Sustainable Development of an Optimized Design Model for Groundwater Purification Units: A Solution for Irrigation Use in Rural Communities

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ABSTRACT

Groundwater is an essential resource for both irrigation and drinking water, particularly in arid and semi-arid regions where it often serves as the only dependable source. However, its quality is increasinlgy threatened by factors such as urbanization, population growth, and the overuse of chemical fertilizers in agriculture. hese challenges are particularly acute in Saudi Arabia, where groundwater quality deterioration poses significant obstacles to sustainable water use. This study proposes an optimized design for groundwater purification units aimed at improving water quality for irrigation. The proposed systems integrate coagulation with advanced purification methods, including nanofiltration or sand filtration, to effectively remove contaminants and enhance groundwater suitability for agricultural use. Nanofiltration excels in removing dissolved salts, organic molecules, and microorganisms, while sand filtration offers an economical solution for reducing suspended solids and turbidity By addressing critical water quality challenges, the model ensures more sustainable agricultural practices and a cleaner water supply for local communities. This research underscores the need for effective water management and purification strategies to safeguard groundwater as a reliable and safe resource for future generations, especially in regions like Saudi Arabia that face severe water scarcity and pollution pressures.

Keywords-water treatment; groundwater quality; irrigation; groundwater purification; sustainable design

I. INTRODUCTION

Groundwater is a vital resource, providing nearly half of the world's drinking water and 43% of global irrigation needs [1]. It is also a primary source of freshwater, with current groundwater extraction accounting for about 26% of the total freshwater withdrawn globally [2]. One major advantage of groundwater for drinking water supplies is its natural protection from pollutants [3]. In arid and semi-arid regions, groundwater is often the only reliable water source, supporting river base flows and groundwater-dependent ecosystems. Saudi Arabia, as an arid country with low rainfall, suffers from the problems of water scarcity and limited renewable water resources. Approximately 50% of its potable water is sourced from seawater desalination, 40% from the extraction of nonrenewable groundwater, and just 10% from surface water in the mountainous southwest of the country [4]. This minimal precipitation is the principal source of replenishment for the groundwater system.

Shallow groundwater near major cities has become increasingly polluted due to various human activities, such as industrial effluents, agricultural fertilizers, and domestic sanitation practices, as illustrated in Figure 1. This contamination introduces a range of components into irrigation water, including natural and anthropogenic substances with salinity being a particularly critical issue [5]. In addition to dissolved salts, irrigation water often contains suspended solids (SS), which pose a risk of clogging micro-irrigation systems.

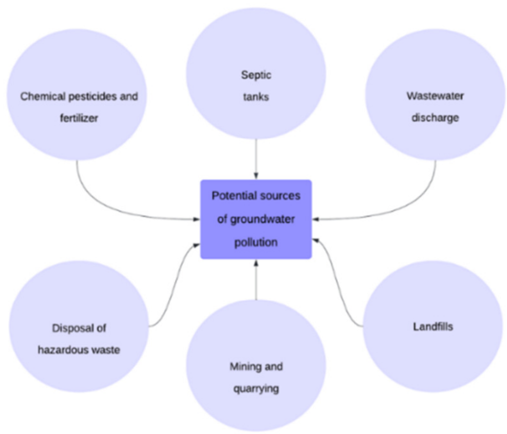

Fig. 1. Poteltial sources of groundwater pollution.

Water quality concerns have broadened over time, encompassing physicochemical, biological, and microbiological attributes that significantly impact both agricultural productivity and environmental health. Factors used to evaluate irrigation water include [6-8]: (i) chemical quality, including salinity; toxicity hazards for the soil and plants; and damage to the irrigation system, such as pipe corrosion, (ii) physical quality, focusing on issues like the presence of suspended solids or other impurities that can clog irrigation systems, and (iii) biological quality, including issues caused by microorganisms harmful to humans, animals, soil, plants, and irrigation systems. Although chemical evaluations are commonplace, assessments of physical and biological attributes are relatively rare in the literature. A holistic evaluation should incorporate meteorological conditions, soil characteristics, and other variables affecting the utility of water in agriculture and landscape management. Efforts to classify water for irrigation typically focus on salt composition and total concentration [9], recognizing that factors such as crop type, soil quality, climate, and irrigation practices also significantly influence water's utility.

Saudi Arabia's groundwater faces mounting challenges from over-extraction and pollution stemming from urbanization, industrialization, and agricultural activities [10]. Modern agricultural advancements, including the extensive use of pesticides, chemical fertilizers, and treated sewage recycling, worsen groundwater contamination. These pollutants cause substantial changes in water quality, including elevated levels of nitrates, fluorides, and total dissolved solids (TDS), posing critical environmental and agricultural challenges [11-12]. Numerous studies have explored methods for treating such contamination [13-15]. In light of the aforementioned challenges, clean water is an invaluable resource in the Kingdom of Saudi Arabia and requires proper conservation. Municipalities are allocating substantial technical, human, and financial resources to remediate polluted seas and groundwater to provide clean drinking water to customers. This study aims to develop two water purification system configurations to provide sustainable and clean water for domestic and irrigation purposes in rural Saudi Arabia. Such technologies are vital for improving the quality of life, supporting environmental resilience, and promoting sustainable management in the country's water scarce environment.

II. PROPOSED DESIGN OF THE WATER PURIFICATION UNIT

The proposed methodology integrates coagulation process with either Nanofiltration (NF) or Rapid Sand Filtration (RSF) to offer a sustainable and cost-effective solution for enhancing the quality of groundwater for irrigation purposes. The groundwater parameters before treatment are shown in Table I.

TABLE I. CHARACTERISTICS OF THE GROUNDWATER BEFORE TREATMENT

Parameter	Value
pH	9.0
TDS	> 2000 mg/L
Electrical Conductivity (EC)	> 5000 μS/cm
Turbidity	100 NTU

For both purification systems, the average flow rate is assumed to be $Q_{avg} = 50\ m^3/d$.

A. *Intake Tank Design*

To optimize the flow dynamics and filtration efficiency, the intake tank configuration for both purification systems was carefully designed using fundamental fluid mechanics equations. The intake tank is equipped with a strainer to filter out debris and suspended solids from the incoming water before it enters the purification process. This strainer ensures that large contaminants, such as leaves, sediment, or organic matter, are removed, protecting the downstream components, like pumps and filtration units, from clogging or damage. A velocity of 0.5 m/s was assumed inside the gravity pipe.

- Calculation of the diameter of the pipe (D_{pipe}) that conveys groundwater into the tank:

$$Q_{avg} = A_{pipe} \cdot \text{Velocity} \quad (1)$$

$$A_{pipe} = \frac{50\,\frac{m^3}{d}}{\left(0.5\,\frac{m}{s}\cdot 86400\,\frac{s}{d}\right)} = 0.001\ m^2$$

$$\text{Area} = \frac{\pi}{4}\cdot D^2 \quad (2)$$

$$D_{pipe} = \sqrt{0.001\ m^2 \cdot 4/\pi} \approx 0.04\ m$$

A detention time of 20 minutes and a tank depth of 2.5 m were assumed to calculate the intake tank's volume and the corresponding diameter.

- Tank diameter (D_{tank}):

$$Q_{avg} = \frac{\text{Volume}}{\text{Time}} \quad (3)$$

$$V_{tank} = \left(\frac{50\,\frac{m^3}{d}}{1440\,\frac{min}{d}}\right)\cdot 20\ min \approx 0.7\ m^3$$

$$\text{Area} = \frac{\text{Volume}}{\text{depth}} \quad (4)$$

$$A_{intake\ tank} = \frac{0.70\ m^3}{2.5\ m} = 0.28\ m^2$$

$$D_{tank} = \sqrt{0.28\ m^2 \cdot 4/\pi} \approx 0.6\ m$$

To design the strainer for the intake tank, a water velocity of 0.15 m/s was assumed to ensure efficient filtration without causing excessive flow resistance. Equations (1) and (2) were utilized to calculate the strainer's diameter:

- Strainer diameter ($D_{strainer}$):

$$A_{strainer} = \frac{50\,\frac{m^3}{d}}{\left(0.15\,\frac{m}{s}\times 86400\frac{s}{d}\right)} \approx 0.004\ m^2$$

$$D_{strainer} = \sqrt{0.004\ m^2 \cdot 4/\pi} \approx 0.07\ m$$

The diameter of the strainer holes is assumed to be 12 mm and is used to calculate the number of holes:

$$A_{hole} = \frac{\pi}{4}\cdot (12\ mm)^2 = 1.13\cdot 10^{-4}\ m^2$$

$$\text{Number of holes} = \frac{A_{\text{strainer}}}{A_{\text{hole}}} \quad (5)$$

$$\text{Number of holes} = \frac{0.004\ \text{m}^2}{0.000113\ \text{m}^2} = 36\ \text{holes}$$

Figure 2 illustrates the intake tank system after dimensioning.

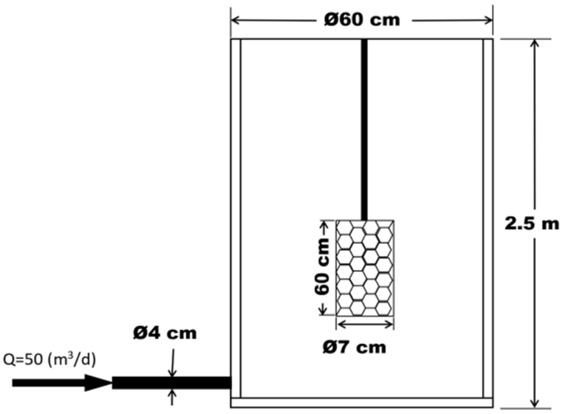

Fig. 2. Configuration of the intake tank system.

B. Coagulation Process Design

In water treatment facilities, coagulation is a key process for removing suspended solids, organic matter, and other impurities, ensuring the provision of safe drinking water for communities. It involves the addition of chemicals, known as coagulants, like alum and ferric chloride, to the water, which neutralize the charges on the suspended particles, causing them to clump together into larger aggregates called "flocs" [16]. Additionally, coagulants help adsorb dissolved organic materials onto these flocs, further enhancing the removal of contaminants during the subsequent solid/liquid separation stages. By aggregating particles, this process simplifies and enhances the efficiency of the filtration stages, allowing for an easier extraction of impurities. To calculate the dimensions of the coagulation tank, alternatively called square flash mixer tank, it was assumed that the time of flash mixer is 1 min and the depth equals 1.5 m.

From (3): $V_{\text{coagulation}} = \left(\frac{50\frac{\text{m}^3}{d}}{1440\frac{\text{min}}{\text{d}}}\right) \times 1\ \text{min} \approx 0.03\ \text{m}^3$

From (4): $A_{\text{coagulation}} = \frac{0.03\ \text{m}^3}{1.5\ \text{m}} \approx 0.02\ \text{m}^2$

$\text{side length} = \sqrt{0.02} \approx 0.15\ \text{m}$

The mixer power (in hp) is calculated by:

$$\text{Power} = G^2 \cdot \mu \cdot V_{\text{coagulation}} \quad (6)$$

where G is the velocity gradient assumed as $G = 1000\ \text{s}^{-1}$, μ is the water dynamic viscosity equal to $1.0087 \times 10^{-3}\text{N}\cdot\text{s}/\ \text{m}^2$, and $V_{\text{coagulation}}$ is the coagulation tank volume.

$\text{Power} = (1000\ \text{s}^{-1})^2 \cdot 1.0087 \times 10^{-3}\ \frac{\text{N}\cdot\text{s}}{\text{m}^2} \times 0.03\text{m}^3 = 30.26\ \text{W} = 0.04\ \text{hp}$

For the coagulant, an optimum aluminum sulfate $Al_2(SO_4)_3$ (alum) dosage of 25 mg/L was used, with an alum density of 600 kg/m^3. The coagulant daily load was calculated by:

$$\text{Coagulant Daily Load} = \text{Dosage} \cdot Q_{avg} \quad (7)$$

$\text{Coagulant Daily Load} = \frac{25\ \text{mg}}{\text{L}} \cdot \frac{1000\ \text{L}}{1\ \text{m}^3} \cdot \frac{1\ \text{kg}}{1\times10^6\ \text{mg}} \cdot \frac{50\ \text{m}^3}{\text{d}} = 1.25\frac{\text{kg}}{\text{d}}$

$\text{Volumetric load} = \frac{\text{Coagulant Daily Load}}{\text{density of coagulant}} = \frac{1.25\frac{kg}{d}}{600\frac{\text{kg}}{\text{m}^3}} = 0.002\frac{\text{m}^3}{\text{d}}$

Figure 3 depicts the diagram of the coagulation tank dimensions.

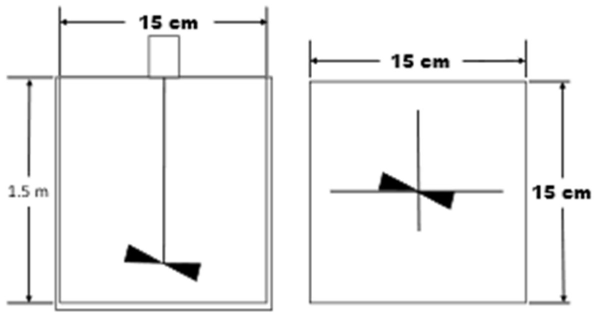

Fig. 3. Diagram of the coagulation tank.

C. NF process design

NF membranes are among the most efficient water purification technologies, with their characteristics being similar to those of ultrafiltration and reverse osmosis membranes [17-18]. With pore sizes ranging from 1 to 10 nanometers, NF membranes are capable of filtering out impurities while retaining essential minerals. This technology is widely employed across industries, such as pharmaceutical companies, food and beverage production, and wastewater treatment. A feed tank is placed before NF to control the water supply.

For the design of the NF unit, the feed tank's volume was set to 1.0 m³, with an assumed depth of 1.0 m:

(4): $A_{\text{feed tank}} = \frac{1.0\ \text{m}^3}{1.0\ \text{m}} = 1.0\ \text{m}^2$

(2): $D_{\text{feed tank}} = \sqrt{1\text{m}^2\ \cdot 4/_{\pi}} = 1.15\ \text{m}$

The power required to operate the pump is calculated by:

$$\text{Power} = \frac{\text{P}\cdot\text{Q}}{600} \quad (8)$$

where Power is measured in kW, P is the pressure in bar (for this study P = 10 bar), and Q is the Q_{avg} in L/min.

$\text{Power} = \frac{10\ \text{bar}\ \left(\frac{50\frac{\text{m}^3}{\text{d}}\cdot1000\frac{\text{L}}{\text{m}^3}}{1440\frac{\text{min}}{\text{d}}}\right)}{600} = 0.58\ \text{kW}$ or 0.78 hp.

A 350 mm diameter and a depth of 50 cm for the NF unit, was utilized:

$$A_{nanofiltration} = \frac{\pi}{4}\,(0.35\text{ m})^2 = 0.0962\text{ m}^2$$

The volume of the NF unit:

$$V_{nanofiltration} = A \cdot \text{depth} = 0.0962\text{ m}^2 \cdot 0.5\text{ m} = 0.048\text{m}^3$$

$$\text{Contact time} = \frac{V}{Q_{avg}} = \frac{0.048\text{ m}^3}{50\frac{m^3}{d}\cdot\frac{1}{1440}\frac{min}{d}} = 1.39\text{ min}$$

To calculate the flux:

$$J = \frac{\text{Volume}}{\text{Time}\cdot\text{Area}} \quad (9)$$

$$J = \left(\frac{0.048\text{ m}^3}{1.39\text{min}\cdot 0.0962\text{ m}^2}\right) \times 1440\frac{\text{min}}{\text{d}} = 519.95\ \text{m}^3/\text{d}\cdot\text{m}^2$$

Figure 4 depicts the diagram of the water filtration system using membrane technology (NF).

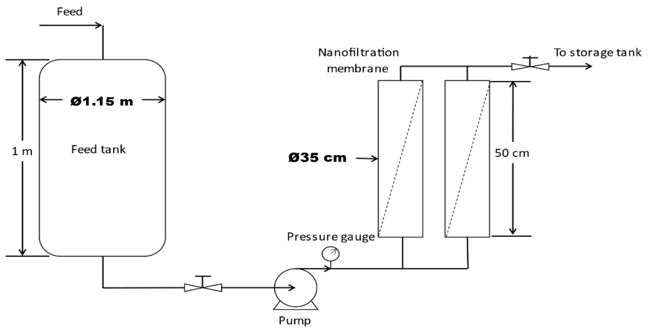

Fig. 4. The layout of the water filtration system using membrane technology.

D. RSF Design

The RSF is widely employed for water purification due to its high efficiency in removing impurities and particles. The key principle of RSF involves passing water through a bed of sand at a high velocity. In addition, the filters need to be periodically backwashed to prevent clogging by the retained solids [19]. For the design, the filter's dimensions were calculated using the following assumed values:

- Velocity = 10 m/h
- Dimension ratio: $\frac{L}{W} = \frac{1.25}{1}$.

$$\text{Area} = \frac{\text{flow rate}}{\text{velocity}} = \frac{50\frac{m^3}{d}\cdot\frac{1}{24}\frac{h}{d}}{10\frac{m}{h}} = 0.2\text{ m}^2$$

Two filters were utilized, so, each filter had a surface area of 0.1 m^2.

To find the width of each filter:

$$W = \frac{\text{Area}}{L} = \frac{A}{1.25W} \rightarrow W = \sqrt{\frac{0.1m^2}{1.25}} = 0.29\text{ m}$$

$$L = \frac{0.10}{0.29} = 0.345\text{ m}{\sim}35\text{ cm}$$

To calculate the dimensions of the sand layer, the following assumptions were made:

- Velocity = 10 m/h
- effective sand size d= 0.6 m,
- terminal head loss h = 1.8 m
- break-through index B = 0.0004

$$L = \frac{Q\cdot d^3\cdot h}{B\cdot 29323} \quad (10)$$

$$L = \frac{10\frac{m}{h}\cdot(0.6\,m)^3\cdot 1.8\text{ m}}{0.0004\cdot 29323} = 0.33\,m$$

While L<0.6 m, it is acceptable to assume a depth of 0.6 m.

Regarding the gravel layer, the depth was distributed for different gravel sizes, with the smallest being found at the top and the largest at the bottom (assumptions: k =12 and the size of gravel is 2 mm):

$$L = 2.54\ \cdot k\ \cdot \log(d) \quad (11)$$

$$L = 9.20\text{ cm}.$$

The total depth is, thus, 48.9 cm ~ 50.0 cm.

Table II shows the distribution of the gravel layers with different gravel sizes.

TABLE II. GRAVEL LAYERS WITH DIFFERENT GRAVEL SIZES

Gravel size (mm)	2	5	10	20	40
Depth (cm)	9.2	21.3	30.5	39.7	48.8
Increment (cm)	9.2	12.1	9.2	9.2	92

Considering the lateral, 5 mm were used for the perforation diameter, and the distance between the laterals was 80 mm. The corresponding calculations were performed using the following equations:

$$\frac{\text{The total area of perforations}}{\text{Area of filter}} = 0.3\% \quad (12)$$

$$\text{The total area of perforations} = 0.10\text{ m}^2\cdot\frac{0.3}{100} = 0.0003\text{ m}^2$$

$$\text{Area of perforations} = \frac{\pi}{4}\cdot\left(\frac{5}{1000}\text{m}\right)^2 = 0.00002\text{ m}^2$$

$$\text{The total area of laterals} = 2\cdot 0.0003\text{ m}^2 = 0.0006\text{ m}^2$$

$$\text{Number of laterals} = \frac{0.36}{0.08} = 4.5\text{ laterals}$$

$$\text{Total number of laterals} = 2\cdot 4.5 = 9.0\text{ laterals}$$

$$\text{Area per lateral} = \frac{0.0006\text{ m}^2}{9} = 67\text{ mm}^2$$

$$\text{Diameter per lateral} = \sqrt{0.000067\text{ m}^2\cdot 4/_{\pi}} = 0.0092\text{ m}$$

$$\text{Number of perforations} = \frac{0.0003\text{ m}^2}{0.00002\text{ m}^2} = 15$$

$$\text{Number of perforations per lateral} = \frac{15}{9} = 1.7$$

Area of manifold $= 2 \cdot$ total area of laterals $= 2 \cdot 0.0006 = 1200\ \text{mm}^2$

$$\text{Diameter of manifold} = \sqrt{0.0012\ \text{m}^2 \cdot {}^{4}/_{\pi}} = 0.04\ \text{m}$$

$$\text{Length of lateral} = \frac{(0.29-0.04)\text{m}}{2} = 0.1\ \text{m}$$

For the trough design, the backwashing rate was 10 m/h, the trough width was 0.25 m, and the distance between troughs was 1.25 m.

$$\text{The flow rate of backwashing} = 0.10\text{m}^2 \cdot 10\,\frac{\text{m}}{\text{h}} = 1\,\frac{\text{m}^3}{\text{h}}$$

$$\text{Flow rate per trough} = \frac{4}{2} = 2\,\frac{\text{m}^3}{\text{h}}$$

$$Q = 2.49\ bh^{3/2} \quad (13)$$

$$h = \sqrt[3/2]{\left(\frac{{}^{2}/_{60^2}}{2.49\times0.10}\right)} = 0.017\ \text{m} = 1.7\ \text{cm}$$

Figure 5(a) illustrates the diagram of the filter bed, providing details for the laterals and manifolds of the RSF dimensions and locations, whereas Figure 5(b) presents the overall diagram of a rapid sand filter.

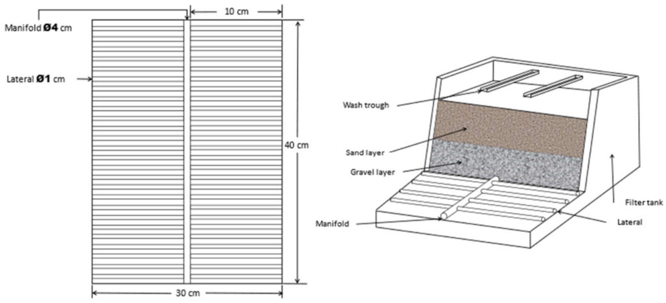

Fig. 5. (a) Diagram of the filter bed of RSF, (b) overall diagram of RSF.

Figures 6 and 7 display the two optimized purification units proposed by this study for the filtration and purification of contaminated groundwater.

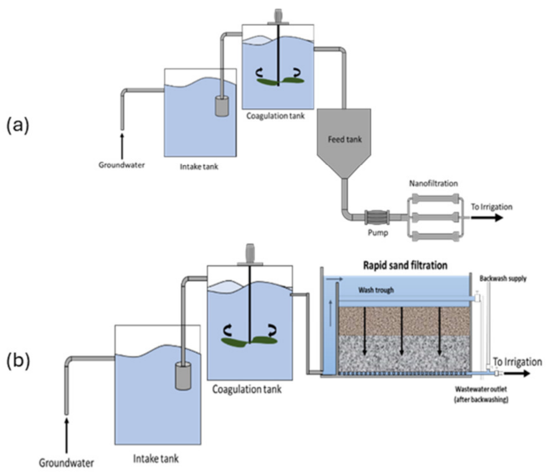

Fig. 6. Diagram of the proposed purification systems (a) NF, (b) (RSF)

III. RESULTS AND DISCUSSIONS

In this study, two water purification methods—NF and RSF—were evaluated for their effectiveness in treating groundwater for irrigation and domestic use in rural areas. Both proposed models can have high TDS and salinity removal efficiency and are suitable for irrigation purposes. The expected water quality parameters after purification are outlined in Table III.

TABLE III. EXPECTED CHARACTERISTICS OF THE TRATED GROUNDWATER

Parameter	Value
pH	6.5-8.50
TDS	> 100 mg/L
Electrical Conductivity (EC)	> 250 µS/cm
Turbidity	10-12 NTU

Nanofiltration, known for its ability to filter particles as small as one nanometer, demonstrated high efficiency in removing a wide range of contaminants, including dissolved salts, organic molecules, and microorganisms [20]. This membrane-based technology has significant advantages over traditional filtration methods, offering high-quality water while preserving essential minerals needed for irrigation. In terms of performance, the NF system achieved a flux rate of 519.95 m^3/day per membrane unit, ensuring sufficient treatment capacity for medium-sized agricultural operations. The advanced filtration capabilities of NF make it particularly suitable for areas with high concentrations of dissolved contaminants, including agricultural runoff, industrial pollution or saline intrusion [4]. Thus, the nanofiltration system involves higher capital costs due to the inclusion of advanced membrane technology and high-pressure pumps, which are essential for achieving optimal filtration performance.

On the other hand, the second purification unit proposed in this study integrated coagulation with rapid sand filtration. RSF, a well-established method in water treatment, excels at removing suspended solids and particulate matter. This low-cost, robust system operates with a filtration rate of 10 m/h, making it ideal for continuous operation in rural settings. The system's design, including a fine sand layer over a graded gravel bed, optimizes filtration rates and ensures uniform water distribution through the system. Rapid sand filtration, while less effective in removing dissolved salts and smaller contaminants compared to NF, offers significant advantages in terms of scalability, ease of maintenance, and lower operational costs. It also improves water clarity, reducing suspended solids that could otherwise clog irrigation systems, making it a practical solution for rural areas where resources may be limited. A fundamental comparison between the two proposed models has been illustrated in Table IV.

In both systems, the use of coagulation as a pretreatment step significantly improved filtration performance by reducing the load of impurities that would otherwise compromise the efficiency of the filtration units.

TABLE IV. COMPARISON BETWEEN THE TWO PROPOSED METHODS

Criteria	NF	RSF
Filtration Efficiency	1-10 nm pore size, capable of removing dissolved organics, heavy metals, and salts	Larger pore size, effective for particulate matter but less efficient for dissolved impurities
Flow Rate (Q)	50 m³/day	50 m³/day
Energy Consumption	0.78 hp, high energy requirement	Minimal energy consumption
Pressure Requirement	10 bar	Low-pressure filtration
Contaminant Removal	Effective in removing chemical contaminants	Effective in removing suspended particles and sediments
Maintenance	High, requires periodic membrane cleaning and replacement	Low, regular sand cleaning/backwashing needed
Capital Cost	Higher due to membrane technology	Lower capital cost due to simpler sand filter setup
Operational Cost	Higher, membrane replacement, energy	Lower, simple backwashing and minimal power
Contact Time	1.39 min	Higher contact time, depending on sand depth
Purification Quality	High-quality output, retains beneficial minerals while removing harmful substances	Good quality for particulate and microbial removal, but not as efficient with dissolved contaminants

IV. CONCLUSIONS

This study evaluated two purification systems for treating groundwater in the rural communities of Saudi Arabia. The first system integrates coagulation with Nanofiltration (NF), while the second combines coagulation with a Rapid Sand Filtration (RSF) process. Given that groundwater in certain parts of Saudi Arabia is often brackish, the primary objective of these designs was to improve irrigation water quality, thereby enhancing crop yield and agricultural output. Both systems incorporate coagulation as a pretreatment step, which enhances the efficiency of the downstream filtration processes by reducing particulate and impurity loads. The NF system demonstrates exceptional effectiveness in removing chemical pollutants, dissolved salts, and microorganisms, and is, hence, considered ideal for highly saline or heavily contaminated groundwater. However, the system's advanced technology and operational requirements entail higher initial costs and energy consumption, alongside maintenance demands. In contrast, the RSF system offers a cost-effective approach, efficiently removing suspended solids and particulate matter. It is especially beneficial for rural communities dealing with moderate water quality issues. However, the current paper highlights the need for further investigation into the performance metrics of each system, including contaminant removal efficiencies and long-term operational costs, to better understand their viability for large-scale implementation.

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