Evaluating Household Reverse Osmosis Systems for Microbial Safety: A Case Study from Chennai, India

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Supplemental Online Information

1. Description of schematic diagram

Figure S1 provides a schematic overview of potential contamination points within an RO water system. Key areas identified include the pre-treatment stage, where feed raw water first enters, susceptible to microbial contamination if not properly filtered. During the RO configuration, microbial adhesion can lead to membrane fouling, particularly without effective pre-treatment or routine cleaning, fostering biofilm formation. Post-RO water moves through to the post-treatment stage, a critical point where inadequate maintenance can introduce contaminants. In the storage tank, biofouling may develop if conditions support microbial growth, while at the tap, dispensing can introduce further contamination risks. Lastly, user handling (sampling) poses a risk during interactions, often the final contamination point, underscoring the importance of controlled handling protocols.

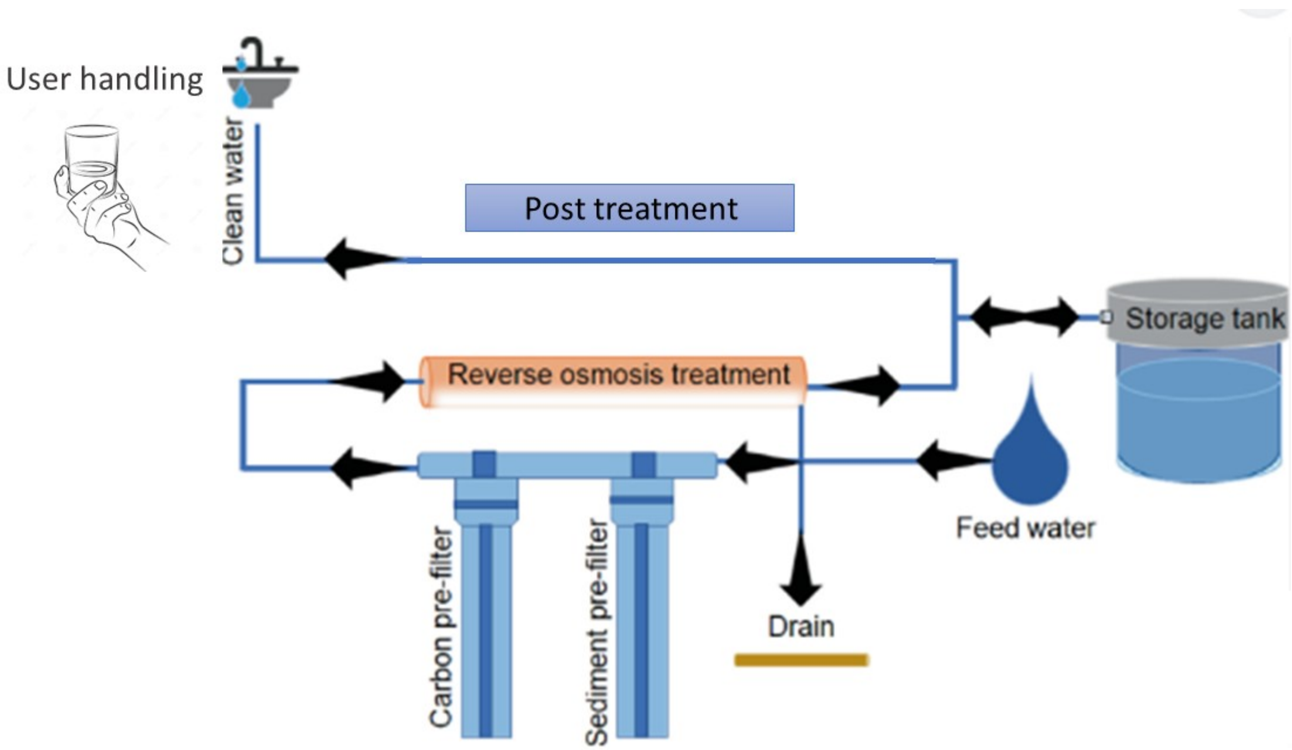


Figure S1: Schematic of Potential Contamination Points in RO Water System, From Pre-Filtration to User Handling.

Figure S2 The research methodology consists of a sequence of stages to ensure comprehensive data collection and analysis. Survey represents the initial stage, where information is gathered to understand the water sources and usage patterns in the study area. Following this, Water Sampling is conducted, where samples are randomly collected from various sources to assess water quality. Field Measurements are then performed, focusing on real-time parameters that can provide immediate insights into water quality conditions. After field data is collected, samples move to the Lab Analysis stage, where in-depth testing identifies contaminants and physical parameters of water. Finally, Data Analysis integrates findings from all previous stages, interpreting the results to draw conclusions about the water quality and potential health impacts, thereby guiding further recommendations or interventions.

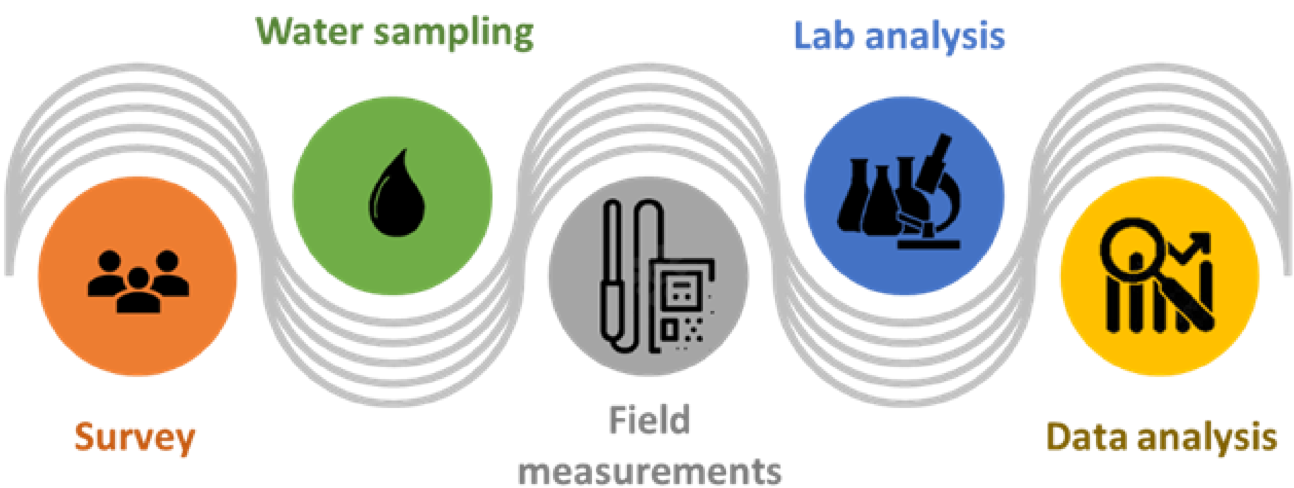


Figure S2: Sequential Flowchart of the Research Methodology.

Table S1 in the Supporting Information provides a comprehensive summary of the water quality testing parameters, methods, and standards applied in this study. It includes specific criteria from both the World Health Organization (WHO) [1] and the Bureau of Indian Standards (BIS) [16], ensuring alignment with international and local standards. Key parameters such as turbidity, pH, temperature, total dissolved solids (TDS), and indicators of microbial presence (e.g., *E. coli*) are detailed along with their acceptable and permissible limits. Additional notes highlight the relevance of each parameter, such as turbidity as an indicator of microbial contamination potential, and pH's influence on water quality. This table serves as a foundation for understanding the rationale behind the testing protocols and their implications for water safety and usability.

Parameters	**Standards WHO and BIS.**	**Notes**
Turbidity	WHO: ≤ 5 NTU Ideally <1 NTU BIS: AL ≤ 1 NTU, PL ≤ 5 NTU AL - Acceptable limit PL - Permissible limit	Indicator of microbial presence, and particles from catchment to point of use

Oxidation-Reduction Potential (ORP)	This value has to be determined on a case-by-case basis; universal values cannot be recommended (WHO)	
pH	6.5-8.5	Affects corrosion and quality
Temperature	WHO: Wherever possible, 25°C >Temp.> 50 °C. Preferably: 20 °C >Temp.>50 °C	Influences density, solubility, DO in water and reaction rates. Rising temperatures support microbial growth
Total Dissolved Solids (TDS)	WHO: ≤ 600 mg/L BIS AL: ≤ 500 mg/L, PL ≤ 2000 mg/L	TDS becomes unpalatable at levels > 1000 mg/l (WHO)
Conductivity	No alternative: >2500 µS/cm but not recommended	Indicates potential pollution
Free/Total Chlorine, Hardness, Alkalinity	WHO: Free chlorine ≤5mg/L Hardness (calcium ions, taste threshold) 100-300 mg/L. BIS: Free residual chlorine: AL≤0.2, PL≤1.5. Alkalinity and hardness as $CaCO_3$: AL ≤ 200, PL ≤ 600 mg/L	Excessive hardness may elevate health risks; chlorine > 4 mg/L can impact breathing. Hardness: soft (0–60 mg/L), moderate (60–120 mg/L), hard (120–180 mg/L). Above ~200 mg/l may cause scale deposition in water system
Dissolved Oxygen (DO)	WHO: No health-based guideline value is recommended.	Low levels lead to mineral dissolution, affecting taste and ecosystem health. Very high levels of DO may impair corrosion of metal pipes
Total coliforms, *E. coli*	WHO: Total coliforms 0/100 mL *E. coli* 0/100 mL. Should not be present in any 100 mL sample BIS: Shall not be detectable in any 100 mL sample	Indicator of fecal contamination. *E. coli* provides conclusive evidence of recent fecal pollution

Table S1: Overview of the water quality parameters, methods and standards (Drinking water standards of the WHO [1] and Bureau of Indian Standards BIS [16].

Quality Assurance and Quality Control (QA/QC) - Text S1

To ensure sampling consistency, measurement accuracy, and data reliability, a structured quality assurance and quality control (QA/QC) framework was implemented throughout the field and laboratory phases. All enumerators underwent standardized theoretical and practical training prior to field deployment, following a detailed standard operating procedure (SOP) covering household surveys, water sampling, on-site testing, and sample handling. Each sampled water source was assigned a unique identifier linked to GPS coordinates, sampling time, and photographic documentation, enabling full traceability across field and laboratory stages.

On-site measurements were conducted using standardized field kits and portable sensors with routine calibration performed according to manufacturer guidelines. Biological samples for *E. coli* and total coliform analysis were collected in sterile containers and transported to the laboratory within 24 hours to preserve sample integrity. Incubation and result interpretation followed established protocols.

Data verification was supported through multiple mechanisms, including automated time-stamping, survey-duration monitoring to flag irregular entries, and expert cross-verification. Spatial consistency was further validated using GIS-based tracking of sampling locations.

This section presents a summary of data collected from 262 water samples obtained from 216 households in Chennai, India. Among these, 69 households using RO systems provided paired samples collected before and after treatment (n = 138 RO samples), while the remaining 124 households provided a single drinking water sample each. The analysis integrates field-based water quality measurements with household-level perceptions to reveal key insights into water quality and public perceptions.

Figure S3 The map provided offers a spatial overview of water sample collection points across Chennai, as part of the Chennai Water Survey. Each blue marker represents a location where water samples were gathered, covering a broad area of the city, from coastal neighborhoods near the Bay of Bengal to inland districts. This distribution allows for a comprehensive assessment of water quality variability across different parts of Chennai, capturing both urban and suburban areas. By visualizing the sampling points, the map highlights the geographic scope of the survey, ensuring that diverse water sources and potential contamination zones are represented in the study.

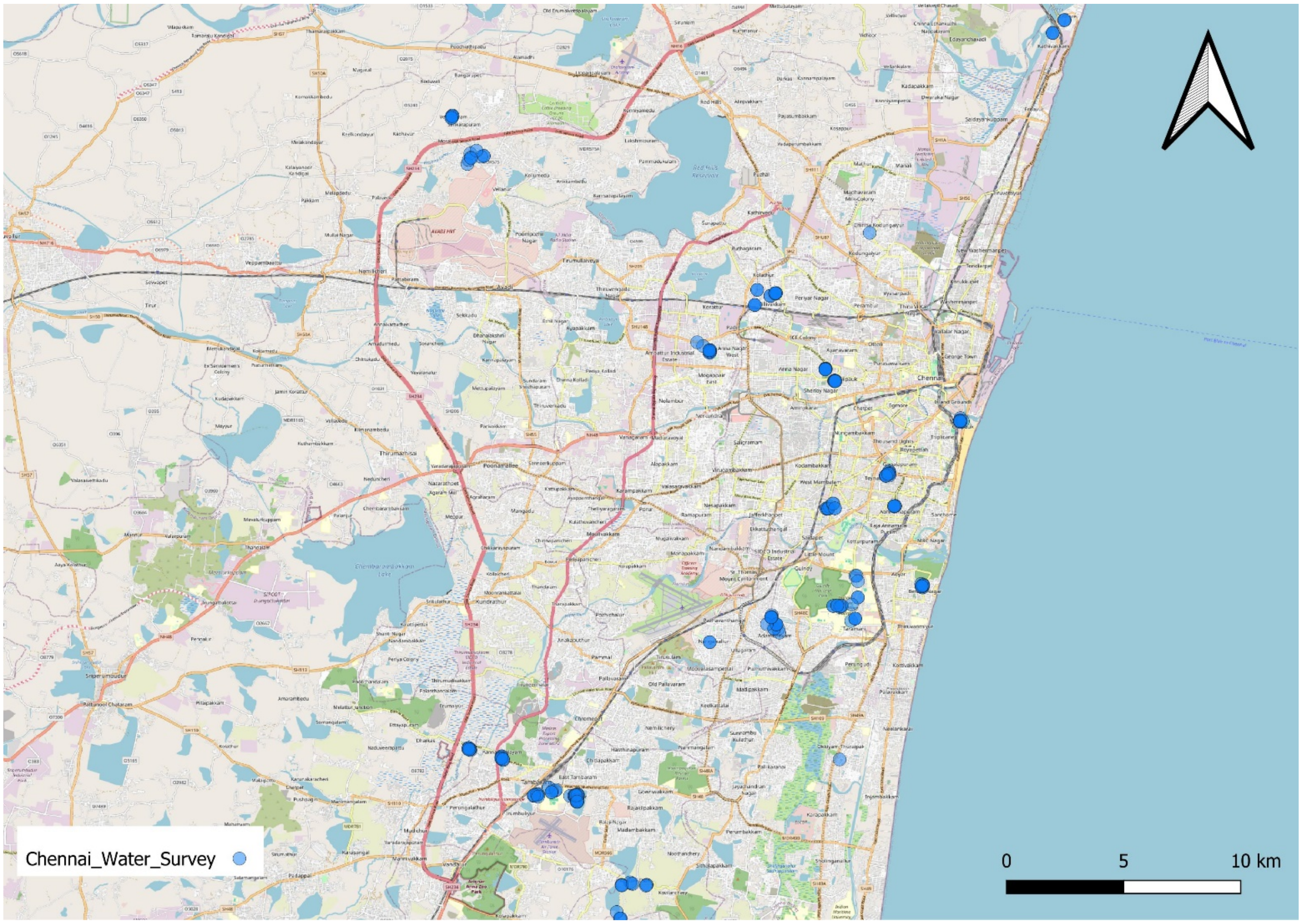


Figure S3: Map of drinking-water sources in the sample area.

Figure S4 provides an overview of the various data categories collected during the household water survey, capturing comprehensive details about water sources, storage, treatment, usage, and perceived quality. Beginning with General Information on survey objectives, it addresses Water Source specifics, distinguishing between natural sources (e.g., lakes, rivers) and artificial sources (e.g., wells, public taps). Household Information and Demographics capture the context of water usage, including household composition, ages, and education levels. Water Storage practices (e.g., bore wells, municipal supply) and Water Treatment methods are examined, along with Water Treatment Info like duration and place. Additionally, the overview assesses Health Impacts potentially linked to water quality Water Usage for different purposes, and Water Quality Tests. Finally, Perception of Quality and Water Supply availability are included to understand users' subjective experiences with their water, adding depth to the survey’s findings on drinking water safety and reliability.

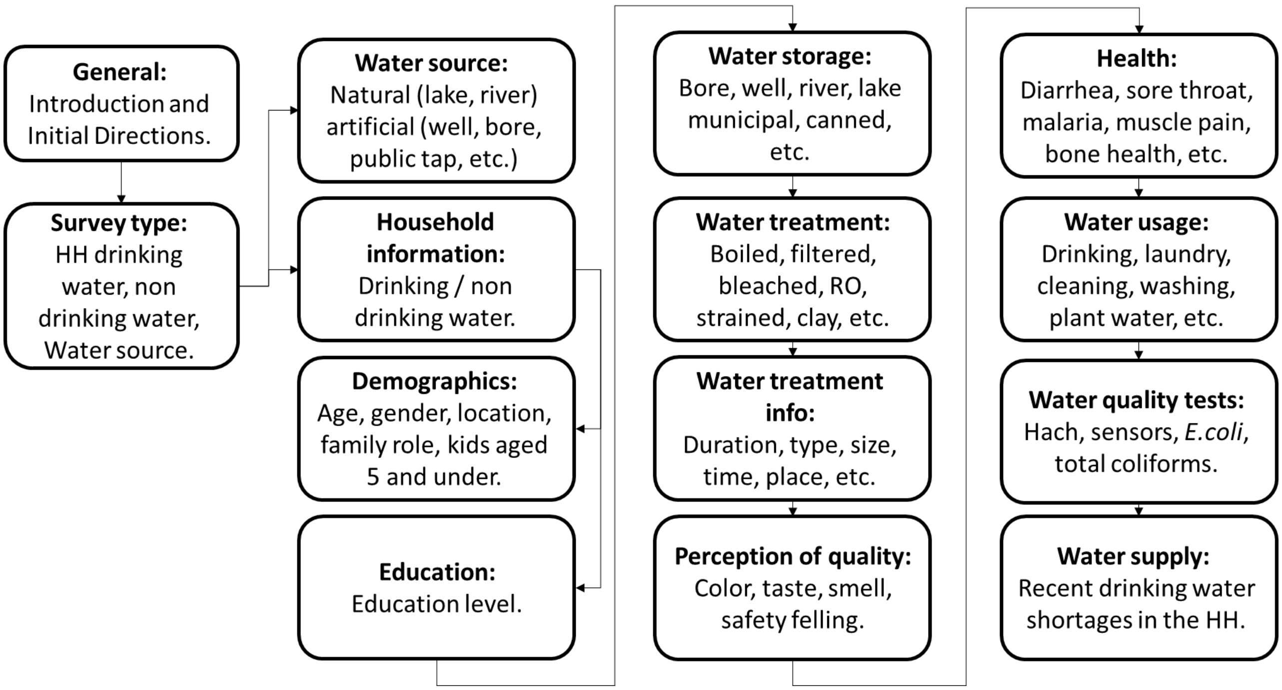


Figure S4: The survey tool flowchart.

Figure S5 the complete survey:

Water Monitoring Survey

Submission ID

Example: XX01091225 (initials-day, month)

____

Date yyyy-mm-dd

____

When testing households please use the following introduction:

____

Hi, my name is... I'm taking part in checking the quality of our drinking water in the area.

____

This project is part of a research done by IITM, Tel Aviv University and …

____

For this purpose, I will need to ask you a few questions on your water practices at home, and test a cup of your drinking water.

____

It will take about 15 minutes. Are you willing to participate?

____

General

Researcher name

____

Water source information (if water source)

Please select the relevant type of water source

- Natural
- Artificial

Please specify the type of natural source (if natural source)

- Lake
- River
- Other

Specify other.

____

Please specify the type of artificial source (if artificial source)

- **Open well**
- **Bore well**
- **Reservoirs**
- **Pumping station**
- **Piping system**
- **Public tap**
- **Other**

Specify other.

____

Please specify the origin of this source's water (if artificial source)

- River
- Lake
- Metro / Municipal distribution
- Ground water
- Rainwater
- Pond

Effluent

Other

Specify other.

____

Please name the source

Choose a differentiating name that will allow identifying this source in the future

____

Is the source covered?

- The source is fully covered
- The source is partially covered
- The source is not covered (i.e., completely open)

N/A

Please take a picture of the source

Household information (if household drinking water)

In this part of the survey, please direct all survey questions to the household respondent

---

What is your name?

Respondent gender

- Female
- Male
- Other

How old are you?

- 18-29
- 30-39
- 40-49
- 50-59
- 60 or older

What is your family role?

- Parent
- Grandparent
- Daughter / son
- Other

Specify other.

What is your education level?

None

Primary school (1-6 years)

Secondary school (6-12 years)

Undergraduate

Postgraduate

How many children under the age of 5 live in this household? ____________________

Water distribution and storage (if household drinking water)

What is the source of your drinking water?

Bore / Ground

Metro / Municipal distribution

Canned water

Tanker truck / Lorry

Open well

River / Lake

Other

Specify other.

____

When you take water to drink, where do you take it from?

- Tap (pipeline)
- Container
- Canned water
- RO system
- Packaged water

Please take a picture of the drinking water storage

Click here to upload file (<10MB)

Is your drinking water stored in a roof tank?

- Yes
- No

Do you clean your roof tank?

- Yes
- No

When was the last time you cleaned your roof tank? (If roof tank)

- Last 6 months
- This year
- Prior to this year

Water treatment (if household drinking water)

Did you treat today's drinking water?

- Yes
- No

How did you treat today's drinking water? (if treated)

- ☐ RO
- ☐ Water filter
- ☐ Boiled
- ☐ Strained
- ☐ Clay pot filter
- ☐ Bleached/Chlorinated
- ☐ Other

Specify other.

____

When was the last time the RO maintenance service arrived? (If RO)

- ○ In the last 3 months
- ○ In the last 6 months
- ○ In the last year
- ○ Never
- ○ My RO system is less than 6 months old

When did you last treat the water we are testing? (if treats)

- ○ Never Today
- ○ Earlier this week
- ☐ Prior to this week
- ○ I don't remember

What material is the container made of? (if container)

- Plastic
- Clay
- Aluminum

Other

Specify other.

____

What is the size of the container? (if container)

- 1-5L
- 6-10L
- 11-20L
- 21-50L
- 51-70L

71-100L

>100

Is the container covered? (if container)

- Yes
- No

Is the container on the ground? (if container)

- Yes
- No

When did you last clean your container? (if container)

- Today
- This week
- This month
- This year
- Prior to this year

Never

Did you use detergents for cleaning your container? (if container)

- Yes
- No

Is your water placed less than 2 meters away from cooking environment?

- Yes
- No

For the next section, please ask the respondent to fetch a glass of drinking water and observe

____

How were the water taken out?

- Pouring directly from the container
- Using container's tap
- Using a cup or a jug

Other

Specify other.

____

While getting water out of the container, did the respondent's hand touch the water?

- Yes
- No

Water assessment (if household drinking water)

How do you feel about the safety of your drinking water today?

- Very good
- Good
- Satisfactory
- Bad

Very bad

Have you or another resident in this household recently suffered from one of the following

- Diarrhea
- Sore throat
- Muscle pain
- Change in your teeth health
- Malaria
- Joint pain
- Bone health issues

None of the above

Other

Specify other.

____

When was the last time this household didn't have enough drinking water?

This month

This year

Before this year

Never

5 in 1 test

Total chlorine

0 0.5 1 2 4 10

Free chlorine

0 0.5 1 2 4

10

Hardness

0 25 50 120 250

425

Alkalinity

0 40 80 120 180

240

pH

6.2 6.8 7.2 7.8 8.4

pH test

pH first sample

WHO standard: 6.5-8.5

pH second sample

pH third sample

ORP test

ORP first sample

WHO standard: 300-500mV

ORP second sample

ORP third sample

Conductivity test

Conductivity first sample

WHO standard: 200-400 μS/cm

____

Conductivity second sample

____

Conductivity third sample

____

TDS test

TDS first sample

WHO standard: < 300ppm

____

TDS second sample

____

TDS third sample

____

Temperature

Please insert temperature

____

Turbidity test

Turbidity first sample

WHO standard: < 1 NTU

____

Turbidity second sample

____

Turbidity third sample

____

Biological tests

E. coli result - ***to add 24 hours after conducting the test***

- ○ Positive for E. coli
- ○ Negative for E. coli

Total Coliforms result - ***to add 24 hours after conducting the test***

- ○ Positive for Total Coliforms
- ○ Negative for Total Coliforms

MPN EC result - ***to add 24 hours after conducting the test***

Value above 10 is dangerous for consumption

____

MPN TC result - ***to add 24 hours after conducting the test***

Value above 10 is dangerous for consumption

____

Pre-treatment water testing (if treats)

» 5 in 1 test

Total chlorine

0 0.5 1 2 4 10

Free chlorine

0 0.5 1 2 4

10

Hardness

0 25 50 120 250

425

Alkalinity

0 40 80 120 180

240

pH

6.2 6.8 7.2 7.8 8.4

» pH test

pH first sample

WHO standard: 6.5-8.5

____

pH second sample

____

pH third sample

____

» ORP test

ORP first sample

WHO standard: 300-500mV

____

ORP second sample

____

ORP third sample

____

» Conductivity test

Conductivity first sample WHO standard: 200-400 µS/cm

____

Conductivity second sample

____

Conductivity third sample

____

» TDS test

TDS first sample

WHO standard: < 300ppm

____

TDS second sample

____

TDS third sample

____

» Temperature

Please insert temperature

____

» Turbidity test

Turbidity first sample

WHO standard: < 1 NTU

Turbidity second sample

Turbidity third sample

» Biological tests

E. coli result - ***to add 24 hours after conducting the test***

- ○ Positive for E. coli
- ○ Negative for E. coli

Total Coliforms result - ***to add 24 hours after conducting the test***

- ○ Positive for Total Coliforms
- ○ Negative for Total Coliforms

MPN EC result - ***to add 24 hours after conducting the test***

Value above 10 is dangerous for consumption

MPN TC result - ***to add 24 hours after conducting the test***

Value above 10 is dangerous for consumption

Additional comments

Figure S6 provides an overview of participants' perceptions of water safety. Most respondents rated water safety positively Figure S6a, this distribution suggests that a majority of participants feel confident in the safety of their water, though some room for improvement remains. Figure S6b compares satisfaction with water quality based on the presence or absence of household water treatment. This suggests that while household treatment may improve water satisfaction, many respondents find their water satisfactory without additional treatment.

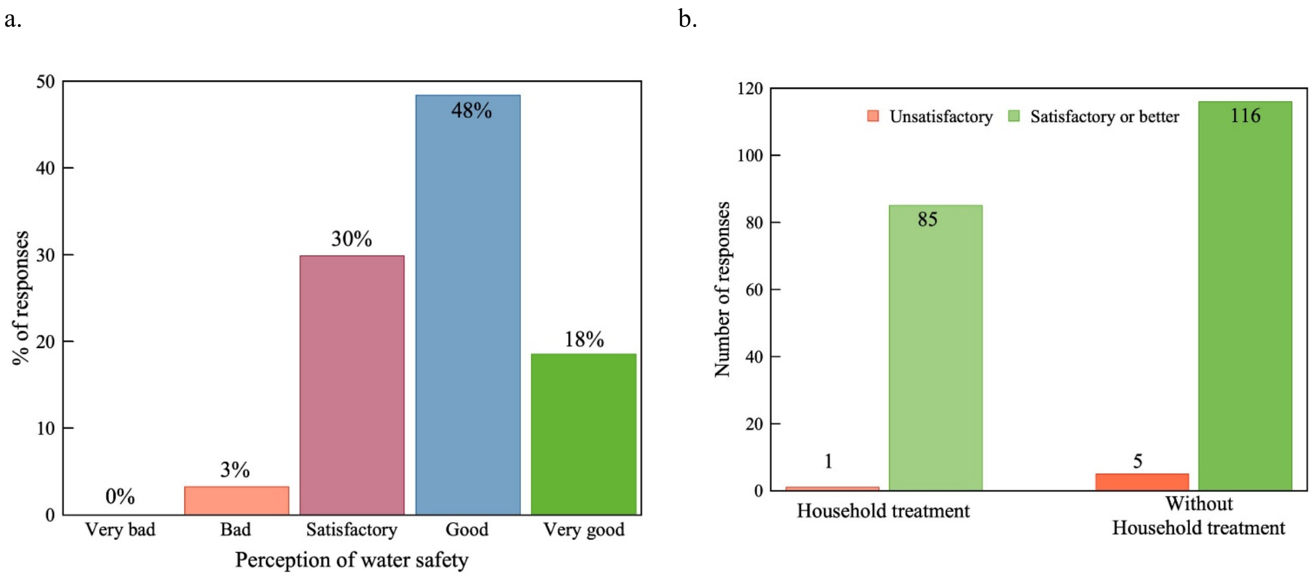


Figure S6: (a) How do you feel about the safety of your drinking water today? (n = 210). (b) How do you feel about the safety of your water with and without household (HH) treatment (n = 210).

Additional analysis of the data presented in Figure S7 explores the correspondence between sensory perceptions and measured water quality parameters. Water samples reported as having a chlorine odor exhibited higher oxidation-reduction potential (ORP) values, suggesting a link between perceived chemical odor and oxidative conditions. Similarly, samples described as having an earthy taste showed elevated conductivity levels, while reports of rusty-colored water were associated with higher turbidity. These patterns indicate that respondents' sensory observations may reflect underlying physical and chemical characteristics of the water, reinforcing the potential of user-reported perceptions as preliminary indicators of water quality in household contexts.

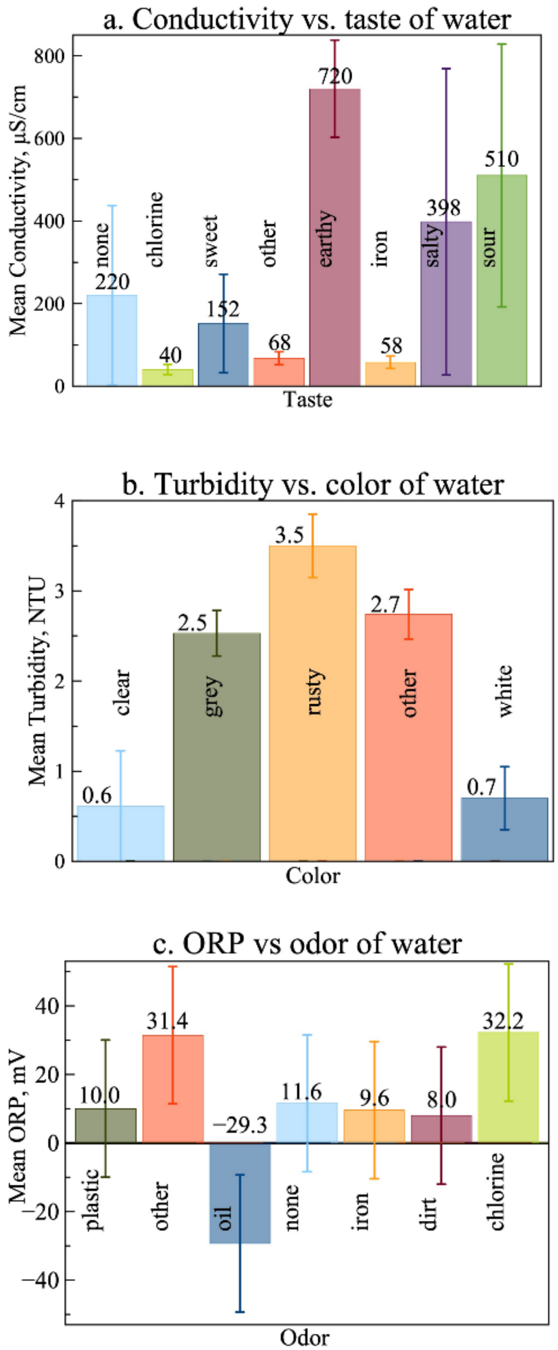


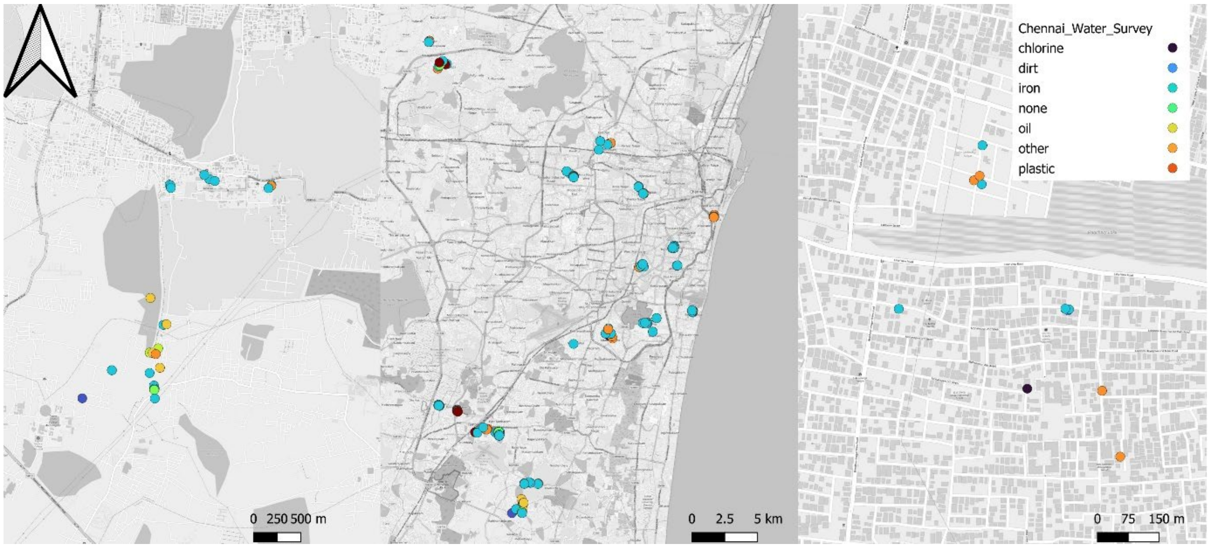
Figure S7: Physical parameters (conductivity, turbidity, and ORP) vs. subjective parameters (taste, color, and odor)

Survey data and spatial analysis provide insights into how different communities perceive and interact with drinking water quality. Urban design often mirrors the behavioral significance of drinking water, showing how communities value and interact with water quality. For example, densely populated areas with limited access to clean water face challenges in water management and distribution. Additionally, the presence of green spaces, water treatment systems, and infrastructure improvements can relate to attitudes toward sustainability and environmental responsibility. Figure S8 shows a series of four maps, each representing a different attribute of water quality as reported in a survey: Perception, Taste, Color and Odor. These maps show the geographic distribution of survey responses across the city, of Chennai. The purpose of these maps is to visually convey the spatial patterns of water quality perceptions in the surveyed area, which can be used for targeted public health interventions, infrastructure development, and further research into water quality issues. The detailed zoom-in of the perception map on the right highlight's specific neighborhoods with varying water quality, revealing local issues such as infrastructure problems or contamination sources.

On the taste map, different contaminants are distributed unevenly across the region. For instance, areas with "dirt" or "plastic" issues may indicate poor waste management practices, while "iron" or "oil" contamination could point to industrial pollution or groundwater quality issues. The "clear" water points highlighted on the color map suggest areas where the water's appearance is free from visible impurities such as sediment, rust, or discoloration. However, while clear water may appear safe, it does not guarantee the absence of microbial or chemical contaminants, emphasizing the need to combine physical appearance assessments with laboratory testing for a comprehensive understanding of water quality. Additionally, areas with "dirt" identified on the odor map may indicate insufficient cleaning of storage tanks, pipes, or filters, leading to the accumulation of dirt-like odors

Perception:

Taste:


Chennai_Water_Survey
chlorine
dirt
iron
none
oil
other
plastic
0 250 500 m
0 2.5 5 km
0 75 150 m

Color:


Chennai_Water_Survey
clear
grey
other
rusty
white
0 250 500 m
0 2.5 5 km
0 75 150 m

Odor:

Figure S8: Spatial maps overlaid with the perception, taste, color, and odor of water quality.

Figure S9 illustrates the analysis of the data from a social and behavioral perspective uncovered some interesting findings, distinguished between households using RO systems for water treatment and those consuming non-treated drinking water.

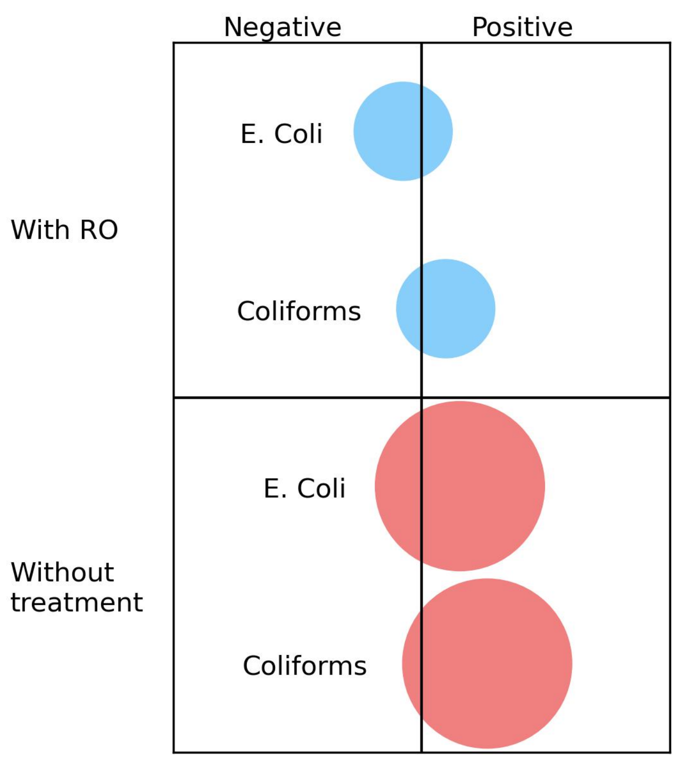


Figure S9: Social data for households using RO compared to non-treated water.

2. Observations from Round 2) Independent Validation)

As part of the continued development of the People's Water Data initiative, a second field implementation round (Round 2) was conducted between August - October 2024. While the analyses presented in the main manuscript rely solely on data collected during Round 1, Round 2 was performed with a separate cohort of households and an expanded survey instrument designed to address knowledge gaps identified in the initial phase. In particular, Round 2 introduced detailed variables related to RO system maintenance, including the timing of filter and membrane replacement, the type of technician providing service, system age, and household self-maintenance practices that were not captured in the Round 1 questionnaire. These additional variables are therefore not included in the quantitative analyses reported in the article; however, they provide essential contextual information that supports the interpretation of microbial findings from Round 1. The supplemental figures presented below summarize key observations from Round 2 and offer qualitative insights into maintenance-related patterns that influence RO performance in household settings. Socio-demographic characteristics of the Round 2 are summarized in Table S2.

Characteristic	**Category**	**n (%)**
Age group (years)	<18†	15 (5.8)
	18–24	20 (7.7)
	25–34	72 (27.7)
	35–44	51 (19.6)
	45–54	36 (13.9)
	55–64	38 (14.6)
	≥65	28 (10.8)
Gender (≥18 years)	Female	126 (51.4)
	Male	119 (48.6)
Family role (≥18 years)	Head of household	101 (41.2)
	Spouse of head of household	93 (38.0)
	Daughter/son	41 (16.7)
	Other family member	10 (4.1)
Education level (≥18 years)	Literate, no formal schooling	12 (4.9)
	Secondary or higher secondary	42 (17.1)
	College without degree	22 (9.0)

	General degree	146 (59.6)
	Professional degree	23 (9.4)
Children under 5 in household (≥18 years)	0	129 (52.7)
	1	44 (18.0)
	2	54 (22.0)
	3	10 (4.1)
	4	3 (1.2)
	≥5	5 (2.0)
Household area (≥18 years)	<55 sq ft (<5 m^2)	35 (14.3)
	55–162 sq ft (5–15 m^2)	103 (42.0)
	>162 sq ft (>15 m^2)	107 (43.7)

**Respondents under 18 years of age were excluded from analytical sections, as children are typically not responsible for RO system maintenance decisions. They are reported here for descriptive completeness only.*

Table S2: Socio-demographic characteristics of Round 2 respondents

Water distribution and storage

Among 245 households, drinking water sourcing and storage practices varied. Approximately half of the households (48.6%, n = 119) relied on stored water, including plastic or metal containers, branded or non-branded canned water, and traditional clay pots. A total of 43.3% (n = 106) reported using household treatment units, primarily reverse osmosis (RO) systems or other filtration devices, while 8.2% (n = 20) collected drinking water directly from the tap (pipeline).

Biological test results

Among 242 households tested in Round 2, *E. coli* was detected in 46.7% of samples (n = 113; 95% CI: 40–53%). This overall positivity rate provides contextual background for the maintenance-related stratified analyses presented below and is shown by water source in Figure S10.

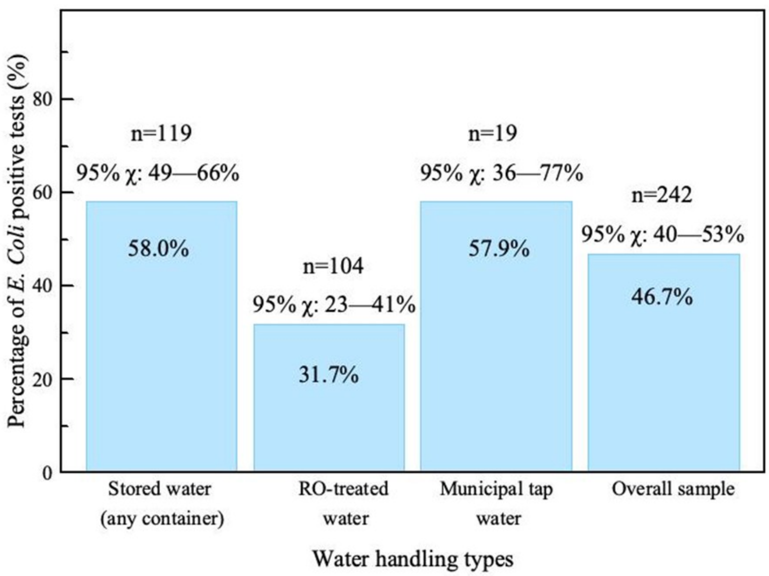


Figure S10. *E. coli* test results by water source (Round 2).

RO system service type

E. coli positivity in RO-treated drinking water varied by the type of RO system servicing (Figure S11). Systems maintained through private service providers showed the lowest *E. coli* positivity (12.5%, n = 48), followed by systems serviced by company technicians (30.0%, n = 30). Higher contamination levels were observed among households relying on partial servicing approaches, including parts replacement combined with self-maintenance (37.5%, n = 8) or specialist assistance (41.7%, n = 12). Systems that received no maintenance exhibited the highest *E. coli* positivity (83.3%, n = 6). Pairwise chi-square comparisons suggested higher contamination among systems lacking professional servicing compared to privately serviced systems, although these differences did not reach conventional statistical significance. Given the small subgroup sizes and wide confidence intervals, these findings should be interpreted with caution.

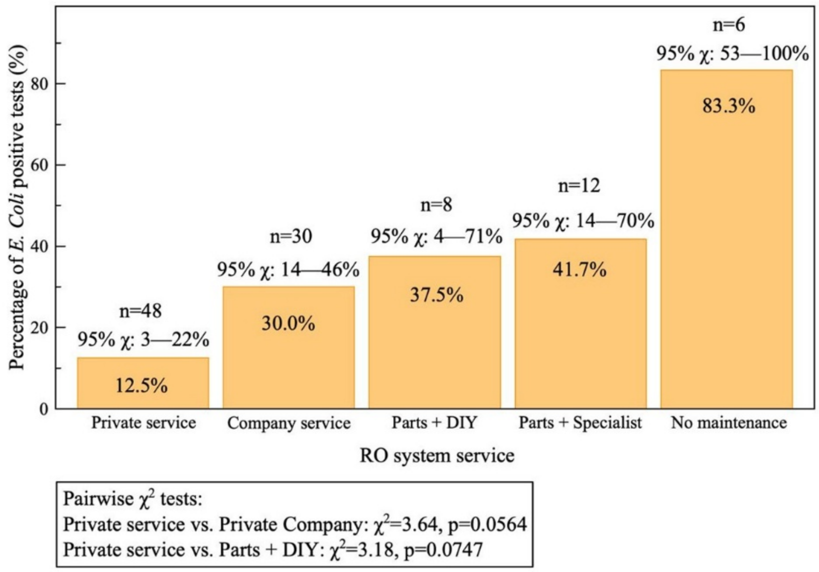


Figure S11. *E. coli* positivity by RO system service type (Round 2).

RO system maintenance frequency

E. coli positivity in RO-treated drinking water varied by self-reported RO system maintenance frequency (Figure S12; n = 104). Systems reported to be maintained every three months showed the lowest *E. coli* positivity (13.8%, n = 29), followed by systems maintained every six months (17.8%, n = 45). In contrast, systems maintained only once per year exhibited substantially higher contamination (42.9%, n = 21), while households that were unable to report their maintenance frequency ("don't know") showed the highest *E. coli* positivity (77.8%, n = 9). Pairwise chi-square comparisons indicated no significant difference between three- and six-month maintenance intervals ($p = 0.65$), but a significant increase in contamination when maintenance was performed annually compared with every six months ($\chi^2 = 4.71$, $p = 0.03$). Given the small subgroup sizes and wide confidence intervals, these findings should be interpreted with caution.

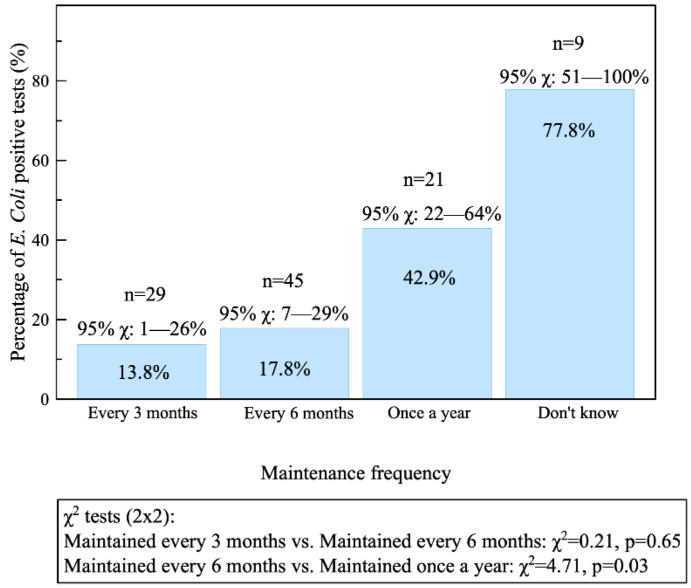


Figure S12. *E. coli* contamination by maintenance frequency (Round 2).