulbaz pilot project, national policies should focus on supporting renewable energy solutions for rural water supply, including the following:

a. Financial support mechanisms: Recent studies emphasize the importance of financial support mechanisms for renewable energy projects. A research in Slovenia highlights the effectiveness of operational support for solar power plants (Gornjak et al., 2024), while a study in Cameroon demonstrates how feed-in tariffs and power purchase agreements attract investment in solar PV projects (Njoke et al., 2023). These findings suggest that tailored financial policies are crucial for supporting PV-RO systems. Given the high initial costs of PV-RO systems (USD79.5 per capita in the Qala-e-Gulbaz case), policies should focus on creating donor funding frameworks and subsidy schemes that can ease the financial burden on rural populations.

b. Sustainable water management practices: The significant brine disposal (50% of the source water) from PV-RO systems calls for policies supporting brine management technologies like Zero Liquid Discharge (ZLD) and reuse in agriculture. ZLD allows recycling all water, minimizing waste and environmental impacts (Cipolletta et al., 2021). Reusing brine in agriculture has shown promise for hydroponic culture and agricultural production (Da Silva Dias et al., 2021; Jiménez-Arias et al., 2022).

c. Local-level capacity building: Training local operators, as was done for the Qala-e-Gulbaz system, should be a national priority. Policies that encourage technical training programs for local technicians can help lower O&M costs and ensure long-term system reliability. Recent studies highlight that successful capacity building requires context-specific training, integration of local knowledge, and financial support for continuous learning (Nurdin & Baharuddin, 2023). Additionally, incentivizing the development of local expertise in maintenance and troubleshooting will reduce dependency on foreign specialists.

d. Regulatory framework: Establishing a robust regulatory framework is essential to ensure the quality, safety, and long-term sustainability of PV-RO water filtration systems. Standards should be developed for system design, water quality monitoring, brine disposal, and technical certifications for operators. Regulatory bodies' mandates should include overseeing implementation and ensuring compliance with environmental and health standards. As per Magazine team (2024), the upcoming Hassyan solar-powered desalination plant in Dubai – a project to become the world's most energy-efficient – demonstrates strict adherence to environmental regulations, particularly in brine discharge management, by selecting discharge areas based on ecological sensitivity and limiting environmental impacts.

e. Research and development: Integrating research and development (R&D) into the policy framework is essential for advancing photovoltaic-powered reverse osmosis desalination technologies. The Nidal Hilal Project (2025) has led to significant innovations in membrane technology, including the development of self-cleaning membranes, which are crucial for improving the sustainability of desalination processes. These advancements underscore the need for policies that support continuous R&D investments to drive technological progress in PV-RO desalination.

4. Conclusion

The study of the piloted photovoltaic reverse osmosis (PV-RO) system for drinking water treatment in Qala-e-Gulbaz Village demonstrates its potential as an effective solution to address water quality issues caused by pollution and over-exploitation of groundwater aquifers in Kabul Province. The system shows high removal efficiencies for salinity, TDS, various chemicals, and bacteria. However, challenges – such as high initial cost, significant wastewater disposal, and the need for professional operators leading to high O&M costs – have been identified. To optimize the system's efficacy and sustainability, the recommendations include enhancing system efficiency, improving wastewater management, reducing initial costs via financial support, implementing training programs, and developing a comprehensive policy framework. The findings of this study highlight the viability of PV-RO systems as a sustainable water treatment alternative, contributing to improved water quality and public health.

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