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Research Paper

A case study of comparative techno-economic and life cycle assessment of tap water versus household reverse osmosis-based drinking water systems in a North Indian city

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ABSTRACT

Household reverse osmosis (RO)-based water purifiers have gained popularity in India due to concerns about the quality of tap water. However, the widespread adoption of these systems has significant impacts on water pricing and the environment. The objective of this study was to assess the techno-economic performance and life cycle assessment (LCA) of household RO-based water purifiers in Srinagar city of North India. Our results demonstrate that household ROs reduce the concentration of important dietary minerals such as fluoride and magnesium in drinking water by 50%. In addition, the average total water cost from a household RO is three to four times more than what is being paid for tap water. Two different scenarios were compared in LCA. The first scenario was safe drinking water from a conventional drinking water treatment plant (scenario 1), while the second scenario was water from a household RO system (scenario 2). The results showed that the environmental impacts of abiotic depletion, acidification of water bodies, eutrophication, global warming and ozone depletion in scenario 2 were higher than in scenario 1. The findings infer that water utilities should encourage citizens to rely on conventional tap water as a cheaper and environmentally friendly option compared to household ROs.

Key words: drinking water, household reverse osmosis, Life Cycle Assessment (LCA), techno-economic assessment, water quality

HIGHLIGHTS

- Household RO-based systems reduce few dietary minerals from tap water by 50%.
- TWC/m^3 of household RO-based systems is three to four times more than tap water.
- LCA of conventional tap water and household RO-based systems was carried out.
- Household RO-based systems have more environmental impacts than tap water.

1. INTRODUCTION

Access to safe drinking water is a fundamental human right and a global concern (WHO 2017). Unfortunately, in India, less than 50% of the population has access to safe drinking water, resulting in an economic burden of USD 600 million per annum due to waterborne diseases (UNICEF 2022). To provide safe drinking water, conventional drinking water treatment plants (DWTP) in India typically use coagulation, sedimentation, filtration, and disinfection to remove organic content and pathogens. However, there has been a noticeable shift in behavior among citizens who are installing reverse osmosis (RO)-based water purifiers in most residential and commercial buildings. In fact, more than 10 million units were sold in India during the 2019–2020 financial year, and sales in the Indian market are expected to grow at a compound annual value growth rate of 9% from 2020 to 2026. European Commission regulations (1998) and the BIS 10500 (2012) also define the standards for safe drinking water. However, the failure of tap water to meet these standards and intermittent supply of water (Mohapatra *et al.* 2014) results in public perception of risk to health and loss of trust, leading to the use of alternate sources such as bottled water and household RO-based water purifiers (Doria *et al.* 2009).

RO technology has been found to be more than 90% efficient in removing dissolved pollutants, making it a simple and effective solution at the household level (Malan & Sharma 2023). This process uses high-pressure membranes to reject most impurities, resulting in lower concentrations of pollutants in the effluent water compared to the inlet water. The efficiency of RO-based water purifiers varies with the type of impurity, with larger toxic ions being removed more effectively than smaller ones. For example, household RO systems have been reported to remove heavy metals such as arsenic in western United States and rural areas of northern India (Walker *et al.* 2008; Malan & Sharma 2023).

Comparative assessments of drinking water alternatives have been reported in different cities worldwide (Fantin *et al.* 2014). Studies comparing conventional tap water and bottled water in Italy (Botto 2009) and Spain (Garfi *et al.* 2016) have concluded that tap water is the most environment-friendly option. Similarly, a study in Switzerland comparing the environmental impact of drinking water and bottled mineral water found that tap water was more favorable (Jungbluth 2006). However, these results may not be fully applicable to other regions, particularly India, as regional water prices, availability of source water, and equipment and energy costs can vary.

Therefore, the aim of this study was to evaluate the technical, economic, and environmental impacts associated with drinking water supply alternatives in a northern city of India. The scenarios for evaluation were drinking water from a conventional DWTP (scenario 1) and a household RO water purifier (scenario 2). The assessment was conducted from the perspectives of water quality, the unit cost of water over the lifecycle of the system, and the environmental impact of the systems using a life cycle assessment (LCA) approach.

2. METHODOLOGY

2.1. Study area

The area selected for this study was Srinagar city of Jammu and Kashmir (a union territory in northern India). The details about the study area and its map are mentioned in section S1 and Figure S1 (supplementary material), respectively.

The selection of the study area was based on the prevalence of household RO-based water purifiers in the region and its proximity to the data collection. Two DWTPs were selected which serve two different suburbs in the city. The treatment configuration of both DWTPs consists of coagulation, sedimentation, rapid sand filtration and chlorination. The treatment capacity DWTPs was 25 million liters per day (MLD) and 38 MLD. The samples of the tap water and the effluent of household reverse osmosis (ROs) were collected from the suburbs being served by the selected DWTPs. A total number of 20 samples of tap water and household ROs were collected. The data were also obtained from the 20 household ROs for the economic assessment and the life cycle analysis (LCA).

2.2. Analysis of water quality

The samples of the tap water and the effluent from the household ROs were collected to comparatively assess the water quality of the two alternatives of drinking water. Those households were selected for the sampling which have installed household ROs and the tap water and RO effluent samples were collected from them. The samples were preserved and analyzed for physicochemical water quality parameters and heavy metals. The parameters were analyzed according to standard methods (APHA 2002) and the results were compared with the drinking water quality standards of India (BIS 10500 2012) and the World Health Organization (WHO 2017).

2.3. Economic assessment

For the economic assessment, the total water cost per cubic meter of produced water (TWC/m^3) paid by a consumer was used for a comparative assessment of tap water and household RO. The cost of tap water from the conventional DWTP as paid by the customer to the service provider was assumed to be TWC/m^3 in scenario 1. In the case of scenario 2, TWC/m^3 of RO effluent for the operational time of 4 h/day over its operational lifetime (7 years) was calculated as below. The 4-h usage used in this study is based on the daily requirement of water for cooking and drinking and the average flow rate of the RO unit.

For TWC/m^3 of scenario 2, the input costs taken for RO units were divided into the following two categories:

(a) CAPEX (Capital Expenditure)

This cost includes the contribution of the initial purchase cost of a single RO unit over the assumed life cycle towards per m^3 of RO purified water produced. For individual RO units, this cost was derived by dividing the initial buying cost of the unit by the total purified water produced by a unit over its life cycle of 7 years using the following equation.

$$\text{CAPEX} = \frac{\text{Initial buying cost of RO unit}}{\text{Water produced over assumed life cycle}} \tag{1}$$

(b) OPEX (operational expenditure)

The operational cost of the RO unit includes the cost of tap water which is used as an influent to the RO unit, cost associated with the electricity, membrane replacement, and technical support. The operational cost is taken as the net present value (NPV) summed over the life cycle of the RO unit. The cost of tap water to produce 1 m^3 of RO purified water (T_i) is calculated based on the efficiency of the RO unit which was 75% according to manufacturer guidelines of RO units according to the following equation.

$$T_i = \frac{\text{Tap water cost per annum}}{\text{Efficiency of RO unit} \times \text{RO influent flowrate per annum}} \tag{2}$$

Electricity cost per m^3 of RO water produced (E_i) was calculated as the yearly electricity charges for an RO unit assuming 4 h usage and local electricity tariff data (Equation (3)). The electricity consumption of the RO units was calculated based on the average wattage of 10 household RO units.

$$E_i = \frac{\text{Electricity cost per annum}}{\text{Electricity consumption of RO unit per annum}} \tag{3}$$

Maintenance cost per m^3 RO water produced (M_i). For each unit costs required for membrane replacement and labor were collected as yearly costs. The total operational cost (C) was found by summing the three costs (C) in the form of NPV using the following equation.

$$\text{NPV} = \sum_{1}^{n} C/(1+i)^n \tag{4}$$

where i is the interest rate (6%), n is the lifetime of the RO unit in years (7 years). NPV gives the value of money in the present time compared to money received in the future based on an interest rate.

In order to get the relevant data for RO units, a questionnaire was prepared for house owners. Other missing data for units were obtained from manufacturers, electricity tariff from Jammu and Kashmir Power Development Department (JKPDD 2022), and water tariff from Jammu & Kashmir State Water Regulatory Authority (JKSWRRA 2021). The detailed calculation is shown in Table S2 (supplementary material) and the data collected from the field are shown in Table S4 (supplementary material).

2.4. Life cycle analysis

LCA is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service (ISO 14040 2006). Normally the cradle to grave approach is used which includes material and energy uses and release of emissions to the environment from the stage of raw material extraction to disposal of the final product after its usage lifecycle. LCA has four main stages which are goal and scope definition, inventory analysis, impact assessment and interpretation of results (ISO 14040 2006). But we restrict our study to the operational phase only in both the scenarios chosen. The software used for LCA was openLCA which is an open-source software. Details on the scope, system boundaries, and inventory analysis of the adopted LCA approach as mentioned in the supplementary material.

2.5. Sensitivity analysis

A sensitivity analysis (SA) in LCA is necessary to assess the robustness of outcomes and identify the significant factor influencing the outcome from the model (Padey *et al.* 2013). The simplest and most common method of SA is local SA, in which the impact of incremental changes around a significant reference factor on the model output is studied (Pannier *et al.* 2018).

Accordingly, the selected parameter of energy consumption of household RO system was changed to different values to check the validity of LCA results, and three alternatives were considered. The wattage of the unit was considered 30 W in the base case (which means 2 kWh/m^3). The three alternative wattages considered for SA were 35, 40, and 45 W corresponding to 2.33, 2.67, and 3 kWh/m^3, respectively.

3. RESULTS AND DISCUSSION

3.1. Conventional water quality and heavy metal analysis

In this study, we evaluated the drinking water quality parameters and heavy metal concentrations in tap water and household RO water purifiers in two study areas in northern India. The purpose of the study was to determine the effectiveness of household RO water purifiers in improving drinking water quality and to assess whether they were necessary in these study areas. The samples were analyzed for various water quality parameters including turbidity, chlorides, alkalinity, hardness, and coliform. Heavy metal concentrations in the samples were also determined. The results were compared with both Indian and WHO standards for drinking water quality. The results showed that the tap water from both study areas met the desirable limits of both Indian and WHO standards for all the parameters except turbidity in study area 2. The mean turbidity value of tap water samples was 5.6 NTU with a maximum value of 8 NTU, whereas the standard limit is 1–5 NTU.

The household RO water purifiers were also found to satisfy the Indian and WHO standards for drinking water quality, including turbidity (3.6 NTU) (Table 1). However, the installation of household RO water purifiers further decreased the water quality parameters, which appeared ineffective and unnecessary in the selected study areas. The turbidity levels were the only factor that seemed to justify the installation of household RO water purifiers. However, it would have been more sustainable and cost-effective if turbidity is controlled at DWTPs or at the household level by conventional approaches

Table 1 | Water quality of the effluent from the household ROs and the corresponding tap water in selected study areas

		Study area 1		Study area 2			
Parameter	**Unit**	**Tap water**	**Household RO**	**Tap water**	**Household RO**	**BIS 10500 2012**	**WHO 2017**
pH		7.6 ± 0.1	7.2 ± 0.8	7.5 ± 0.1	7.6 ± 0.2	6.5–8.5	6.5–8
Turbidity	NTU	3.4 ± 0.9	3.2 ± 1.3	5.6 ± 0.1	3.6 ± 0.9	1–5	1–10
Total dissolved solids	mg/L	236.8 ± 3.3	31.9 ± 14.3	236.9 ± 6.9	34.4 ± 5.1	500–2,000	500 – 1,000
Chloride	mg/L	2.6 ± 1.1	1.4 ± 0.5	7.6 ± 0.54	7.6 ± 0.8	250–1,000	250
Total alkalinity	mg/L $CaCO_3$	92.8 ± 10.5	18.6 ± 1.9	165.6 ± 17.9	50.8 ± 11.4	200–600	20–200
Hardness	mg/L $CaCO_3$	193.2 ± 9.6	92.2 ± 17.3	197.8 ± 10.2	94 ± 19.6	200–600	60–120
Calcium	mg/L	48.2 ± 3.5	22.5 ± 2.7	47.1 ± 3.8	37.3 ± 3.3	75–200	100
Magnesium	mg/L	20.8 ± 1.6	10.7 ± 1.1	18.3 ± 1.4	9.7 ± 1.1	30–100	50
Residual-free chlorine	mg/L	0.1	0.1	0.3 ± 0.3	0.2	0.2–1	0.2–5
Sulphate as SO_4	mg/L	32.6 ± 2.9	5 ± 2.5	ND	ND	150–400	400
Nitrate as NO_3	mg/L	2 ± 1.5	0	1	0	45	10
Fluoride	mg/L	0.5 ± 0.3	ND	ND	ND	0.6–1.2	0.5–1
Dissolved oxygen	mg/L	9.5 ± 1.0	9.6 ± 1.0	9.3 ± 0.8	8.2 ± 0.6	–	–
Total coliforms	MPN/100 mL	ND	ND	ND	ND		
Heavy metals							
Iron	mg/L	ND	ND	ND	ND	0.3	0.03
Zinc	mg/L	1.427	0.123	0.295	0.013	5–15	0.01–3
Copper	mg/L	0.024	0.017	0.030	0.039	0.05–1.5	2
Cadmium	mg/L	ND	ND	ND	ND	0.003	10^{-3}
Lead	mg/L	ND	ND	ND	ND	0.01	0.01

Average values & standard deviation ($n = 20$, 10 tap water samples and 10 RO unit water samples).
ND, not detected.

such as coagulation or sand filtration. Other parameters such as chlorides, hardness, and alkalinity were within acceptable limits for both types of samples from both study areas, although RO units reduced all the values to very small values, reducing them to around half or less for all three parameters. Moreover, coliform bacteria were not detected in the samples from taps and household RO, indicating that the tap water in these study areas was appropriate for drinking in terms of bacterial contamination. These results highlighted that household RO water purifiers were not for improving drinking water quality in the study areas as the tap water was already meeting the desirable limits of drinking water quality parameters except for turbidity in one study area that could have been controlled by other low-cost treatment approaches such as coagulation or sand filtration.

The samples were analyzed for the presence of heavy metals in tap water and household ROs. Iron, lead, and cadmium were not detected in any of the tap water or RO samples. However, zinc and copper were found in both tap water and RO samples, but they were within permissible limits (Table 1). Household RO units increased the copper concentration in the effluents, which may be due to the re-mineralization provision in them. The concern is the tradeoff between safe drinking water from taps and using household ROs, which not only increases the cost of drinking water but also reduces the necessary minerals that are essential for the human body. The magnesium levels in tap water were 20 mg/L, which decreased by 50% in household RO water. The recommended dietary allowance of magnesium for an adult of 19–51 years of age is 400–420 mg daily for men and 310–320 mg for women (NIH 2022). A 2-L daily intake of tap water can fulfill 10–13% of the magnesium requirement, while using RO water can only fulfill 5% of the daily magnesium requirement. This issue is more significant, especially if the traditional diet is not adequate in providing the required magnesium. The lack of magnesium is associated with an increased risk of heart disease. A related incident occurred in Israel where the government-initiated methods to re-mineralize desalinated water before supplying it to the public (Shlezinger *et al.* 2018). However, in this study, the public using household ROs is supplied with adequately mineralized water. But they consume RO-purified water, which decreases their nutrient intake and may cause concern. Similar findings were observed for fluoride in this study, which is an essential nutrient for dental health, especially in communities that are not using fluoride-rich toothpaste. The concentration of fluoride in tap water was observed to be 0.5 mg/L, whereas it was not detected in the household RO effluents. A 2-L consumption of such tap water will satisfy 50% of the recommended 2.6 mg/day of fluoride requirement for an adult (NIH 2022), whereas RO purified water reduced that to 0%. These findings suggest further research into investigating the factors that led to the adoption of household ROs for drinking water and solving them so that the public can rely on safe drinking water from their taps. Furthermore, the efficiency of 75% for the RO units leads to extra pressure on the distribution system, as more water is needed as input to the units. The reject water is highly concentrated with very high total dissolved salts (TDS) levels, which causes corrosion to pipes. Discharging this water into water bodies leads to increased rates of eutrophication and, for soils, higher salinity.

3.2. Economic assessment

The present study conducted a comparative economic assessment of two scenarios, namely tap water (scenario 1) and household RO effluents (scenario 2), using the benchmark value of TWC/m^3. The TWC/m^3 values were obtained from the water tariff data provided by the Jammu and Kashmir Water Resources Regulatory Authority (JKSWRRA) and assuming a household water consumption of 700 lpd according to the standards of JKSWRRA (JKSWRRA 2021). For the water cost of RO units, the TWC/m^3 was calculated for individual units based on a normal usage time of 4 h/day. The results showed that the average TWC/m^3 of household RO units was Rs 200, which was about nine times higher than the prices of tap water in the study area (Rs 22.3 1/m^3). This higher cost is mainly due to the higher capital and operational expenses associated with the household RO units. The study also compared the water costs obtained in this study with those in other countries where tap water is considered safe for drinking, such as Australia, Switzerland, and South Africa. Although there is a significant difference in the drinking water prices prevailing in India and in these countries. However, the usage of household RO units increased the total water costs to the equivalent tariffs prevailing in these countries (Figure 1(b); Table S1, supplementary material). The results suggest that the usage of household ROs costs consumers in India in the equivalent price range of Australia and Switzerland, where living standards are higher than in India. Therefore, it can be argued that consumers may be willing to pay extra tariffs if they can get safe drinking water from their taps.

It is worth noting that the findings of this study are consistent with previous studies that have reported high water costs associated with household RO units (Linares *et al.* 2016). However, it is important to consider that the usage of household ROs not only increases the water cost but also reduces the necessary minerals that are important for the human body, such as

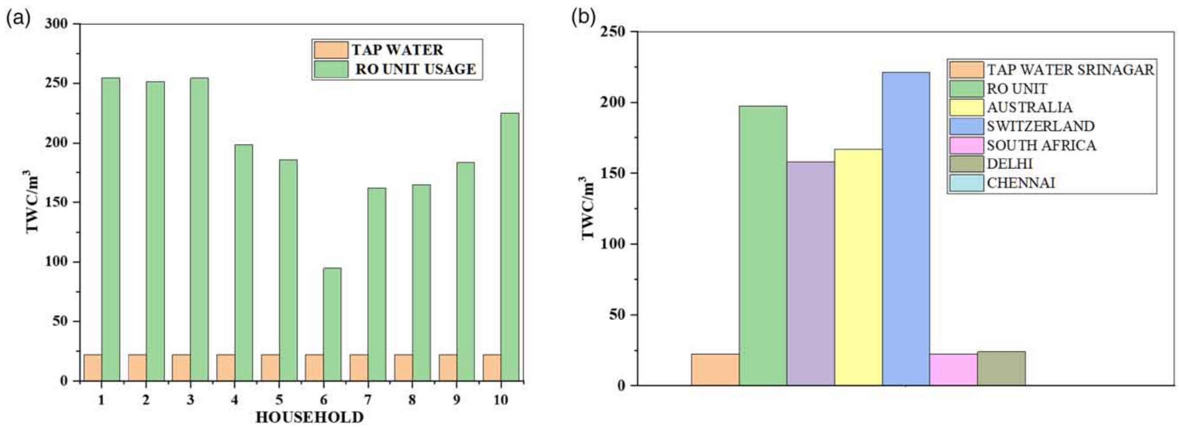

Figure 1 | (a) Total water cost per cubic meter (TWC/m^3) of the tap water and effluents from the household RO units. The TWC for the household RO was calculated for a daily operational time of 4 h and over a life span of 7 years. (b) Comparison of water costs obtained for household ROs and tap water of developed countries.

magnesium and fluoride, as discussed in the previous section pertaining to water quality. Therefore, there is a need to balance the trade-offs between safe drinking water and the net cost of water, as well as the nutrient intake of consumers. Future research should also investigate the factors that led to the adoption of household ROs for drinking water and explore potential solutions to encourage reliance on safe drinking water from taps.

3.3. Life cycle analysis

The previous sections discussed the comparative economic assessment of using conventional tap water and household RO effluents. However, it is also important to consider the environmental impacts associated with both options. Figure 2 shows the results of an environmental impact assessment carried out using the LCA approach, which revealed that conventional tap water has a lower environmental impact than household ROs. The associated impacts of abiotic depletion, acidification of water bodies, eutrophication, global warming, and ozone depletion were 3% higher in household ROs than in conventional tap water.

Abiotic depletion refers to the reduction of non-living resources and was found to be double in the case of household ROs when compared to tap water. This abiotic depletion is primarily due to the manufacturing of RO membranes, which involves the use of non-renewable resources. Similarly, eutrophication, a consequence of the excess concentration of nutrients in water bodies, was double for household RO than tap water, primarily due to the brine production from ROs. The global warming potential, which indicates the impact of greenhouse gas (GHG) emissions such as carbon dioxide on the global climate, was also doubled in the case of household ROs than tap water, mainly due to the consumption of more energy in RO than tap water.

The environmental impact of household RO units versus conventional tap water has been a topic of interest in recent years. Several studies have investigated the environmental impact associated with the use of RO units for household water purification. The findings of this study were consistent with those of Garfí *et al.* (2016), who reported that household ROs have a higher environmental impact than conventional tap water due to the material used for manufacturing RO membranes and the energy-intensive process of RO. This highlights the importance of reducing energy consumption in RO to make it a more environmentally friendly option. Several other studies have also reported similar findings, including a study by Bonton *et al.* (2012), which concluded that RO is an energy-intensive process, and reducing energy consumption is a major concern for reducing the environmental impact of the RO purifier. Another study by Akgul *et al.* (2008) reported that the use of household RO units results in higher environmental impacts compared to conventional tap water due to energy consumption, material usage, and waste production. Similarly, a study by Son *et al.* (2021) reported that the use of RO units for household water purification resulted in higher environmental impacts compared to conventional tap water due to the high energy consumption associated with RO processes. Despite the higher environmental impact associated with household ROs, the usage of these units has increased in recent years due to the perceived benefits of drinking safe and purified water. The findings of this study indicate that consumers might be willing to pay extra tariffs provided they get safe drinking water in their taps.

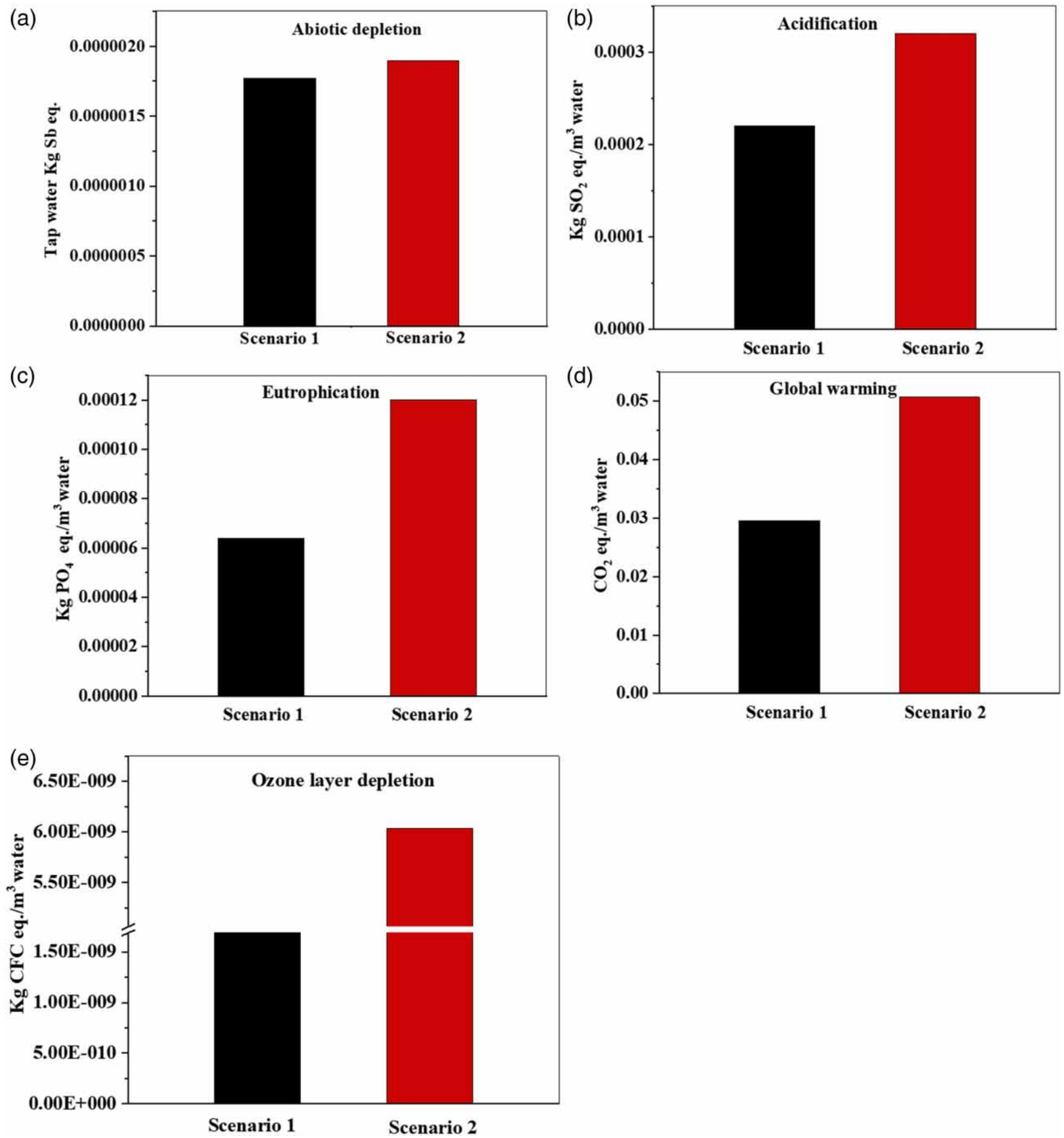

Figure 2 | Possible environmental effects calculated from LCA of tap water and household ROs. Values are calculated according to the production of a functional unit of 1 m^3 of drinking water, scenario 1 is tap water supplied from a drinking water treatment plant (DWTP), and scenario 2 is water from RO purifier at a domestic house hold using tap water from DWTP as an inlet.

Therefore, it is essential to consider both the economic and environmental impacts associated with the usage of household ROs while making policy decisions related to the supply of safe drinking water.

3.4. Sensitivity analysis

SA is a crucial aspect of any LCA to determine the robustness of the results and their dependence on the assumed factors. In this study, the SA was conducted by increasing the energy consumption in scenario 2, i.e., household ROs, from the base case of 2–2.33 kWh/m^3, 2.67 kWh/m^3, and 3 kWh/m^3. The findings revealed that there was a significant increase in the LCA outcomes with an increase in energy input (Table 2). The results suggest that increasing energy consumption has a considerable impact on various LCA outcomes, such as a 513% increase in abiotic depletion, 109.3% increase in acidification, 125% increase in eutrophication, 69.8% increase in global warming, 64% increase in ozone layer depletion, and a 96.6% increase

Table 2 | Results of SA to investigate the outcomes of LCA in scenario 2

Energy consumption (kWh m^{-3} water)	Abiotic depletion ($\times 10^{-5}$) (kg Sb eq.)	Acidification ($\times 10^{-4}$) (kg SO_2 eq.)	Eutrophication ($\times 10^{-4}$) (kg PO_4 eq.)	Global warming ($\times 10^{-2}$) (kg CO_2 eq.)	Ozone layer depletion ($\times 10^{-9}$) (kg CFC eq.)	Photochemical oxidation ($\times 10^{-5}$) (kg C_2H_4 eq.)
2 (base case)	18.90	3.2	1.2	5.1	6.04	1.59
2.33	95.40	5.8	2.3	7.5	8.25	2.71
2.67	1.06	6.2	2.5	8.1	9.07	2.92
3	1.16	6.7	2.7	8.6	9.90	3.14

in photochemical oxidation. These results indicate that the factors assumed in the LCA of household ROs and conventional tap water have a significant impact on the study's outcome.

Additionally, the SA also revealed that shifting to higher capacity RO filters at the domestic level significantly increases the environmental indicators selected, thereby putting an extra burden on the environment compared to scenario 1. Previous studies have also reported similar findings that increasing energy consumption in RO systems has a considerable impact on the environment (Zhou *et al.* 2011; Bonton *et al.* 2012). The results demonstrate that increasing energy consumption in household ROs has a considerable impact on the environment. Therefore, there is a need to explore alternative water treatment methods that are energy-efficient and have a low environmental impact.

4. CONCLUSIONS

This study evaluated the water quality parameters and heavy metal concentrations in tap water and household RO water purifiers in two study areas in northern India. The results indicated that the tap water from both study areas met the desirable limits of both Indian and WHO standards for all the parameters except turbidity in one study area. The household RO water purifiers were also found to satisfy the Indian and WHO standards for drinking water quality, including turbidity. However, the installation of household RO water purifiers further decreased the water quality parameters, which appeared ineffective and unnecessary in the selected study areas. Heavy metals like iron, lead, and cadmium were not detected in any of the tap water or RO samples, and zinc and copper were found in both tap water and RO samples but were within permissible limits. The study also compared the economic assessment of two scenarios, namely tap water and household RO effluents, using the benchmark value of TWC/m^3. The results showed that the average TWC/m^3 of household RO units was about nine times higher than the prices of tap water in the study area. In addition, this study also conducted an LCA to compare the environmental impacts of tap water and household RO water purifiers. The results showed that household RO units had a higher environmental impact than tap water, mainly due to the energy consumption during the production and use of RO units.

The findings of this study may have important implications for policymakers and consumers who are considering household ROs as an option for drinking water. The study suggests that conventional tap water is a more sustainable option, and policymakers should focus on improving the quality of conventional tap water rather than promoting household ROs. Consumers can also make more sustainable choices by using tap water and reducing their reliance on household ROs. The findings suggest further research into investigating the factors that led to the adoption of household ROs for drinking water and solving them so that the public can rely on safe drinking water from their taps.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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