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Evaluating household reverse osmosis systems for microbial safety: A case study from Chennai, India

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BACKGROUND: A combined approach for studying water quality, attitudes, and practices is presented, focusing on urban low- and middle-income households in Chennai, India using reverse osmosis (RO) systems. Challenging the common assumption that in-home water treatment particularly RO fully resolves drinking water safety issues, this article presents one of the first empirical evaluations of the effectiveness of household-level filtration methods.
OBJECTIVES: The study aims to assess the microbial safety of drinking water before and after household RO treatment and to understand how education and awareness influence household water and maintenance practices.
METHODS: The study involved surveys, water sampling, and data analysis, conducted by a multi-disciplinary team from Tel Aviv University, IIT Madras, and local partners. Water samples were collected before and after RO treatment from 216 households (262 samples total), and socio-demographic information, including education levels and water-use behavior, was analyzed.
RESULTS: The findings revealed that while RO systems reduce contamination, 31% of post-RO samples still contained *E. coli*, compared to 71% in untreated water. Furthermore, education levels were found to influence outcomes: 36% of post-RO samples from postgraduate respondents contained *E. coli*, versus 83% among those with lower education levels.

IMPACT STATEMENTS:

- Empirical evaluation of RO system effectiveness in urban Chennai households.
- 31% of post-RO household samples remained contaminated with *E. coli*.
- RO systems reduce contamination but offer limited protection without maintenance.
- Integrated survey and water testing reveal gaps in treatment efficacy perception.
- Post-RO contamination linked to respondent education level and user practices.

Keywords: Drinking water quality; *E. coli*; Household Monitoring; Reverse Osmosis; Survey

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INTRODUCTION

According to the World Health Organization (WHO), in 2022, an estimated 1.7 billion people globally used a drinking water source contaminated with feces. Furthermore, approximately 1 in 5 children lack access to sufficient water to meet their needs [1]. Unsafe drinking water remains a major contributor to diarrheal disease burden, particularly among young children and vulnerable populations. [2]. Per WHO guidelines, water for human consumption must be free from microbiological agents that cause diseases [3]. Effective and consistent household water treatment can successfully ensure water safety. Studies indicate that such treatment is not only effective in inactivating or removing pathogens but also in providing safe water for those without constant access to safe piped water [4]. In low- and middle-income countries, the supply is often intermittent or insufficient, even for those with access to clean water. Hence, storage tanks are essential for short or long-term water supply. The quality of water in these tanks is influenced by factors such as hygiene practices, storage location, the number of people using them, and whether tanks are sealed or covered [1]. However, the handling and storage of water in containers pose a significant challenge, as they increase the risk of in-house microbial contamination [5].

Urban household water treatment methods typically include filtration, reverse osmosis (RO), activated carbon (AC), ultraviolet (UV) disinfection, boiling, and chlorination, as well as combinations of these methods, each addressing specific water quality

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needs. RO systems effectively remove ions and metals, such as nitrate, chloride, magnesium, and arsenic, often in conjunction with post-treatment AC filtration [6]. The inadequacy of tap or drinking water in meeting water quality standards, combined with its irregular supply, contributes to a perceived health risk and a lack of confidence among consumers. This drives the adoption of alternative water sources, such as bottled water and home-based RO systems. The effectiveness of RO treatment, however, and the potential for microbial regrowth and recontamination post-treatment depend on maintenance practices. These include timely replacement of membranes, pre-filters, cartridges, and AC post-filters, which vary based on water usage, quality, membrane rejection percentages, AC removal efficiency, and contaminant levels [7]. Interestingly, RO water purifiers have been shown to achieve a 100% *E. coli* removal rate even after surpassing their rated service life [8]. However, detecting damaged RO membranes can be challenging, and home RO systems are not typically regulated by federal, state, or local laws [9].

Microorganisms in inadequately treated water or on surfaces can proliferate and form biofilms. Biofouling in RO systems is a significant challenge that arises due to the accumulation of microorganisms and their by-products, such as extracellular polymeric substances (EPS), on the membrane surface. This biofilm formation impairs system performance by reducing membrane permeability, increasing energy consumption, and shortening the membrane's lifespan. Furthermore, biofilms can host pathogenic organisms, leading to potential health risks. Figure S1 of the Supporting Information illustrates the failure points in all RO system unit operations, including membrane biofouling, insufficient pre- and post-treatment, and inadequate cleaning and maintenance processes (including system tap). All of these factors can contribute to biofilm development and/or water contamination. Controlling biofouling involves strategies such as membrane surface modifications, physical cleaning methods, chemical treatments, and maintaining proper pretreatment to reduce microbial adhesion and growth [10].

Moreover, fecal-oral pathogens are also transmitted via contaminated food, hands, and utensils, particularly under poor hygiene conditions [4]. These issues highlight the need to extend drinking water quality control beyond the point of distribution to the point of consumption [11]. Research indicates that improved water sources, better hygiene practices such as hand washing and sanitation, and household-level water treatment significantly reduce diarrheal diseases in developing countries [12]. Field studies have identified certain practices and characteristics of containers that could contribute to household water contamination or the spread of diseases. These practices include the use of wide-mouth containers for water collection and storage [12], transferring water between containers [13], and dipping handheld utensils into water instead of using a tap or pouring method [11].

To gather insights on both subjective water aspects (user behavior, practices, and perceptions) and objective data (quantitative water quality data), an integrated methodology combining household surveys with water quality analysis was developed [14]. However, there remains a clear gap in understanding the effectiveness of typical household water treatment systems in urban settings, particularly regarding behaviors, perceptions, maintenance, and the quality of water at the point of consumption.

This research aims to develop a method for assessing and monitoring drinking water in urban cities, through a multi-dimensional approach. The methodology includes (1) a comprehensive survey to understand water-related habits and perceptions, accessible via cellular phones both online and offline, capturing both behavioral and physical water quality parameters; (2) on-site water sampling and measurements of various water quality parameters, along with collecting samples for further laboratory analysis, and (3) compiling all the data collected into a unified platform for thorough analysis. The goal is to provide insights into the current state of drinking water quality, particularly in low-middle-income households using RO systems, by assessing water quality both before and after RO treatment, and to propose methods for improving water safety through better education, maintenance, and community engagement.

Although the present study reports findings from a single round of household sampling (Round 1), later phases (August–October 2024) of the People's Water Data (PWD) initiative introduced additional survey components that were not included in the original data-collection tool. In a subsequent round (Round 2, conducted with a separate cohort), new variables related to RO system maintenance, such as filter replacement schedule, technician type, and system age, were incorporated. While these expanded components were not part of the Round 1 dataset analyzed in this manuscript, insights from Round 2 inform the interpretation and contextualization of the findings presented here.

MATERIALS AND METHODS

Design and implementation of data-collection protocol

This study's data-collection method was carefully developed through field experiments based on knowledge acquired from prior field projects involving the AmriTAU survey [14, 15]. A trial-and-error methodology was employed to ensure the survey's relevance and effectiveness, with constant adaptations to align with field conditions. The research team comprised an interdisciplinary group from Tel Aviv University (TAU), IIT Madras (IITM), Stella Maris College, Madras Christian College (MCC), and Engineering without Borders (EWB) in Chennai. The diverse team, which included students and faculty from sciences, engineering, and social sciences, ensured a holistic understanding and interpretation of both the technical and societal aspects of our findings.

Figure S2 of the Supporting Information illustrates the sequential stages of the research methodology. The process begins with a survey to gather data on water-related behavior and perceptions, followed by water sampling for on-site analysis. Some of the samples undergo laboratory analysis. The final stage involved data analysis, where the collected data is processed and evaluated to draw conclusions about the water safety and quality in the studied area.

It is important to note that the Round 1 survey tool did not include detailed questions on RO maintenance practices, such as filter replacement frequency, time since last service, type of service provider, or membrane age. These variables were introduced only at a later stage of the program (Round 2) and were collected from a separate sample. Following the completion of Round 1, a second field implementation round (Round 2) was conducted between August and October 2024 as part of the continued development of the PWD initiative. Round 2 followed the same household-visit protocol but involved a different set of neighborhoods and households ($n = 226$) and employed an expanded survey instrument designed to address knowledge gaps identified in Round 1. Round 2 incorporated detailed variables related to RO system maintenance that were not captured in the initial survey, including the timing of filter and membrane replacement, the type of technician performing the service, self-maintenance practices, and reported system age.

The research methodology included the following phases:

1) Initial assessment and protocol refinement: The research started with a participatory urban assessment involving field visits, testing water quality sensors, and carrying out a survey. Initially, the project focused on mapping and testing public drinking water sources within the IITM campus, including natural water bodies, wells, and public taps. Findings from these initial field tests were used to refine the survey and field procedures.
2) Local Engagement and Training: In the second phase, emphasis was placed on integrating and training local students. The survey was translated into the local language and adapted to ensure cultural relevance and accuracy.
3) Community Household Survey and Water Testing. During the final phase, random households in the community were visited. Each visit lasted approximately 20 min, during which the research team surveyed the household member responsible for water provision and conducted on-site water quality tests. If the responsible

Table 1. Water quality parameters tested onsite and offsite [22].

Parameter	Location	Class	Test details
ORP, mV	Onsite	Physical	Portable multiparameter probe (Thermo scientific ECPCWP45004K)
Conductivity, µs/cm	Onsite	Physical	Portable multiparameter probe (Thermo scientific ECPCWP45004K)
TDS, mg/L	Onsite	Physical	Portable multiparameter probe (Thermo scientific ECPCWP45004K)
pH	Onsite	chemical	Portable multiparameter probe (Thermo scientific ECPCWP45004K)
Temperature, ˚C	Onsite	Physical	Portable multiparameter probe (Thermo scientific ECPCWP45004K)
Turbidity, NTU	Onsite	Physical	Portable multiparameter probe (Thermo scientific ECTN100IR)
DO, mg/L	Onsite	Physical	Portable multiparameter probe (YSI ECOSENSE ODO200)
Coliform, P/A 100 mL	Offsite	biological	Aquagenx CBT-ECTC-PA
E. coli, P/A 100 mL	Offsite	biological	Aquagenx CBT-ECTC-PA
Free chlorine, mg/L as CaCO3	Onsite	chemical	Hach CAT. NO. 2755250
Total chlorine, mg/L as CaCO3	Onsite	chemical	Hach CAT. NO. 2755250
Total hardness, mg/L as CaCO3	Onsite	chemical	Hach CAT. NO. 2755250
Total alkalinity, mg/L as CaCO3	Onsite	chemical	Hach CAT. NO. 2755250
pH	Onsite	chemical	Hach CAT. NO. 2755250

ORP oxidation-reduction potential, *TDS* total dissolved solids, *DO* dissolved oxygen, *P/A* presence/absence.

member was unavailable, the neighboring household was surveyed instead. Additionally, water samples were also collected for extended laboratory analysis.

Water-quality testing

Table S1 of the Supporting Information provides an overview of the water testing parameters, methods, and standards relevant to the study, along with additional notes that provide the context and rationale for the testing protocols [16]. The water quality parameters were analyzed using sensors, kits, and test strips designed for fieldwork, enabling on-site calibration (Table 1).

The following equipment and methods were used:

1) Thermo Scientific multispectral sensor, Catalog No. ECPCWP45004K is used for measuring pH, Oxidation-Reduction Potential (ORP), Conductivity, Total Dissolved Solids (TDS), and Temperature.
2) Thermo Scientific turbidity sensor, Catalog No. ECTN100IR
3) YSI's Dissolved Oxygen (DO) sensor, Catalog No. ECOSENSE ODO200
4) Hach 5 IN 1 dip kit for testing Free chlorine, Total chlorine, Total hardness, Total alkalinity, pH
5) Aquagenx's biological testing kits for *E. coli* and total coliforms in 100 ml volume, according to catalog No. CBT-ECTC-PA-100. All parameters are measured on-site.

Hach Test Strips provide information on five chemical and physical parameters: Total chlorine (0–10 mg/L), free chlorine (0–10 mg/L), total hardness (as $CaCO_3$, 0-425 mg/L), total alkalinity (as $CaCO_3$, 0–240 mg/L), and pH (6.2–8.4). To conduct a test, the strip was immersed in the water sample for 30 s. The color on the strip was then compared to the reference block on the container to determine the results.

AquagenX *E. coli* potable water quality field test kits (Presence/Absence, P/A) were used to test the water samples for the presence of *E. coli*. For the P/A tests, 100 mL of the tested water was carefully poured into the field kit bag. After a sodium thiosulfate pill dissolved, bacterial broth powder was added and dissolved into the kit bag. The bags were sealed and incubated in an incubator per the manufacturer's protocol at 37 °C for 24 h. Post incubation, the results were observed in ambient light, with yellow/yellow-brown indicating a negative result (absence) and blue/blue-green indicating a positive result (presence).

Household RO system characteristics (Round 1 vs. Round 2)

In Round 1, household RO systems were documented only at a general categorical level. Enumerators recorded whether households used RO, RO&UV, or other point-of-use treatment methods, and photographs were taken when possible. However, no systematic information was collected on system configuration, including the number and type of filtration stages, the presence of sediment or carbon pre-filters, post-carbon polishing units, or UV disinfection modules. Likewise, key operational characteristics, including system age, service history, membrane condition, and filter replacement schedules, were not captured in the Round 1 dataset.

In contrast, Round 2 (August-October 2024), conducted with a separate cohort, introduced a detailed technical profiling of household RO units. Most systems were documented as multi-stage RO purifiers comprising sediment filters, granular or block carbon cartridges, thin-film composite RO membranes, and post-treatment carbon or alkaline filters. Additionally, 43% of households reported integrated UV disinfection modules. System age was recorded (28% <2 years, 41% aged 3–5 years, and 31% >5 years), along with maintenance indicators such as recency of filter replacement, membrane servicing intervals, technician type (manufacturer-certified, independent local technician, or self-maintenance), and visible system integrity (e.g., worn tubing, leaking joints, and accumulation of biofilm near dispensing taps). These variables were introduced after methodological insights derived from Round 1 and, therefore, were not available for quantitative analysis in the present study.

Detailed survey description

Survey overview and objectives, demographics and socioeconomic status. Designed for the urban environment of Chennai, this survey aimed to explore household behaviors and perceptions related to drinking water quality. The survey gathered essential information on the demographics and socioeconomic status of the primary respondent, who was typically the household member responsible for managing drinking water. Collected data included age, gender, family role, presence of children under 5 years old, and education level. The study area map is presented in Fig. S3 of the Supporting Information.

Water quality monitoring and survey tool. The survey incorporated monitoring of the water's chemical, physical, and biological characteristics, assigning a unique submission number to each household. A custom survey was developed using KoboToolBox (https://www.kobotoolbox.org), enabling deployment via a mobile app both in online and offline modes facilitating data consolidation for analysis. The tool captured responses, demographic details, GPS coordinates, and images. An overview of the survey tool is provided in Fig. S4 of the Supporting Information, and the full survey is available in Fig. S5 of the Supporting Information.

Water source identification. In this module, respondents were asked to identify the primary source of drinking water consumed in their household. The options included bore/groundwater, municipal distribution (referred to as 'Metro'), canned water, water from tanker trucks (referred to as 'lorry'), open wells, and rivers/lakes. This identified source was presumed to be the most frequently used. Additionally, they are also asked to specify where they typically take the water for drinking, with choices such as tap (pipeline), container, canned water, RO system, or packaged water. Based on the selected source, the survey included follow-up questions regarding methods and duration of water storage. In households using RO systems, separate samples were collected from both the untreated source ("without HH treatment") and the treated drinking water ("with HH treatment"), enabling a direct evaluation of the treatment system's effectiveness in reducing microbial contamination.

Water treatment methods. This module of the survey investigated whether and how respondents treat water from their primary household source. Treatment methods included the use of RO systems, water filters, boiling, straining, clay pot filters, or bleaching/chlorinating. Respondents who indicated that they treated the water were asked follow-up specific questions about the methods used, such as boiling duration, settling time, the type of vessel used, and any substances added to the water.

Observation of water handling practices. Survey enumerators observed and recorded how respondents pour water for drinking, aiming to understand the practical handling of water in households. This data is crucial, as post-treatment handling practices can significantly influence water quality at the point of consumption. Enumerators noted how water was poured for drinking, with options such as directly from the container, can, or vessel, from the tap, or using a cup or jug. Additionally, enumerators recorded whether the respondent's hand touched the water during the pouring process, as such practices can introduce contamination post-treatment. Special attention was given to households using RO systems, and the influence on water quality at the point of consumption. This module also included capturing images of the treatment systems used. Additionally, respondents were asked to allow enumerators to collect water samples from both the untreated source ("without HH treatment") and the treated drinking water ("with HH treatment" for households that treat their water), particularly focusing on households that use RO systems. These samples were analyzed for the indicators listed in Table 1, including *E. coli*, to assess the effectiveness of the treatment methods and the impact of user practices on water safety.

Subjective water quality assessment. This part of the survey is designed to collect respondents' subjective assessments of their water quality. Respondents were asked to describe the water's color, with options ranging from clear to white, rusty, or grey. For taste, respondents provided feedback using terms such as chlorine, earthy, salty-sour, iron, sweet, or any other taste they associate with their water. Additionally, they describe the water's odor, using descriptors such as dirt, iron, chlorine, plastic, oil, or any other scent they perceive in the water.

Perceptions of water safety and health concerns. In this section, the respondents were asked about their perception regarding the safety of the drinking water they consumed on the day of the survey. They were asked about their current feelings regarding water safety and whether they or any other household members had recently experienced illnesses potentially linked to water quality such as diarrhea, muscle pain, sore throat, etc. Such questions are crucial for gaining insights into the perceived health impacts related to the water source, contributing significantly to a broader understanding of public health concerns related to water quality. However, it is important to note that responses to these questions are subjective and may be influenced by individual perceptions and experiences.

Water sampling and analysis. This survey involved collecting water samples from two key points: the household's primary source and its drinking water. Enumerators requested respondents to provide a glass of their drinking water as they would consume it on the day of the survey (Where did you get your drinking water from today?). Respondents were also asked about their perceptions of their drinking water's safety ("How do you feel about the safety of your drinking water today?"). The analysis differentiated between two types of water quality observations: 'with' and 'without' household (HH) treatment. 'Without HH treatment' refers to the water samples taken directly from the household's primary source (as bore or well water, municipal, etc.). In contrast, 'with HH treatment' refers to water that has undergone any household treatment process (such as RO systems, boiling, etc.). In some cases, water samples are collected both pre- and post-treatment to assess the effectiveness of HH methods in removing contaminants, such as *E. coli*. The survey records the number of tests conducted for physical, chemical, and biological measurements, as detailed in Table 1.

For households using RO systems, water samples were collected from two defined points: pre-RO, representing source water before household treatment, and post-RO, representing drinking water collected after passage through the household RO system at the point of consumption. These terms are used consistently throughout the manuscript to describe untreated and RO-treated water, respectively.

RESULTS AND DISCUSSION

This section presents a summary of data collected from 262 households in Chennai, India, through water quality fieldwork, revealing key insights into water quality and public perceptions (detailed in supporting information Text S1).

Sources of drinking water

This section aims to identify the primary source of water currently used in households. The options include (1) piped supply (directly to the household); (2) collection from public sources; (3) household-owned sources (e.g., private wells or rainwater harvesting structures); (4) water tankers (5) commercial sources (either self-collected or delivered in bottles or cans); (6) in household treatments (such as RO systems). The primary source is presumed to be the one most frequently used for drinking water.

Additionally, respondents are asked about any secondary water sources they might use, their awareness of treated drinking water available from public sources in the community, their perceptions of its quality, and its use (whether for domestic purposes or as drinking water). Depending on the primary water source indicated, specific follow-up questions explore collection/delivery methods, and source reliability or scarcity.

The flow map (Sankey diagram) in Fig. 1 summarizes the distribution of water sources used by households in our sample. Among the surveyed households ($n = 242$); 59 accessed tap water piped from a centralized water-treatment plant; 38 collected water in containers from various sources such as groundwater, piping, or tankers; 76 households received canned drinking water, packaged in bottles or cans, delivered to their homes; and 69 sourced their water from household RO treatment systems. Additionally, Fig. 1 illustrates how each category of users is divided into those who treat their source water at the household level and those who do not, as well as how the water was handled for drinking, which is critical for understanding potential contamination risks.

In Chennai, a comprehensive survey was conducted to evaluate drinking water conditions, involving multiple sites and participants from various institutes. The survey covered 262 water samples from 216 households. The decision to survey both treated and source water was key to assessing the effectiveness of household water treatment systems, particularly RO systems, in removing contaminants such as *E. coli*. This approach enabled the identification of potential differences in water quality between the source and the treated water, emphasizing the need for regular maintenance and proper handling practices. Mapping the surveyed locations is crucial for spatial analysis and understanding the distribution of water quality issues. Additionally, it helped identify areas that may require targeted interventions or further investigation, highlighting the value of conducting the survey in 23 different locations across Chennai.

This diverse geographic coverage provides a broader perspective of the variability of drinking water conditions across the city. Ensuring consistency in survey methods and data collection is essential for reliable results. More than 60 students, acting as surveyors, from four different institutes participated, following a standardized method to guarantee the comparability of the data collected. This approach not only increased the manpower for the survey but also provided valuable learning experiences for the students participating in the process. Including local students from communities in interpreting results and developing potential solutions is especially beneficial, as community involvement is key

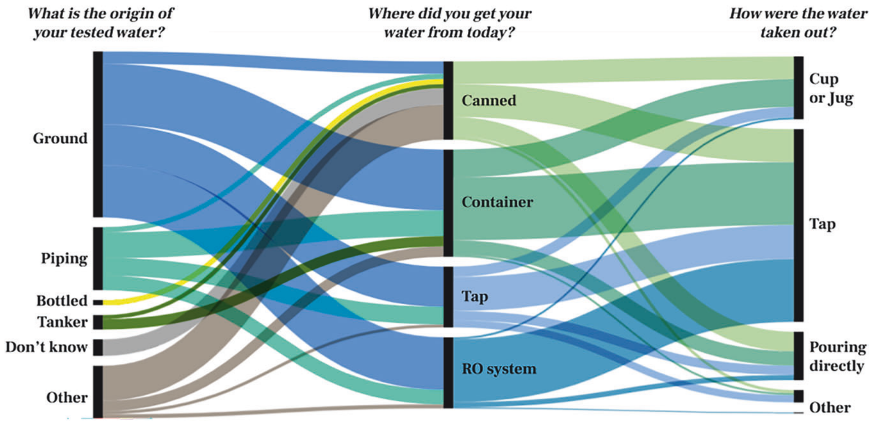

Fig. 1 Distribution of Household Drinking Water Sources, Collection Methods, and Point-of-Use Practices ($n = 242$). The figure shows the origin of the tested water, the point from which drinking water was collected, household treatment use, and point-of-use handling practices.

for the long-term future success and sustainability of water quality initiatives. Considering demographic factors such as gender, education, households with children under 5 years old, age groups, and access to drinking water is crucial for a comprehensive understanding of the population's characteristics and needs.

Demographic data

Figure 2 illustrates the demographic data of survey respondents. The data shows that the survey included participants from a range of educational levels, with 'educated groups' defined as those holding a master's degree or higher. According to the data, 49% of respondents have an academic education which suggests that this parameter may be considered a non-influencing factor. The majority of survey respondents were women, accounting for 69%. This may be due to the timing of the survey, conducted during the daytime hours when the men might be at work, or it could reflect the role of women as primary caretakers of the household, including responsibility for water management.

Understanding the demographics of households, especially regarding the presence of young children, is crucial when assessing access to clean drinking water. The fact that 31% of the respondents reported having children under the age of 5 years is significant. Access to clean and safe drinking water is essential for their health and well-being, as young children are more susceptible to the adverse effects of poor water quality [2]. In a study by Park et al. (2018), an *E. coli* waterborne outbreak at a school camp affected 188 individuals (30.9%) from three schools resulting in acute gastrointestinal symptoms. The outbreak was linked to improperly treated drinking water, as supported by epidemiological findings and an epidemic curve consistent with a continuous-source outbreak [17].

When analyzing survey results, it is essential to consider how responses might vary across age groups. The survey sample reflects the population's age distribution, with 75 respondents aged 18–25 years, 56 aged 26–35 years, 51 aged 36–45 years, 23 aged 46–60 years, and 43 respondents aged over 60 years old. The broad age distribution of the survey captures the perspectives and experiences of individuals across different age groups. This representativeness allows for more accurate assessments of the population's views and circumstances regarding water treatment practices and water quality perceptions. Interestingly, most respondents believe they have sufficient drinking water in their households. This perception is significant as it reflects not only the actual availability of water but also the respondents' satisfaction with their current water supply situation. However, despite this belief, it is crucial to cross-reference subjective perceptions with objective data on water quality particularly concerning contamination risks like *E. coli* to verify the safety of the water post-treatment through RO systems and ensure that these perceptions align with actual water safety.

A correlation was observed between education level and the presence of *E. coli* in drinking water (Fig. 2a). For respondents with postgraduate degrees, 36% reported an incidence of *E. coli* contamination in their drinking water while for non-educated respondents, this value increased to 83%. This highlights the critical role of user knowledge, practices, and proper water handling in preventing contamination, particularly in households using RO systems.

Such correlations can provide valuable insights into the potential factors influencing water quality. Education can significantly influence behavioral practices related to water use and sanitation. For example, as observed in our case, a study conducted in rural China by Wang et al. (2018) found that respondents with higher education levels demonstrated greater awareness of water quality and pollution incidents compared to those with lower education levels [18]. Education often provides individuals with better access to information. People with higher education levels may be more informed about the importance of safe water handling, potential sources of water contamination, ways to purify water and may follow better hygiene practices, which can enhance the effectiveness of household water treatment systems such as RO systems and consequently reduce the risk of contamination post-treatment. Additionally, Deng et al. (2021) suggested that the five key elements for the design of sustainable HH treatment include treatment capability, environmental friendliness, user experience, economic viability, and social acceptance [19].

Education is often linked to socioeconomic status (Fig. 2b). Higher socioeconomic status may provide individuals with the means to access improved water sources, invest in water treatment technologies such as RO systems, and live-in environments with better water infrastructure. The significant difference in RO treatment usage rates between those with no education to high school (less than 1%) and those educated above undergraduate (29%) highlights disparities in water treatment and awareness of maintenance practices, which are not uniformly adopted across different educational backgrounds, potentially impacting water safety.

Social behavioral aspect of water quality perception

To understand the social and behavioral aspects of water quality perception, the question "How do you feel about the safety of your drinking water today?" was posed. Figure S6a of the Supporting Information shows a five-category Likert scale ranging from 'Very bad' to 'Very good'. The findings indicate that most participants perceive the water quality as good to very good, with many considering it at least satisfactory. Similarly, in a study by Wang et al. (2018), dissatisfaction was mainly attributed to sensory properties

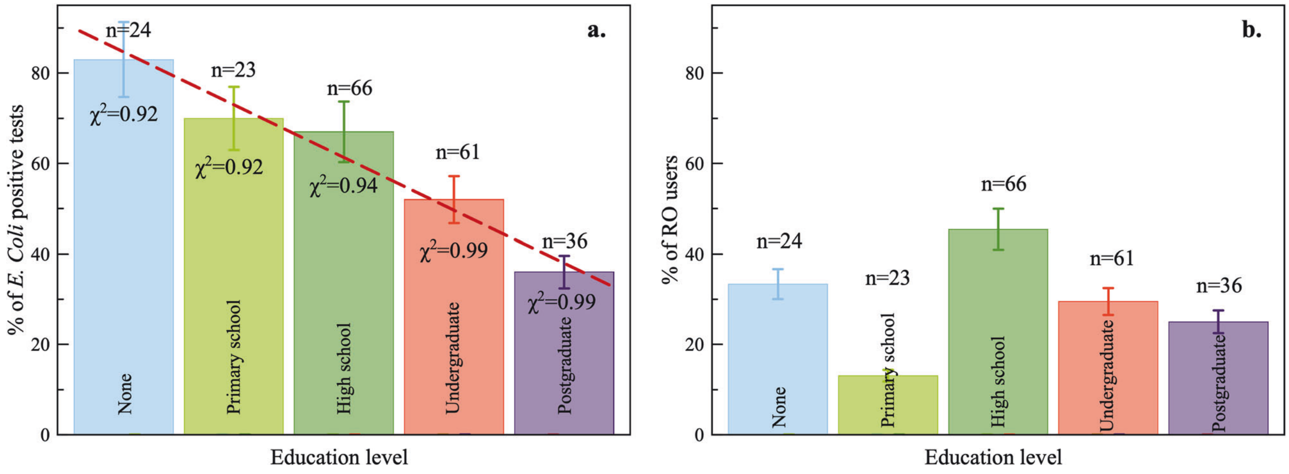

Fig. 2 Education level of respondents in relation to *E. coli* presence and RO treatment use ($n = 246$). a Education level of respondents according to the presence of *E. coli*. **b** Education correlated with using RO treatment, with the darker shade indicating RO treatment use.

such as turbidity, rust color, or unpleasant taste and odor [18]. Notably, the perception of water as good to very good persists even in the presence of *E. coli* contamination, which is a significant and intriguing observation. This situation highlights a potential gap between public perception and the actual biological safety of the water. Similarly, Ajith et al. (2023) observed no correlation between the presence of *E. coli* in drinking water and respondents' subjective evaluations of water quality after HH treatment. Instances of unsafe water due to *E. coli* contamination were not reflected in respondents' perceptions, highlighting the critical need for regular water testing [15]. It underscores the need for education and community engagement to raise awareness about microbial contamination risks, such as *E. coli*. This may reflect a lack of awareness or accurate information among the public regarding the presence of *E. coli* in water and the associated health risks.

As previously shown, public perception of water quality is often influenced by aesthetic factors, such as clarity, taste, and odor, which may not necessarily align with the presence of microbial contaminants. Figure S6b of the Supporting Information shows a comparison of respondents' satisfaction with their drinking water based on whether they treat the water at home or not. The majority of both groups are satisfied with their water quality, but satisfaction is marginally higher in households that treat their water. This suggests that while household treatment may improve water satisfaction, many respondents find their water satisfactory even without additional treatment. Similarly, in a study by Ajith et al. (2023), most participants reported perceiving their water quality as satisfactory after applying their treatment methods [15]. In another study, a multinomial logistic regression model was used to examine the relationships between public satisfaction with drinking water quality and its influencing factors. The results showed that age, sex, and education level were not significantly related to satisfaction levels. However, the residential area significantly affects public satisfaction with drinking water quality [18]. This aspect should be further investigated in future studies.

Figure 3 illustrates the relationship between the perception of water quality based on color, taste, and odor, as well as perception of post-RO system water. When respondents were asked to assess the quality of the water with their senses, such as color, taste, or smell (odor), the majority reported that the water was clear, without taste or odor. The data indicates a strong association between the perception of clear color and the absence of odor and taste. Among 66 observations of clear color, 61 were reported without odor and 46 as tasteless. This suggests that individuals often link visual clarity with the absence of detectable odor and taste. The finding that the perception of water as clear, odorless, and tasteless aligns with an overall assessment of the water as good to very good indicates that these sensory attributes contribute significantly to individuals' positive perception of water quality.

From the 66 observations related to RO treatment systems, all were perceived as clear. This aligns with the effective filtration capabilities of RO systems, which remove dissolved components and particles from water, resulting in visibly clear water. Among these 66 observations, 61 were reported as odorless. For taste perception, 46 observations indicated no taste, while 15 noted a sweet taste. This suggests that, in a subset of cases, respondents associate a sweet taste with the water treated by RO systems. The positive perceptions of clear water, no taste, and in some cases, a sweet taste collectively contribute to an overall positive perception of water quality among those using RO treatment systems.

The KoboToolBox evaluates drinking water's color, taste, and odor as reported by respondents, linking these characteristics to water's physical properties, as shown in Fig. S7 of the Supporting Information. Interestingly, water reported as having a chlorine odor had higher ORP values, indicating chlorine presence compared to odorless water. Interestingly, Paz et al. (2024) showed that chlorine-based residual disinfectants are the main oxidants affecting ORP in distribution water, but other factors like source water quality and treatment processes also influence the final ORP value, which strengthens the use of ORP as an indication for chlorine odor [20]. An earthy taste corresponded with higher conductivity levels. Additionally, water reported as having a rusty color showed significantly higher turbidity compared to clear water. This indicates that simple observational methods can be effective in predicting water quality.

Survey-based spatial analysis highlights the interaction between communities and drinking water quality across Chennai. Figure S8 of the Supporting Information presents maps based on respondent reports of perception, taste, color, and odor. These visualizations reflect how aspects of urban design, infrastructure, and water access shape public perceptions of drinking water. While clear water appearance is commonly associated with safety, the spatial distribution of reported sensory attributes reveals localized concerns, such as unpleasant tastes or odors, which may indicate contamination or infrastructure issues. The maps support the identification of areas requiring targeted interventions and emphasize the need to complement sensory-based assessments with water quality monitoring.

Objective measures of water quality

Figure 4 displays the values of conductivity, TDS, turbidity, pH dissolved oxygen, and ORP across different treatment methods:

HH Treatment, No HH Treatment, RO Treatment, Boiling Treatment and Non-Drinking Water. The classification of treatment methods is based on household-reported water practices collected during the field survey, with the corresponding survey questions shown in Figure S5. HH Treatment refers to any household-level action applied to drinking water before consumption. No HH Treatment indicates drinking water consumed without household-level intervention and does not imply unsafe water. RO Treatment and Boiling Treatment are analyzed as distinct subcategories within HH Treatment due to their different treatment mechanisms and expected physicochemical effects. Non-Drinking Water refers to water sampled from household sources not designated for drinking and is included as an environmental reference.

The average electrical conductivity (EC) value was approximately 375 µS/cm, with a range from 117 to 742 µS/cm. The TDS concentrations varied from 56 to 350 mg/l. The average turbidity was around 0.8 NTU, with a range from 0.2 to 1.8 NTU. The RO treatment demonstrated a significant reduction in TDS, conductivity, and turbidity, suggesting that the RO system is effective in lowering these water quality parameters. Lahnsteiner et al. (2018), in a pilot-scale test, largely validated the RO results observed in laboratory-scale experiments, with over 97% conductivity removal supporting our findings [6], and consistent with the anticipated performance of RO treatment.

For pH values, the results across all treatment methods show no significant difference, as the mean pH value ranged from 6.6–7.5, with an average of 7.0 and with standard deviation of 0.64. However, the mean pH value for the RO-treated water was the lowest among the selected methods. The DO level was 6.8 mg/l for natural water and nearly zero for boiled water. This indicates that DO measurements in the context of drinking water are not as critical as they are for natural water sources, such as rivers, lakes, and streams, where DO is essential for the health of aquatic ecosystems. ORP is a measure of the tendency of a solution to either gain or lose electrons in a chemical reaction. ORP is not a primary parameter for monitoring system RO performance, with values averaging 26.30 ± 44.28 mV. The results indicate no significant difference in ORP values between the RO treatment and other methods. TDS, conductivity, and turbidity are more reliable indicators of RO system performance in ensuring safe water quality. However, these parameters do not provide information about biological contamination that may occur post-RO treatment.

Comparison between treated and non-treated water

Figure S9 of the Supporting Information presents a social and behavioral analysis of the data, uncovering interesting findings and distinguishing between households using RO systems for water treatment and those consuming drinking water without household RO treatment (pre-RO). The presence of biological contaminants, particularly *E. coli* and total coliforms, in both pre-RO drinking water (source water before household treatment) and post-RO drinking water (collected after passage through the household RO system) raises important concerns regarding the effectiveness of RO systems in the overall safety of post-RO treated water, highlighting the need for proper maintenance and handling practices. In the study by Dorota Papciak et al. (2022), researchers evaluated the impact of biofilm on installation materials on tap water quality and safety. Fractal and bacteriological analyses revealed a chaotic build-up of microorganisms during early biofilm formation, with unstable layers detaching and potentially reaching drinking water flowing through the tap. After 25 days, the biofilm fully and permanently covered the material's surface [21], highlighting the potential presence of biofilms post-RO treatment.

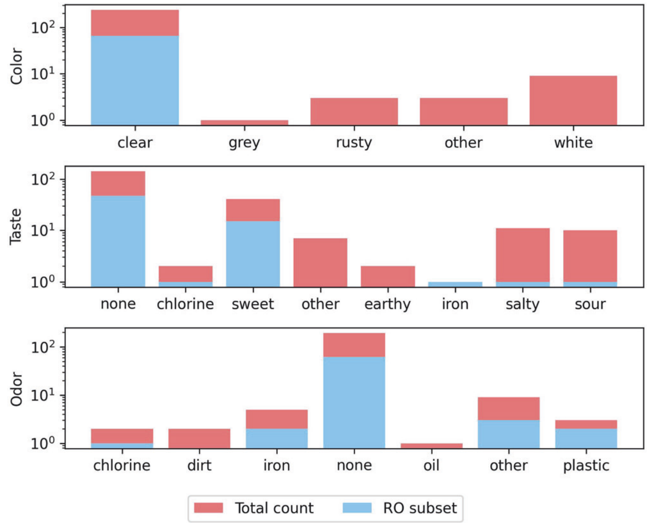

Fig. 3 Perception of water quality by color, taste, odor, and RO subset. The figure shows respondent-reported sensory perceptions of drinking water quality, including color, taste, and odor with emphasis on the RO subset.

The results show that 31% of post-RO drinking water samples contained *E. coli*, while 74% of post-RO samples contained total coliforms only. In contrast, pre-RO drinking water showed substantially higher contamination, with 71% of samples testing positive for *E. coli* and 88% for total coliforms. Although RO treatment reduced the overall prevalence of biological contamination relative to pre-RO water, the persistence of *E. coli* and coliforms in post-RO samples raises concerns regarding the adequacy of RO systems in ensuring microbial safety under real household conditions. While RO, as a properly maintained unit operation, can reduce biological contaminants, its effectiveness as a system in fully removing microbial contamination from drinking water is questionable without proper maintenance and system integrity. It is essential to assess contributing factors such as source water quality (pre-RO), regular monitoring, maintenance frequency, system design, and post-treatment handling practices. A study by Ajith, et al. (2023) indicated that the implemented treatment methods, including boiling and potentially other technologies, fail to consistently produce safe water. Contamination may result from factors such as storage duration, handling practices, and the condition of containers, which may be uncovered or improperly managed. The data does not provide clarity on whether the effectiveness of treatment practices differs or if traditional methods consistently enhance water quality [15]. A comprehensive approach to water treatment is essential to ensuring that households have access to clean and safe drinking water. Previous studies have shown that alternative household water treatment methods, including UV disinfection and chlorination, can effectively reduce microbial contamination under controlled conditions. Still, their real-world performance is similarly constrained by maintenance, user behavior, and post-treatment storage practices. UV systems, for example, are sensitive to lamp aging and power reliability, while chlorination efficacy depends on correct dosing and sufficient residual contact time. These findings align with our observations, reinforcing that no single household treatment technology guarantees microbiological safety without proper maintenance and safe handling practices.

These findings suggest that treatment effectiveness cannot be evaluated solely based on the technology itself but must consider the full pathway from pre-RO source water to post-RO point of consumption.

Upon detailed examination *of E. coli* and total coliform levels in pre-RO and post-RO drinking water, our study identified significant disparities in bacterial concentrations across various regions in Chennai (Fig. 5). For example, on the left side of the

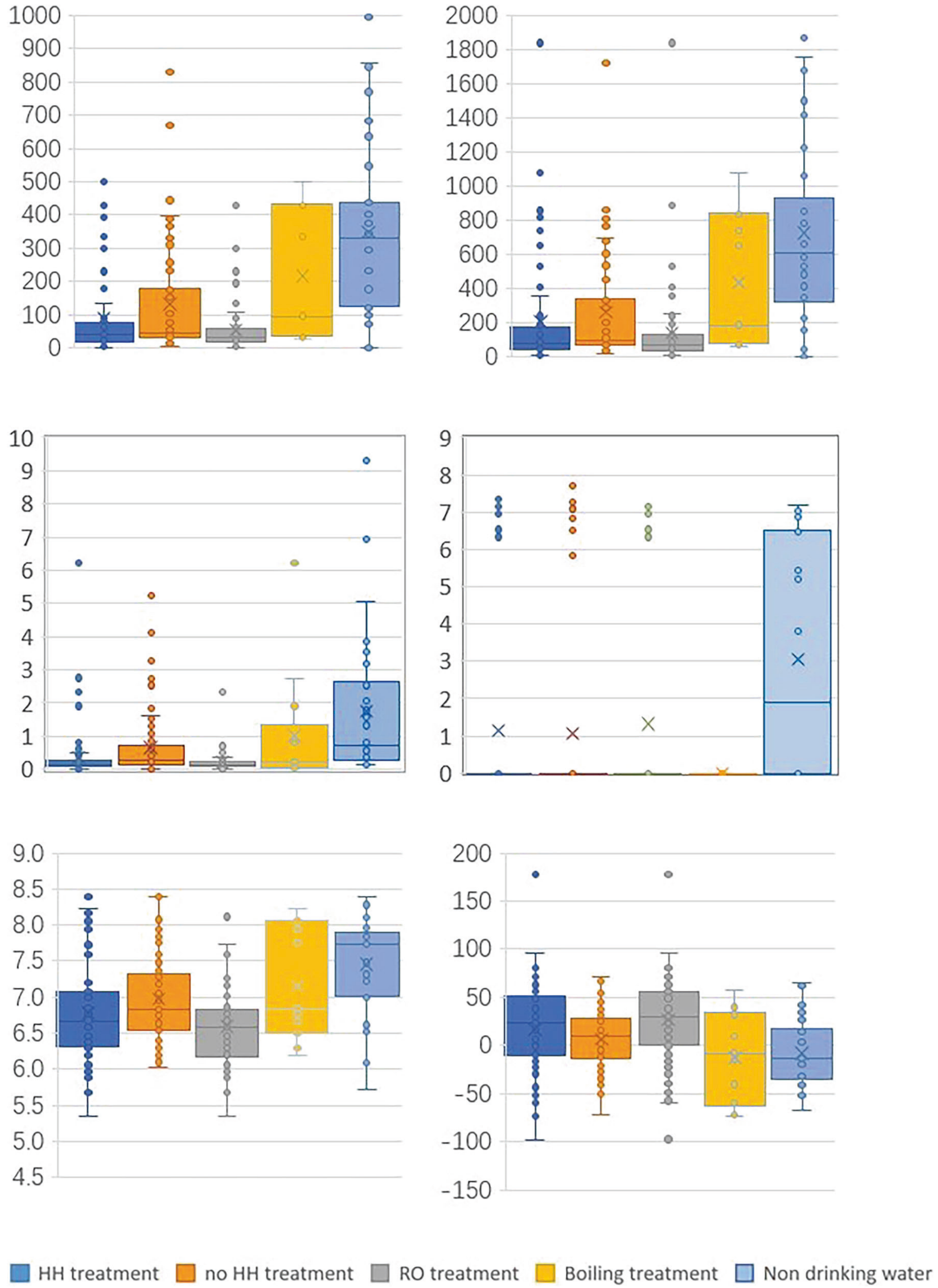

Fig. 4 Water quality parameters based on water treatment methods. The figure presents the measured water quality parameters across the different treatment categories.

upper map, contamination in both pre-RO and post-RO drinking water highlights systemic challenges in water quality management. Contamination in post-RO drinking water indicates inefficiencies in treatment processes or recontamination post-treatment, often caused by poorly maintained infrastructure, such as pipelines and storage tanks, or improper handling practices. Similarly, the presence of coliforms in treated water, as shown in the lower map, points to failures in the treatment process or post-

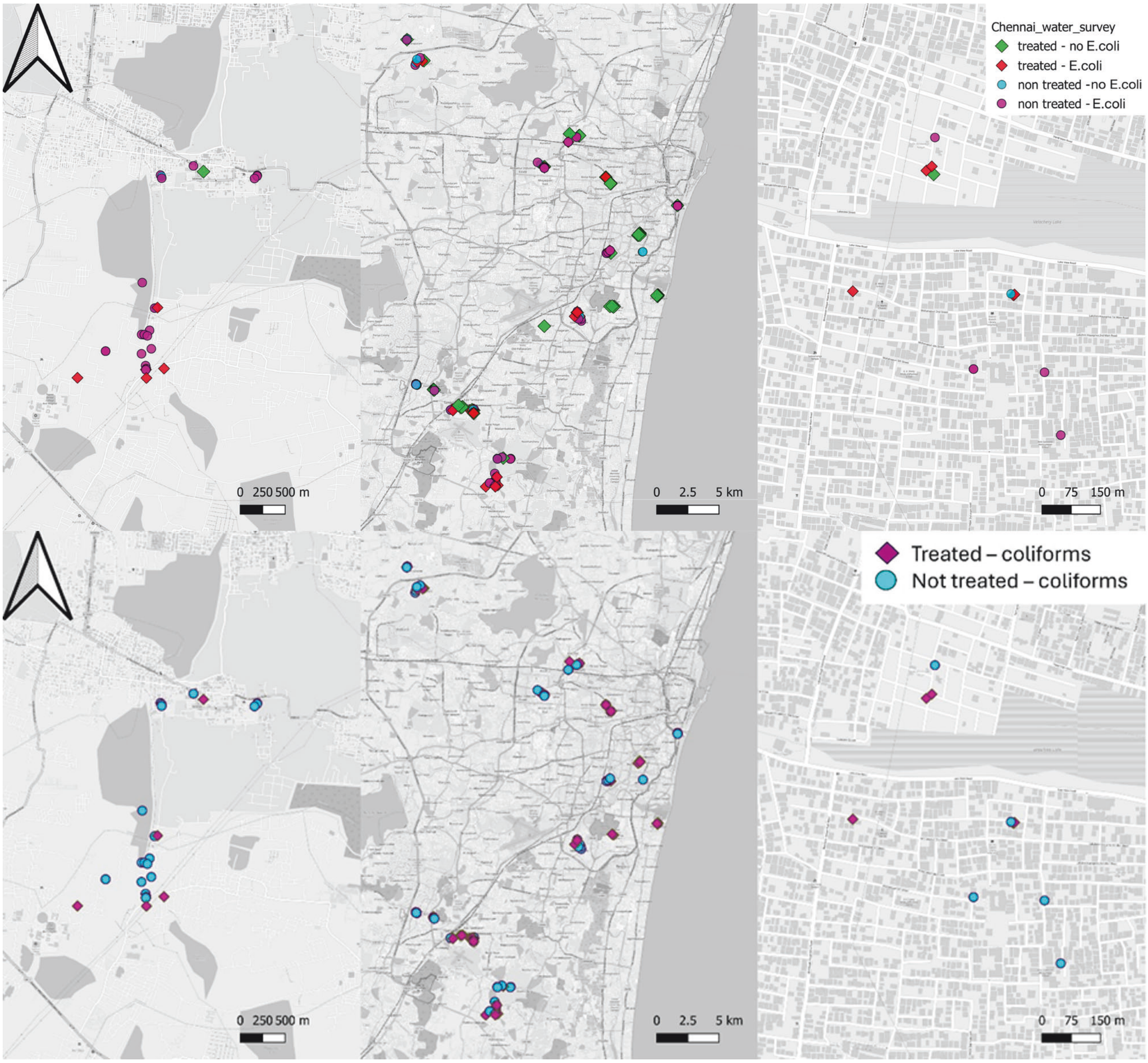

Fig. 5 Spatial distribution of *E. coli* and total coliform contamination in household drinking water pre-RO (not treated) and post-RO (treated). The figure shows the spatial locations of microbial contamination across the surveyed household drinking water samples.

treatment contamination, emphasizing the need for improved treatment systems and better maintenance of infrastructure. These differences may link to the initial quality of the water source and the structural integrity of the water distribution systems in place. The findings suggest that while RO systems can improve water quality, external factors such as environmental conditions and infrastructure maintenance also play a critical role in ensuring water safety. This points to the need for targeted improvements in water sourcing and infrastructure maintenance to enhance safety and health outcomes.

Normalized parameters

The analyzed parameters were normalized to observe the differences between pre-RO (source water before household treatment) and post-RO (drinking water collected after passage through the household RO system) water (Fig. 6). The data indicate a significant reduction in water hardness due to RO treatment, with the mean hardness decreasing from 0.69 ppm pre-RO to 0.08 ppm post-RO samples. The statistical analysis yielded a *p*-value close to zero, suggesting that this reduction is not due to random chance but is a direct effect of RO. Similarly, the results show a substantial decrease in alkalinity, with the mean alkalinity levels dropping from 0.825 ppm pre-RO to 0.225 ppm post-RO samples. The analysis reveals a p-value close to zero, indicating a statistically significant reduction in alkalinity. In contrast, although a decrease in *E. coli* levels was observed after RO treatment, this change was modest and not statistically significant ($p = 0.5197$). As a result, the reduction in *E. coli* is not visually prominent in the normalized boxplot representation, as the observed variation falls within the natural variability of the dataset. This explains why the decrease in *E. coli* is present in the underlying data but does not manifest as a strong shift in the graphical distribution. Similarly, total coliform levels showed no meaningful change between pre-RO and post-RO samples, with a *p*-value of 0.7315, indicating no statistically significant reduction.

In contrast, the analysis of other water quality parameters such as turbidity, conductivity, TDS, ORP, pH, DO yielded p-values close to zero. This reinforces the effectiveness of RO systems in

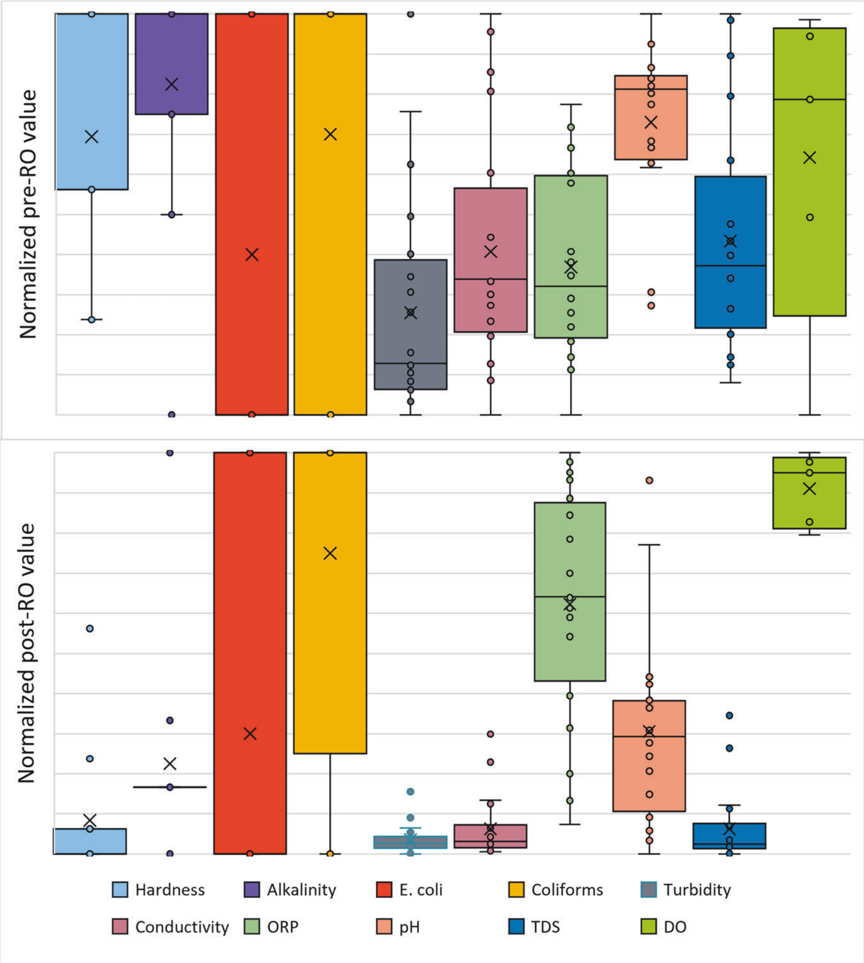

Fig. 6 **Normalized distribution of physical, chemical, and biological water quality parameters in pre-RO and post-RO household drinking water.** The figure shows the normalized comparison between pre-RO and post-RO samples for the measured water quality parameters.

improving physical and chemical characteristics of water, such as TDS and turbidity. However, the limited and statistically insignificant reduction in *E. coli* highlights that RO treatment alone may not be sufficient to ensure microbiological safety, underscoring the importance of proper system maintenance and complementary disinfection measures.

Observations from Round 2 on RO maintenance (independent validation)

Maintenance-related variables were not collected in the Round 1 dataset. To provide contextual insight into potential mechanisms underlying the 31% post-RO *E. coli* positivity observed in Round 1, we refer to findings from an independent follow-up field implementation (Round 2), conducted approximately one year later with a separate cohort of households. These data were collected using comparable field protocols but were not pooled with the Round 1 dataset and are presented here for qualitative interpretation only.

Figure 7 shows *E. coli* positivity in RO-treated drinking water by RO system age. Systems installed within the past year had the lowest *E. coli* positivity, while older systems showed higher contamination levels, with the highest positivity observed in systems older than five years.

Figure 8 shows *E. coli* contamination by time since the last RO system maintenance. Systems maintained within the past three months had the lowest proportion of *E. coli* positive samples, while substantially higher contamination was observed among systems maintained within the past year or never maintained.

Taken together, the Round 2 observations suggest that system aging and longer maintenance intervals are associated with increased post-RO microbial contamination. Although subgroup sizes were limited and confidence intervals were wide, these patterns are consistent with reduced microbiological performance under real household conditions and support the interpretation that persistent post-RO contamination observed in Round 1 is not solely attributable to membrane rejection limitations. Additional analyses from Round 2, including contamination patterns by maintenance practices and servicing characteristics, are provided in the Supporting Information (Figs. S10, S11, S12).

CONCLUSION

The study examined the presence of *E. coli* in drinking water post-household RO systems in low-to-middle-income areas of Chennai, revealing critical insights into water safety and treatment effectiveness. Collecting and analyzing 262 samples and 216 households, the findings highlight significant differences in water quality between various sources and post-RO-treated water. Importantly, samples were collected both before and after RO treatment (pre- and post-RO), allowing a direct evaluation of treatment performance.

While RO systems reduced contamination, 31% of post-RO samples still contained *E. coli* compared to 71% in non-treated water, demonstrating that RO systems improve physical and chemical water parameters but are insufficient in fully eliminating biological contaminants. RO system effectiveness depends heavily

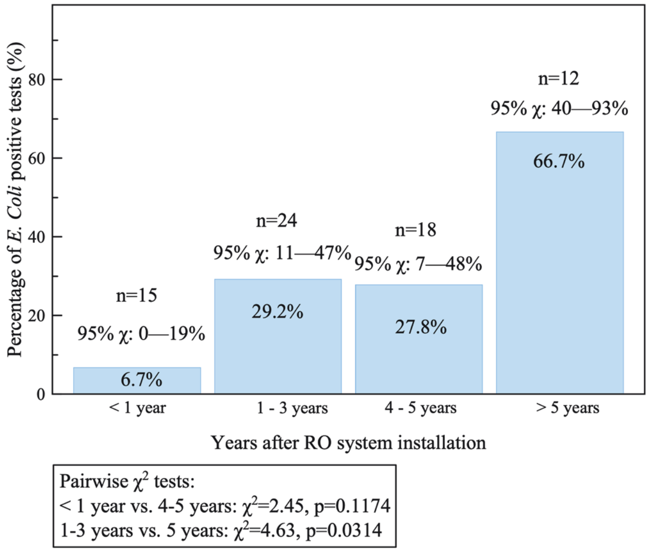

Fig. 7 ***E. coli* positivity by RO system installation year (Round 2).** The figure shows *E. coli* positivity in RO-treated drinking water according to the reported RO system installation year.

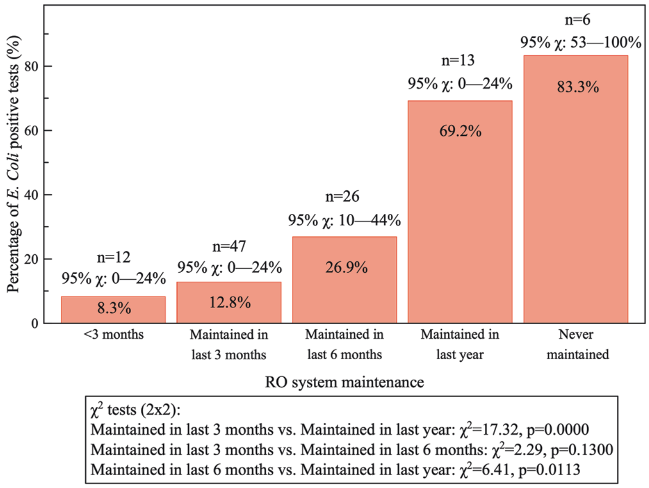

Fig. 8 ***E. coli* positivity by time since last RO system maintenance (Round 2).** The figure shows *E. coli* positivity in RO-treated drinking water according to the reported time since last RO system maintenance.

on regular maintenance and proper water handling practices, as public perceptions often overestimate water safety. Education level was found to be a decisive factor, with *E. coli* present in 36% of samples from postgraduate respondents versus 83% among the uneducated. These results suggest that the efficacy of RO systems is closely linked to contextual factors such as source water quality, infrastructure conditions, and user practices.

Taken together with insights from later rounds of the PWD initiative, these findings highlight the need for structured maintenance guidance, technician training, and standardized servicing practices. From a practical perspective, community-level awareness programs, maintenance reminders, and public health communication on safe handling practices could substantially reduce microbial risks even without changes to system hardware. Such behavioral and educational interventions showed significant impact in households participating in Round 2 of field implementation, where improved awareness was associated with markedly lower contamination levels. Additional supporting analyses from Round 2, presented in Figs. S10–S12 of the Supporting Information, illustrate how maintenance frequency and servicing quality strongly shape microbial outcomes.

For household water treatment systems such as RO to achieve their full potential in safeguarding public health, a multi-faceted approach combining technical solutions with behavioral interventions is essential. To conclude, these findings underscore the urgent need for education, public awareness campaigns, the development of basic maintenance and servicing standards, and proper maintenance protocols to enhance the performance of RO systems or any household water treatment system to mitigate health risks.

Study limitation

A key limitation of this study is its focus on maintenance-related variables. Service frequency, membrane replacement, technician type, and system age were not captured in the Round 1 survey tool. These variables were added only in Round 2, conducted with a separate cohort, and could not be included in the quantitative analyses reported here. As a result, although this study identifies post-RO microbial contamination, it cannot statistically assess the role of maintenance practices. Future research that systematically integrates these variables will be essential to understand the factors influencing RO system performance fully.

DATA AVAILABILITY

The data supporting this article are included in the main article and its supporting Information files. No additional datasets have been deposited in an external repository.

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AUTHOR CONTRIBUTIONS

The manuscript was written through contributions from all authors. All authors have given approval to the final version of the manuscript. S.K. played a central role in the study's design and implementation, coordinated the overall research process, guided the fieldwork, supported data interpretation, and led the manuscript writing. She also supervised and coordinated the work of T.L., Sh.B.G., T.I., and A.S. during their fieldwork and related research activities. T.L. was a key partner in the fieldwork and worked closely with S.K. to build and improve the survey from its early version. B.H. led the data analysis, helped shape the research story, and prepared numerous graphs that supported the selection and presentation of the main findings. S. Seth was involved in all field sessions, conducted laboratory testing on the collected samples, and supported both laboratory and field logistics, including procurement and coordination. T.N. took part in field sessions and contributed to sampling and laboratory testing. A.S. participated in one of the field sessions, collaborated with S.K. on several survey questions, and contributed only to the analysis of the Round 2 dataset. Sh.B.G. and T.I. joined S.K. and T.L. in the fieldwork. T.I. also built the initial version of the survey in Kobo. R.B. supported graph design and statistical analysis. M.G., T.D., and D.G. supported the field activities by involving their students in the project. H.M. and T.P. supervised the study, provided scientific guidance, and gave feedback throughout the research and writing process.

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COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

All methods reported in this manuscript were performed in accordance with the relevant guidelines and regulations. Ethical approval for this study was obtained from the Institutional Ethics Committee (IEC) of the Indian Institute of Technology Madras, India (Approval No. IEC/2024-02/PT/16; valid from 21 June 2024 to 20 June 2027). The study was conducted in accordance with the Indian Council of Medical Research (ICMR) National Ethical Guidelines for Biomedical and Health Research Involving Human Participants (2017). Informed consent to participate was obtained electronically at the beginning of each survey, and the survey was not continued unless consent was provided.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41370-026-00911-5.

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