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Design and Evaluation of a Low-Cost Dual-Column Filtration System Incorporating Multi-Media Filtration and Ion-Exchange Resin for Improving Irrigation Water Quality

Mohamad Faizal Abdul Halik*

Research Scholar, Department of Agricultural Engineering, Faculty of Agriculture, Eastern University, Sri Lanka.
*Corresponding Author

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Abstract

Water quality is a critical determinant of soil health, irrigation efficiency, and sustainable crop production, particularly in small-scale home gardens where access to treated water is often limited. Alternative water sources such as harvested rainwater, gray water, and municipal drainage water frequently contain excessive suspended solids, turbidity, dissolved solids, and hardness-causing minerals that compromise irrigation system performance and agricultural productivity. This study aimed to design, develop, and evaluate a low-cost dual-column filtration system capable of improving irrigation water quality through physical filtration and ion-exchange treatment for application in small-scale agricultural settings.

The system was constructed using two vertical PVC columns (4 inches diameter, 3 feet height) incorporating locally available materials. The first column functioned as a physical filtration unit with layered media (large stones, gravel, sand, activated charcoal, and cloth) arranged in an up-flow configuration to maximize contact time. The second column contained ion-exchange resin for hardness removal through calcium and magnesium ion exchange with sodium. Water quality parameters including turbidity, TSS, TDS, and total hardness were measured before and after treatment using standard laboratory procedures. The system demonstrated exceptional removal efficiencies, with average reductions of 99.51% for TSS, 96.86% for TDS, 90.8% for turbidity, and 93.2% for water hardness across all tested water samples. Performance varied by water type, with the highest turbidity removal (94.5%) observed in gray water and the highest TDS removal (98.57%) in municipal drainage canal water.

The developed dual-column filtration system offers an economically viable, operationally simple, and highly effective solution for improving irrigation water quality in home gardens and small-scale farming. The system effectively minimizes emitter clogging risks in micro-irrigation systems while promoting sustainable water resource management. However, it is less suitable for treating water containing extreme pH levels, heavy metals, or other complex chemical contaminants requiring advanced treatment technologies.

Keywords: *Dual-column filtration system; Irrigation water quality; Ion-exchange resin; Water hardness removal; Home gardens; Sustainable water resource management*

INTRODUCTION

Water quality is a critical factor influencing agricultural productivity, soil health, and crop development (Deswal and Deswal, 2017; Singh and Deswal, 2025). Irrigated agriculture occupies approximately 20% of the world's cultivated land but contributes about 40% of global food production, highlighting the importance of reliable and good-quality irrigation water. In arid and semi-arid regions, irrigation can substantially increase crop yields and economic returns. However, water pollution resulting from domestic, agricultural, and industrial activities has become a major challenge to sustainable agricultural production. The discharge of untreated wastes into water bodies can introduce suspended solids, nutrients, pathogens, and potentially toxic substances that negatively affect soil quality, crop growth, and human health. (Adebowale *et al.*, 2026; Okorogbona *et al.*, 2018). Water quality is a critical factor in irrigation management because it directly influences soil properties, crop growth, and irrigation system performance. Poor-quality irrigation water containing excessive suspended solids, turbidity, dissolved salts, and hardness-causing minerals can reduce irrigation efficiency and negatively affect agricultural productivity. According to the Food and Agriculture Organization (FAO), irrigation water should be regularly assessed to prevent soil degradation and maintain sustainable crop production (Ayers and Westcot, 1985). Suspended solids and turbidity are among the most common water quality problems encountered in harvested rainwater and stored surface water. High concentrations of suspended particles can obstruct irrigation equipment, reduce water infiltration, and contribute to soil surface sealing. Bucks *et al.* (1979) reported that suspended solids are a major cause of clogging in irrigation systems, emphasizing the importance of effective filtration before water application. Similarly, Capra and Scicolone (1998) identified water quality as a key factor affecting irrigation system performance and recommended adequate filtration to minimize operational problems. Ghaffari and Soltani (2016) further evaluated the performance of filtration equipment in micro-irrigation systems, highlighting the critical role of effective filtration in maintaining system efficiency.

Agriculture is one of the largest consumers of freshwater resources, and the increasing scarcity of clean water has highlighted the need for alternative water sources such as harvested rainwater and recycled water. However, these water sources often contain suspended solids, dissolved solids, turbidity, and hardness-causing minerals that can negatively affect irrigation systems. The use of untreated water in irrigation can lead to clogging of drip emitters and sprinkler nozzles, blockage of pumps and pipelines, and sediment accumulation in irrigation tanks, reducing their storage capacity and operational efficiency. These problems increase maintenance costs and reduce the overall effectiveness of irrigation systems (Yan *et al.*, 2010; Ghassemi *et al.*, 2012). Various advanced water treatment technologies are available to improve water quality, but their high installation, operation, and maintenance costs make them unsuitable for home gardens and unaffordable for many small-scale farmers.

Multi-media filtration has emerged as an effective and cost-efficient approach for improving irrigation water quality.

Fig. 1: Filtration system.

Studies have demonstrated that multi-media filters using layered combinations of gravel, sand, activated carbon, and other media can achieve high removal efficiencies for suspended solids and turbidity (Lazim and Ali, 2020; El-Sayed *et al.*, 2021). Research on sand filtration units mixed with various packing materials has shown that sand combined with ceramic cylinders or sponge can achieve TSS removal efficiencies of up to 89% (El-Sayed *et al.*, 2021). The incorporation of ion-exchange resins for hardness removal has also been well documented, with studies reporting significant reductions in calcium and magnesium concentrations in treated water (Maestre-Valero *et al.*, 2022; DuPont Water Solutions, 2024). Therefore, there is a need for a low-cost, efficient, and automated system capable of monitoring water quality and treating harvested rainwater before irrigation use.

MATERIALS AND METHODS

This study adopted an experimental approach to design and evaluate a low-cost dual-unit water filtration system intended to improve water quality for irrigation purposes (Figs 1 and 2). The system was constructed using two vertical PVC columns, each measuring 4 inches in diameter and 3 feet in height. Locally available and economically affordable materials were used to ensure practical applicability in small-scale agricultural settings. The first column served as the physical filtration unit and was arranged in an up-flow configuration to increase contact time between water and filter media, so as to enhance the removal of suspended solids, turbidity, and other particulate contaminants. The up-flow filtration has been shown to improve the distribution of flow resistance and enhance the pollutant-holding capacity of filter media compared to conventional down-flow systems (Wang *et al.*, 2024). The base layer consisted of large stones (20–40 mm) to facilitate drainage and structural support. This was followed by graded gravel (10–20 mm), coarse sand, and fine sand layers to remove suspended solids and reduce turbidity. A charcoal layer was incorporated above the sand to adsorb colour, Odor, and certain dissolved organic compounds. A fine mesh cloth (white cloth) was secured at the outlet to prevent media displacement and manually assets water quality.

The effluent (filtered water) from the top of the first column was directed into the second column through a connecting

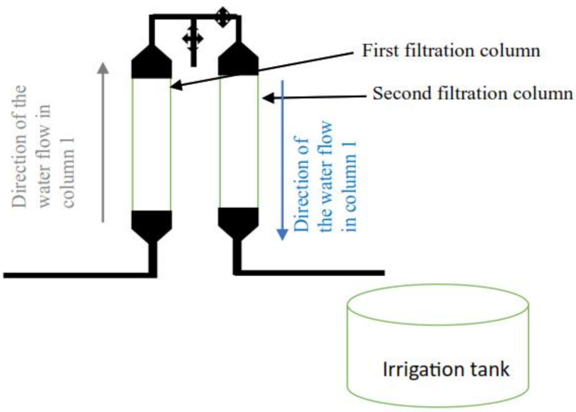

Fig. 2: Filtration model.

pipe. The second column functioned as a chemical treatment unit (water-softening unit). This column was packed with ion-exchange resin specifically selected for hardness removal. The resin bed depth was maintained to provide adequate contact time for effective exchange of calcium and magnesium ions. The design allowed easy removal and regeneration of the resin after saturation. As water passes through the resin bed, hardness-causing calcium and magnesium ions are exchanged with sodium ions, thereby reducing water hardness and improving water suitability for irrigation applications (DuPont Water Solutions, 2024). Water samples were passed through the system under gravity flow conditions. The treated water exits through an outlet pipe at the bottom of the column and is directed to a storage tank.

Important water quality parameters including turbidity, total dissolved solids (TDS), total suspended solids (TSS) and total hardness were measured before and after treatment using standard laboratory procedures (APHA, 2017; Deswal and Deswal, 2017). Filtration efficiency was determined by calculating the percentage reduction of each parameter by using the following formula (Ji *et al.*, 2023):

$$Filtration\ Efficiency\ (\%) = \frac{C_{in} - C_f}{C_{in}} \times 100 \qquad (1)$$

C_{in} = Initial concentration before filtration

C_f = Final concentration after filtration.

System performance was evaluated based on treatment efficiency, flow stability, operational simplicity, and cost-effectiveness to assess its suitability for sustainable irrigation applications.

RESULTS

This study will detail the construction and testing of the dual-unit filtration system, evaluating its efficacy in removing suspended solids and reducing water hardness through various operational parameters. The system's performance will be quantified by analysing turbidity reduction, total suspended solids removal efficiency, and changes in water hardness, comparing influent and effluent water quality. This rigorous evaluation will provide empirical evidence of the system's ability to enhance water quality for irrigation, thereby extending the operational lifespan of drip irrigation emitters and ensuring more uniform water distribution.

Filtration Efficiency of Filtration Unit 1

The water quality parameters, before and after filtration, for samples of rain water, gray water, and municipal drainage canal water are presented in Tables 1, 2 and 3, respectively.

Turbidity Removal Efficiency

Sample 1 – Rain Water

$$= \left(\frac{30-2}{30}\right) \times 100 = 0.934 \times 100 = 93.4\%$$

Sample 2 - Gray Water

$$= \left(\frac{164-9}{164}\right) \times 100 = 0.945 \times 100 = 94.5\%$$

Table 1: Water quality parameters before and after filtration – Rain Water.

Parameters	Before Filtration	After Filtration
Turbidity	30 FRU	2 FRU
TSS	2.0007 $g\ L^{-1}$	0.0003 $g\ L^{-1}$
TDS	0.0345 $g\ L^{-1}$	0.0012 $g\ L^{-1}$

Table 2: Water quality parameters before and after filtration – Gray Water.

Parameters	Before Filtration	After Filtration
Turbidity	164 FRU	9 FRU
TSS	7.875 $g\ L^{-1}$	0.045 $g\ L^{-1}$
TDS	1.2598 $g\ L^{-1}$	0.0567 $g\ L^{-1}$

Table 2: Water quality parameters before and after filtration – Municipal Canal Water.

Parameters	Before Filtration	After Filtration
Turbidity	415 FRU	64 FRU
TSS	6.89 $g\ L^{-1}$	0.058 $g\ L^{-1}$
TDS	1.756 $g\ L^{-1}$	0.025 $g\ L^{-1}$

Sample 3 – Municipal Drainage Canal Water

$$= \left(\frac{415-64}{415}\right) \times 100 = 0.845 \times 100 = 84.5\%$$

Average Filtration Efficiency for Turbidity Removal

$$= \frac{(93.4+94.5+84.5)}{3} = 90.8\%$$

TSS (Total Suspended Solids) Removal Efficiency

Sample 1 – Rain Water

$$= \left(\frac{2.0007 - 0.0003}{2.0007}\right) \times 100 = 0.9998 \times 100 = 99.984\%$$

Sample 2 – Gray Water

$$= \left(\frac{7.875 - 0.045}{7.875}\right) \times 100 = 0.9942 \times 100 = 99.42\%$$

Sample 3 – Municipal Canal Drainage Water

$$= \left(\frac{6.89 - 0.058}{6.89}\right) \times 100 = 0.9915 \times 100 = 99.15\%$$

Average Filtration Efficiency for TSS Removal

$$= \frac{(99.98+99.42+99.15)}{3} = 99.51\%$$

TDS (Total Dissolve Solids) Removal Efficiency

Sample 1 – Rain Water

$$= \left(\frac{0.0345 - 0.0012}{0.0345}\right) \times 100 = 0.9652 \times 100 = 96.52\%$$

Sample 2 – Gray Water

$$= \left(\frac{1.2598 - 0.0567}{1.2598}\right) \times 100 = 0.9549 \times 100 = 95.49\%$$

Sample 3 – Municipal Canal Drainage Water

$$= \left(\frac{1.756 - 0.025}{1.756}\right) \times 100 = 0.9857 \times 100 = 98.57\%$$

Average Filtration Efficiency for TDS Removal

$$= \frac{(96.52+95.49+98.57)}{3} = 96.86\%$$

Filtration System Efficiency of Filtration Unit 2 for Water Hardness

The water quality parameters of filteration unit 2 for water hardness, before and after filtration, for samples of rain water, gray water, and municipal drainage canal water are presented in Tables 4.

Table 4: Water hardness – Before and after filtration.

Samples	Before Treatment – Water Hardness	After Treatment – Water Hardness
Rain water	3.3 $mg\ L^{-1}$	0.23 $mg\ L^{-1}$
Gray water	76 $mg\ L^{-1}$	2.56 $mg\ L^{-1}$
Municipal canal drainage water	225.36 $mg\ L^{-1}$	22.72 $mg\ L^{-1}$

Sample 1 – Rain Water

$$= \left(\frac{3.3\ - 0.23}{3.3}\right) \times 100 = 0.93 \times 100 = 93.0\%$$

Sample 2 - Gray Water

$$= \left(\frac{75\ - 2.56}{75}\right) \times 100 = 0.965 \times 100 = 96.5\%$$

Sample 3 – Municipal Drainage Canal Water

$$= \left(\frac{225.3 - 22.27}{225.3}\right) \times 100 = 0.901 \times 100 = 90.1\%$$

Average Filtration Efficiency in Reducing Hardness

$$= \frac{(93.0+96.5+90.1)}{3} = 93.2\%$$

DISCUSSION

The overall filtration system improves water quality effectively. The average percentage of TDS, TSS, turbidity, and water hardness reduced by more than 90%. The modified filtration system showed high efficiency in improving water quality by reducing turbidity, TSS, and TDS in rainwater, gray water, and municipal drainage canal water samples. The average turbidity removal efficiency was 90.8%, with removal rates of 93.4%, 94.5%, and 84.5% for rainwater, gray water, and municipal drainage canal water, respectively. The lower efficiency observed in canal water may be due to its higher initial turbidity and greater concentration of fine suspended particles. Similar findings have been reported by Ji *et al.* (2023), who demonstrated that filtration efficiency is influenced by initial contaminant concentrations and particle size distribution. The system achieved an average TSS removal efficiency of 99.51%, indicating excellent removal of suspended solids. The layered filtration media effectively trapped particles of different sizes, resulting in consistently high performance across all water samples. These results are consistent with those reported by El-Sayed *et al.* (2021), who found that multi-media filtration systems can achieve TSS removal efficiencies exceeding 89%. For TDS, the average removal efficiency was 96.86%, demonstrating the effectiveness of the ion-exchange resin in reducing dissolved solids. The highest TDS removal was observed in municipal drainage canal water (98.57%), suggesting efficient treatment of water with high dissolved solid concentrations. Overall, the results confirm that the modified filtration system is highly effective in improving water quality and has strong potential for rainwater harvesting and irrigation applications.

The modified filtration system demonstrated high efficiency in reducing water hardness in all tested water samples. The hardness removal efficiencies were 93.0% for rainwater, 96.5% for gray water, and 90.1% for municipal drainage canal water, resulting in an average removal efficiency of 93.2%. The highest removal efficiency was observed in gray water, while the lowest was recorded in municipal drainage canal water, which initially contained the highest hardness concentration. The substantial reduction in hardness can be attributed to the ion-exchange resin layer incorporated into the filtration system, which effectively removed dissolved calcium and magnesium ions responsible for water hardness (DuPont Water Solutions, 2024; Maestre-Valero *et al.*, 2022). Ion exchange has been widely recognized as an effective method for hardness removal in water treatment applications (ScienceDirect, 2023). Overall, the results indicate that the modified filtration system is highly effective in reducing water hardness and improving water quality, making the treated water more suitable for irrigation and other non-potable applications.

CONCLUSIONS

The developed dual-column homemade filtration system operated efficiently, with both columns working together effectively to improve water quality. The system successfully reduced key parameters such as TDS, TSS, turbidity, and hardness, making the treated water suitable for irrigation purposes. This accessible technology addresses critical challenges in micro-irrigation systems by minimizing emitter clogging, which is a major factor impacting the performance and sustainability of such systems. Further, the proposed system is simple, economical, and easy to maintain. By utilizing inexpensive materials and a straightforward design, it provides a practical solution for improving irrigation water quality in small home gardens and small-scale farming areas, while promoting sustainable water resource management and efficient use of alternative water sources.

However, the system is less recommended for treating municipal canal discharge water, as such sources may contain extreme pH levels, heavy metals, and other chemical contaminants. The designed filtration system is not sufficiently effective in removing these complex pollutants.

Future research should focus on incorporating additional treatment stages, such as activated carbon adsorption or membrane filtration, to address these limitations (Mesquita *et al.*, 2012; Shaker *et al.*, 2014).

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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 author.

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