

Review Article

Evaluating the Effectiveness and Public Health Implications of Household Reverse Osmosis Water Filtration Systems: A Narrative Review

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Abstract

Safe drinking water remains inaccessible to a substantial proportion of the global population, a circumstance that has contributed to the widespread adoption of household reverse osmosis (RO) as one of the most common point-of-use (POU) treatment technologies. This narrative review draws on 45 peer-reviewed studies, identified through a non-systematic search of Google Scholar, PubMed, and Scopus (the search terms and approach are detailed in Section 1), to assess the contaminant removal efficiency, water quality outcomes, public health benefits, and documented risks associated with domestic RO units. Thin-film composite (TFC) polyamide membranes, now standard in contemporary household systems, consistently achieve rejection rates exceeding 90% for most dissolved solids, heavy metals, and inorganic contaminants (Greenlee et al., 2009; Kucera, 2015); removal efficiencies for lead, arsenic, and cadmium typically surpass 95%, whereas nitrate rejection is comparatively lower, ranging between 85% and 93% depending on membrane condition and feedwater chemistry (Greenlee et al., 2009; Kucera, 2015). This performance, however, is not without cost. The substantial depletion of essential minerals such as calcium, magnesium, and bicarbonate reduces permeate pH to acidic levels, often below 6.5, raising legitimate questions regarding the long-term nutritional and cardiovascular consequences of consuming demineralized water (Kozisek, 2005; WHO, 2005). Household RO adoption in the Arab region and Iraq specifically is widely reported to have increased substantially over the past two decades, a trend attributed to elevated groundwater salinity and inconsistent municipal infrastructure (Al-Ansari et al., 2014); rigorous, published adoption-rate data at the household level nonetheless remain scarce. Maintenance compliance constitutes a documented concern more broadly, and field studies conducted outside the region have identified microbial re-contamination in poorly maintained systems (Payment, 1989; Payment et al., 1991); comparable Iraq-specific evidence could not be located in the course of this review, a gap identified here as a priority for future work. The review further addresses the environmental burden of brine discharge, cost-effectiveness across income levels, regulatory gaps in developing countries, and the near-total absence of standardized post-treatment remineralization protocols. It concludes by identifying critical gaps in the existing evidence base and proposing directions for future research, with particular attention to settings in which RO systems function as the primary or sole barrier against waterborne disease.

1. Introduction

Safe drinking water constitutes a fundamental determinant of human health. The World Health Organization (WHO) estimates that approximately 2 billion people worldwide rely on drinking water sources contaminated with fecal matter, and waterborne disease accounts for approximately 485,000 deaths annually [1]. Centralized water treatment plants remain the backbone of safe water supply in industrialized nations, yet their reach is considerably less complete elsewhere. Distribution networks in many low- and middle-income countries suffer from aging infrastructure, intermittent supply, and the intrusion of contaminants during transmission [2]. This reality has driven a marked expansion of point-of-use (POU) water treatment technologies, among which household reverse osmosis (RO) systems are among the most commercially successful.

Reverse osmosis membranes exploit a comparatively simple physical principle: when a pressure gradient is applied across a semipermeable membrane, water molecules pass through while dissolved solutes, bacteria, and many organic molecules are rejected. Developed originally for industrial desalination in the 1960s, the technology has since been scaled down into compact under-sink units suitable for domestic use [3]. The global market for household RO units expanded considerably from the early 2000s onward, driven by rising consumer awareness of water quality issues and declining unit costs; the current installed base is estimated in the tens of millions of units, concentrated in South and East Asia, the Middle East, and North America [4]. The appeal of household RO lies in its function as a last line of defense at the point of consumption, removing, in principle, dissolved salts, heavy metals, pathogens, and trace organic chemicals that may survive centralized treatment or enter the supply during transmission. For consumers in regions where tap water quality is unreliable, or where groundwater constitutes the primary source, an under-sink RO unit offers a measure of direct control over water quality. Iraq presents a case in point: decades of conflict, sanctions, and infrastructure degradation have left municipal water systems in many cities operating well below design capacity [5], and anecdotal and market reports indicate rising household RO adoption in Baghdad, Basra, and other major cities as a consequence. Peer-reviewed, city-level adoption data comparable to those available for other MENA countries could not, however, be located; this absence is treated in the present review as an evidence gap rather than an established finding.

The widespread adoption of household RO nonetheless raises questions that manufacturer marketing materials do not typically address. The near-total removal of dissolved minerals, including calcium, magnesium, and bicarbonate, produces water that is acidic, chemically aggressive, and largely depleted of the mineral content that contributes to dietary intake of these essential nutrients [6]. The WHO has stated that water with very low mineral content may carry adverse health effects, particularly for populations already at risk of nutritional deficiency [7]. Practical concerns arise as well: household RO systems typically produce a reject stream, or brine, that is two to four times the volume of purified water, representing a substantial waste of a scarce resource in water-stressed regions [8]. Moreover, while properly functioning membranes constitute highly effective barriers, poorly maintained systems can become breeding grounds for bacteria, particularly within the storage tanks that most household units incorporate downstream of the membrane [9].

This review aims to provide a comprehensive, evidence-based assessment of household RO technology as it relates to drinking water quality and public health. Rather than treating RO as either a panacea or a hazard, the analysis weighs the documented benefits against the documented risks, with particular attention to conditions in the Arab region and Iraq. The paper draws on 45 peer-reviewed publications spanning membrane science, environmental engineering, public health, and water policy, examining removal-efficiency data across a range of contaminants, characterizing the physicochemical properties of RO-treated water, reviewing the epidemiological and nutritional evidence regarding health outcomes, and considering the economic, environmental, and regulatory dimensions of household RO use. The review concludes by identifying gaps in the current literature and proposing directions for research that could help maximize the public health value of this widely adopted technology.

Review Methodology

This is a narrative, not a systematic, review, and is presented accordingly. Sources were identified through non-systematic keyword searches of Google Scholar, PubMed, and Scopus using combinations of the terms “reverse osmosis,” “household,” “point-of-use,” “drinking water,” “demineralization,” “remineralization,” “membrane,” “Iraq,” and “MENA,” supplemented by forward and backward citation chasing from key reviews [3, 4, 10]. No fixed date range, language restriction, or formal inclusion/exclusion protocol, such as PRISMA, was applied, and no independent second reviewer screened the source set. The resulting body of 45 peer-reviewed publications, supplemented by four WHO technical reports and one industry standard, should accordingly be understood as illustrative of the evidence base rather than exhaustive of it. Where regionally specific claims concerning Iraq and the wider Arab region could not be corroborated against a verifiable, indexed source at the time of writing, this is stated explicitly in the relevant section rather than presented as an established finding; such instances are treated as evidence gaps and are consolidated in Section 10.

2. Principles of Reverse Osmosis Technology

Osmosis is a natural phenomenon whereby solvent molecules migrate across a semipermeable membrane from a region of lower solute concentration to one of higher concentration, driven by the difference in chemical potential. Reverse osmosis inverts this process by applying hydrostatic pressure in excess of the osmotic pressure to the concentrated side, thereby forcing pure water through the membrane while dissolved solutes are retained on the feed side [11]. The minimum pressure required corresponds to the osmotic pressure of the feed solution itself; household systems typically operate at 40 to 80 psi (approximately 2.8 to 5.5 bar) in practice, depending on feedwater salinity and membrane characteristics [12]. Virtually all contemporary household RO systems employ thin-film composite (TFC) polyamide membranes, comprising three layers: a polyester support web for mechanical strength, a microporous polysulfone interlayer, and an ultra-thin polyamide active layer, typically under 200 nm thick, at which the actual separation occurs [13]. This active layer rejects solutes through a combination of steric exclusion (size-based rejection), Donnan exclusion (charge-based rejection of ions by the membrane’s fixed surface charge), and solution-diffusion, whereby water and solutes partition differently into and through the membrane matrix [10]. Monovalent ions such as sodium and chloride are rejected somewhat less effectively than divalent ions such as calcium and sulfate, as the latter experience stronger electrostatic repulsion from the negatively charged polyamide surface [3].

A typical household RO system comprises several stages arranged in series. The first is generally a sediment pre-filter, commonly rated

at 5 microns, which removes particulate matter that could otherwise damage or foul the membrane. This is followed by an activated carbon pre-filter that adsorbs chlorine, chloramines, and certain organic compounds, a critical step given that free chlorine degrades polyamide membranes irreversibly [12]. Water then passes through the RO membrane module, after which a post-carbon filter provides a final polishing stage. Because flow through the membrane is slow, typically 50 to 190 liters per day for residential units, most systems incorporate a pressurized storage tank from which the user draws purified water on demand [14].

System performance is characterized by two primary metrics: salt rejection, the percentage of dissolved solids retained by the membrane, and water recovery, the fraction of feed water converted to permeate. Salt rejection for new TFC membranes under standard test conditions typically ranges from 95% to 99% for most dissolved species [11]. Water recovery for household systems is notably lower than for industrial installations, commonly falling between 20% and 50%, such that between one and four liters are discharged as concentrate for every liter of purified water produced [4]. This low recovery ratio reflects, in part, a deliberate design trade-off: operating at lower recovery reduces the risk of membrane fouling and scaling, thereby extending membrane life at the expense of water efficiency.

Membrane fouling, the accumulation of particulate, organic, or biological material on the membrane surface, constitutes the principal operational challenge in any RO system. Biofouling is a particular concern in household units, where intermittent use produces stagnant conditions in the membrane module and storage tank that favor microbial growth [15]. Chemical scaling, caused by the precipitation of sparingly soluble salts such as calcium carbonate and calcium sulfate as their concentration increases in the reject stream, presents a further common issue, particularly in regions with very hard feedwater [16]. Regular filter replacement and periodic membrane sanitization are essential for maintaining performance; compliance with manufacturer-recommended maintenance schedules, however, varies considerably among consumers [9]. Figure 1 summarizes these rejection characteristics across the major contaminant classes.

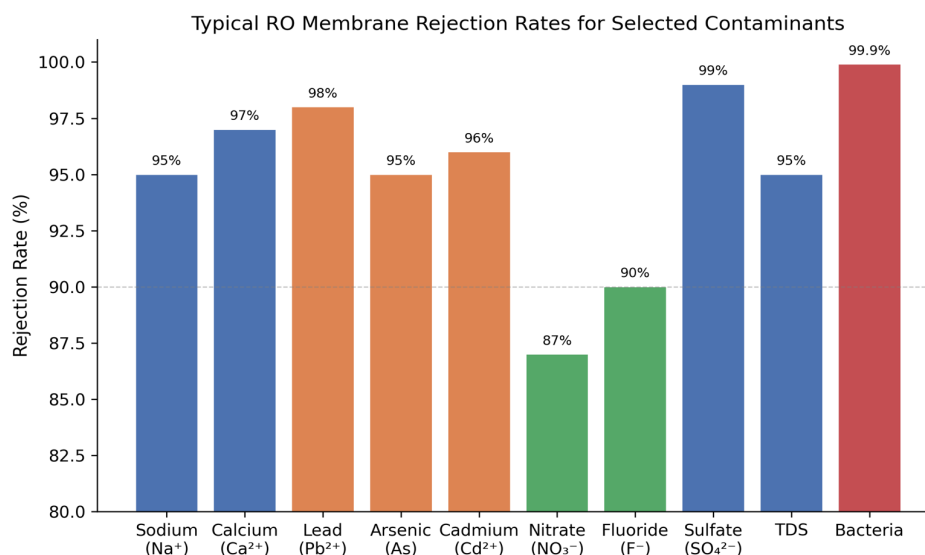


Figure 1: Typical RO membrane rejection rates for selected contaminants under standard operating conditions. Illustrative values within the ranges reported by [10, 12, 17] not extracted point-by-point from a single dataset

3. Removal Efficiency of Contaminants

3.1. Heavy Metals

The capacity of RO membranes to reject heavy metals is among the more compelling arguments for their use in household water treatment. Lead contamination in drinking water, whether originating from aging distribution pipes, soldered joints, or industrial sources, poses a severe neurotoxic risk, particularly to young children [18]. TFC polyamide membranes consistently demonstrate lead rejection rates of 95% to 99% across a range of feedwater conditions [10]. Arsenic presents a comparable case. As a major groundwater contaminant affecting tens of millions of people across Bangladesh, India, and parts of the Middle East, arsenic is rejected at rates exceeding 95% when present as arsenate (As(V)), although rejection of arsenite (As(III)) is somewhat lower and benefits from pre-oxidation [14, 19].

Cadmium and chromium, both associated with industrial discharge and both well-documented toxicants, are likewise efficiently removed by RO: cadmium rejection typically exceeds 96%, and hexavalent chromium rejection ranges from 90% to 97% depending on pH and membrane age [11, 12]. Mercury, though less frequently examined in the context of household RO, has been shown to achieve rejection rates above 95% under laboratory conditions [12]. These figures should not be regarded as fixed, however. Rejection efficiency for any given metal depends on its speciation in solution, feedwater ionic strength, pH, and membrane age and condition, and rejection rates decline as membranes degrade, underscoring the importance of timely replacement.

3.2. Nitrates and Fluoride

Nitrate contamination of groundwater is a widespread problem, driven primarily by agricultural runoff and the overuse of nitrogen-based fertilizers. Elevated nitrate levels in drinking water are associated with methemoglobinemia (blue baby syndrome) in infants and may increase cancer risk in adults through the formation of N-nitroso compounds [20]. RO membranes reject nitrate at rates typically between 85% and 93%, notably lower than rejection rates for divalent anions such as sulfate, which exceed 99% [21]. This comparatively lower

rejection is attributable to the monovalent nature and relatively small hydrated radius of the nitrate ion, which allows a portion to diffuse through the polyamide barrier layer.

Fluoride removal represents another important application. While fluoride at low concentrations, approximately 1 mg/L, is beneficial for dental health, concentrations above the WHO guideline value of 1.5 mg/L are associated with dental and skeletal fluorosis, a condition affecting millions of people in endemic regions across Africa, the Middle East, and South Asia [22]. RO membranes achieve fluoride rejection in the range of 88% to 95%, with performance influenced by pH, given that rejection improves at higher pH where fluoride exists predominantly as the charged F^- ion rather than as undissociated HF, and by the concentration of competing anions in the feedwater [23].

3.3. Microorganisms

The physical pore structure of TFC membranes, with effective pore diameters well below 1 nm in the active layer, provides an extremely effective barrier against bacteria, protozoa, and many viruses. Bacteria such as *Escherichia coli* and *Salmonella* are rejected at rates exceeding 99.9% by intact membranes, and protozoan cysts such as *Giardia* and *Cryptosporidium*, being considerably larger, are essentially excluded entirely [17]. The practical microbiological safety of household RO water, however, depends critically on system integrity and post-membrane conditions. Several studies have recovered heterotrophic bacteria and, in some instances, coliforms from the storage tanks and dispensing faucets of household RO systems, indicating that microbial re-growth in post-membrane components can negate the pathogen removal achieved by the membrane itself [9, 24].

3.4. Pharmaceuticals and Emerging Contaminants

The presence of pharmaceutical residues, endocrine-disrupting compounds, and personal care products in drinking water sources has become an increasing concern over the past two decades. RO membranes are generally effective at rejecting such compounds, although the degree of rejection varies considerably with molecular weight, charge, and hydrophobicity. Kimura et al. [25] and Yoon et al. [26] demonstrated that TFC membranes achieved rejection rates above 90% for most pharmaceuticals with molecular weights exceeding 200 Da, including carbamazepine, diclofenac, and sulfamethoxazole. Smaller, uncharged, and hydrophilic compounds, such as N-nitrosodimethylamine (NDMA), are less effectively removed, with rejection rates sometimes falling below 50% [27]. This variability underscores the importance of characterizing the specific contaminant profile of the feedwater when assessing the adequacy of household RO treatment. Table 1 summarizes reported rejection rates across the contaminant categories discussed above, together with the principal factors influencing performance.

Table 1: Summary of Reported RO Membrane Rejection Rates for Selected Contaminants

Contaminant	Category	Rejection (%)	Key Factor	Reference
Lead (Pb^{2+})	Heavy metal	95–99	pH, membrane age	Greenlee et al., [10]
Arsenic ($As(V)$)	Metalloid	95–98	Speciation, pH	Sato et al., [19]
Cadmium (Cd^{2+})	Heavy metal	96–99	Ionic strength	Baker, [11]
Nitrate (NO_3^-)	Inorganic anion	85–93	Monovalent, small size	Schoeman & Steyn, [21]
Fluoride (F^-)	Inorganic anion	88–95	pH, competing anions	Hu & Dickson, [23]
Sulfate (SO_4^{2-})	Inorganic anion	>99	Divalent, large radius	Fritzmann et al., [3]
<i>E. coli</i>	Bacteria	>99.9	Membrane integrity	WHO, [17]
Carbamazepine	Pharmaceutical	>90	MW >200 Da	Kimura et al., [25]

4. Water Quality Parameters After RO Treatment

4.1. Total Dissolved Solids and Conductivity

One of the more pronounced effects of RO treatment is the reduction in total dissolved solids (TDS). Municipal water supplies typically contain between 200 and 800 mg/L TDS, whereas groundwater in arid regions, including much of Iraq, the Arabian Peninsula, and North Africa, may range from 500 to over 3,000 mg/L [5, 28]. Household RO units routinely reduce TDS to between 10 and 80 mg/L, corresponding to removal rates of 90% to 99% depending on feedwater composition and membrane condition [14] electrical conductivity, being closely correlated with TDS, declines proportionally.

The WHO does not establish a formal health-based guideline value for TDS but suggests that water with TDS below 1,000 mg/L is generally acceptable to consumers, and that water above 300 mg/L may begin to taste flat or “heavy” [29]. At the other extreme, very low TDS water, below 50 mg/L, is sometimes described as tasting “empty” or unpalatable, and its limited buffering capacity renders it susceptible to rapid pH changes upon contact with air or piping materials [6]. This dual concern, elevated TDS in the feedwater and excessively low TDS in the permeate, characterizes household RO operation in many settings. Figure 2 illustrates the TDS reduction achieved by household RO treatment relative to representative feedwater levels.

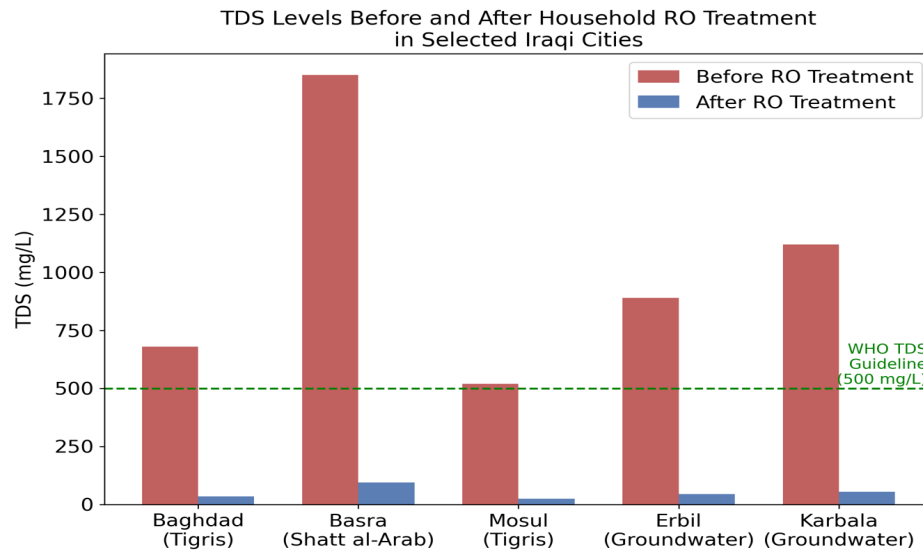


Figure 2: TDS levels before and after household RO treatment, illustrated for a hypothetical set of Iraqi cities. Schematic values within the general TDS-removal ranges reported in the international RO literature (see Section 4.1); no verified multi-city Iraqi household dataset was identified in this review, and this figure should not be read as reporting such a dataset

4.2. pH Reduction

RO membranes preferentially reject bicarbonate ions, the principal buffering species in most natural waters, such that the permeate exhibits substantially lower alkalinity and, consequently, lower pH. Studies have consistently reported RO permeate pH in the range of 5.0 to 6.5, even where feedwater pH falls within the normal range of 7.0 to 8.5 [14] this decline occurs because the removal of bicarbonate shifts the carbonate equilibrium, allowing dissolved CO_2 to drive pH downward. Acidic water is chemically aggressive and can leach metals from downstream plumbing and storage components, potentially reintroducing contaminants such as copper and lead into treated water [30]. The WHO's Guidelines for Drinking-Water Quality note that pH generally has no direct impact on consumers and, unlike contaminants with established health-based guideline values, is not itself assigned one; a pH of 6.5 to 8.5 instead functions as a widely used operational and aesthetic reference range, echoed in many national standards, reflecting concerns regarding corrosivity, taste, and treatment-process efficacy rather than a directly health-based limit. Unremineralized RO permeate frequently falls below this reference range. Figure 3 depicts the corresponding shift in pH between feed water and RO permeate across different source-water types.

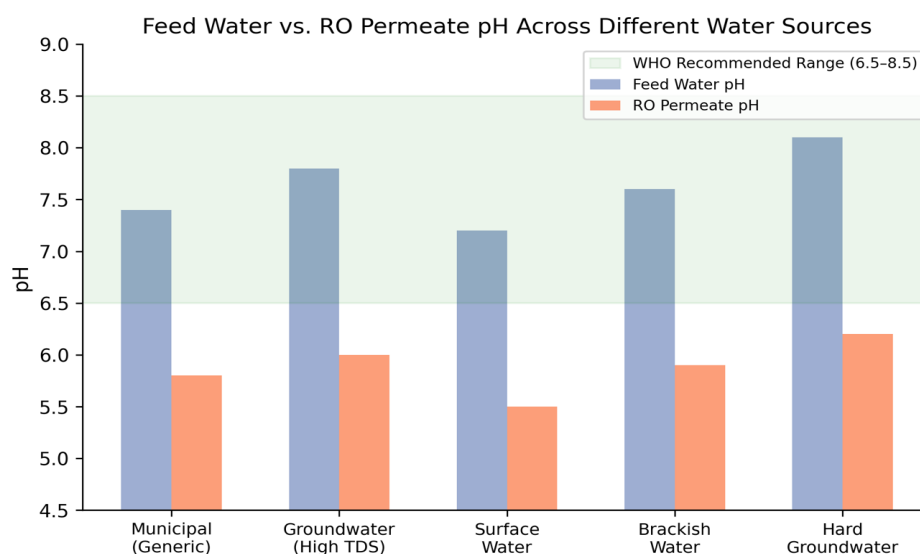


Figure 3: Feed water versus RO permeate pH across different water source types. Illustrative values within the ranges reported by [14] not extracted point-by-point from a single dataset

4.3. Essential Mineral Depletion

Perhaps the most debated consequence of household RO treatment is the removal of essential minerals from drinking water. Calcium, magnesium, potassium, sodium, and trace elements such as zinc and copper are all reduced by 90% to 99% during RO treatment [6]. Although the primary dietary source of these minerals is food rather than water, the contribution of drinking water to overall mineral intake is

not negligible, particularly for calcium and magnesium, where water may supply 5% to 20% of daily requirements depending on the mineral content of the source water [7].

A landmark WHO report from 2005, based on a meeting of experts convened in Rome, concluded that long-term consumption of water with very low mineral content could be associated with increased risks of cardiovascular disease, motor neuronal disease, and pre-eclampsia, although the report acknowledged that the epidemiological evidence was not uniform [7]. Subsequent studies have yielded mixed results. [31], in a systematic review and meta-analysis, reported a statistically significant inverse association between magnesium levels in drinking water and cardiovascular mortality, with a pooled risk estimate suggesting a reduction of approximately 25% in cardiovascular mortality among populations consuming high-magnesium water relative to low-magnesium water; others, by contrast, have argued that confounding variables in ecological studies render causal inference difficult [32]. What remains undisputed is that RO permeate is dramatically depleted of the minerals present in the source water, and that populations relying exclusively on RO water whose diets are otherwise marginal in calcium and magnesium intake may face elevated nutritional risk. Figure 4 compares feed water and permeate concentrations for the principal minerals discussed above, plotted on a logarithmic scale to accommodate their wide concentration range; Table 2 summarizes typical water quality parameters before and after RO treatment alongside the corresponding WHO guideline values.

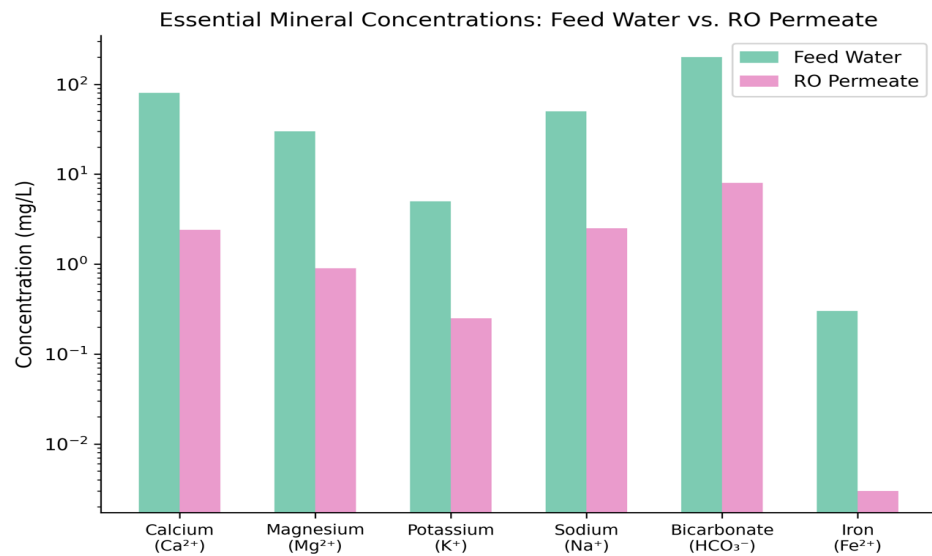


Figure 4: Essential mineral concentrations in feed water versus RO permeate. Note the logarithmic scale. Illustrative values within the ranges reported by [6] and [7] not extracted point-by-point from a single dataset

Table 2: Typical Water Quality Parameters Before and After Household RO Treatment

Parameter	Unit	Feed Water	RO Permeate	WHO Guideline
TDS	mg/L	300–1800	10–80	<1000
pH	N/A	7.0–8.5	5.0–6.5	6.5–8.5
Calcium	mg/L	40–120	1–5	No formal limit
Magnesium	mg/L	10–50	0.3–2	No formal limit
Hardness	mg/L as CaCO ₃	150–500	5–25	No formal limit
Alkalinity	mg/L as CaCO ₃	100–300	5–20	N/A
Sodium	mg/L	20–200	1–10	<200

5. Public Health Benefits and Documented Outcomes

The public health rationale for household RO adoption rests on two pillars: the reduction of chemical contaminants below health-based guideline values, and the prevention of waterborne infectious disease. Substantial evidence supports both, although the strength of that evidence differs considerably between them.

With respect to chemical contaminant reduction, the evidence is strong. In regions where arsenic, fluoride, or heavy metal contamination of groundwater exceeds safe levels, household-level RO treatment can bring these parameters well below WHO and national standards, and the case of arsenic is particularly well documented. In Bangladesh and West Bengal, where groundwater arsenic concentrations frequently exceed 50 micrograms per liter, five times the WHO guideline, household RO and nanofiltration units have been shown to reduce arsenic to below 10 micrograms per liter in treated water [19]. The public health benefit of this reduction is direct and measurable: chronic arsenic exposure at concentrations above 50 micrograms per liter is associated with markedly elevated risks of skin lesions, bladder and lung cancers, and cardiovascular disease [33].

The case of lead offers a further illustration. The Flint, Michigan water crisis in the United States provided a stark reminder of how rapidly drinking water contamination can produce population-level harm. Although the Flint crisis reflected a failure of centralized corrosion control, point-of-use RO filters were among the interventions recommended and distributed to affected households [18]. The effectiveness of these units in reducing blood lead levels among children in Flint has been documented, although the data are complicated by the simultaneous implementation of other interventions, including water source switching and pipe replacement.

The evidence regarding waterborne disease reduction through household RO is somewhat more complex. [34], in a systematic review of household water treatment interventions including filtration, chlorination, solar disinfection, and boiling, concluded that POU interventions collectively reduce the risk of diarrheal disease by approximately 30% to 40%; relatively few studies, however, have isolated RO specifically from other filtration methods within this pooled estimate. The high microbiological rejection rate of intact RO membranes is well established, but the practical bacterial safety of household systems, as noted, depends on post-membrane conditions. Payment et al. [24], in a study of 300 household RO units, found heterotrophic plate counts on R2A medium ranging from 0 to 10^7 CFU/mL, with most reservoirs falling between 10^4 and 10^5 CFU/mL, and identified a correlation between bacterial counts in the storage reservoir and reported gastrointestinal symptoms among the families using these units, suggesting that post-membrane contamination constitutes a widespread practical problem.

In the Gulf Cooperation Council (GCC) countries, where desalinated seawater constitutes the primary municipal supply in many areas, household RO units serve a somewhat different function, providing an additional treatment step for water that has already been desalinated at the municipal level but may accumulate contaminants, including disinfection by-products and trace metals from distribution pipelines, during transmission to the consumer. Consistent with this role, a laboratory-scale study of a household-format reverse osmosis unit by [35] found that RO membranes removed 82% to 84% of trihalomethanes and reduced total dissolved solids by roughly 61%, indicating that RO can be highly effective at removing chlorination by-products from feedwater; this finding, however, was obtained outside the Gulf region, and a dedicated study of household RO performance on GCC desalinated municipal supply was not identified in this review. Related findings on RO-treated water quality have been reported from Kuwait [36].

6. Public Health Risks and Concerns

6.1. Mineral Deficiency and Nutritional Gaps

As outlined in Section 4.3, the near-complete removal of essential minerals from drinking water is a feature of RO treatment that many health scientists regard with concern rather than as an incidental byproduct. The 2005 WHO report on the health risks of demineralized water remains the most frequently cited source on this topic, suggesting minimum levels of approximately 20 to 30 mg/L calcium and 10 mg/L magnesium as protective against cardiovascular and other health risks [7]. RO permeate, absent post-treatment remineralization, almost never meets these thresholds. Epidemiological studies examining the relationship between water mineral content and cardiovascular health have produced results that, while not conclusive, lean consistently toward an association. Kousa et al. [37], in a Finnish study, found an inverse relationship between magnesium concentration in drinking water and acute myocardial infarction among men. Catling et al. [31], in a systematic review and meta-analysis, similarly reported an inverse association between magnesium in water and cardiovascular mortality, with a pooled risk estimate suggesting a reduction of approximately 25% in cardiovascular mortality among populations consuming high-magnesium relative to low-magnesium water. Rubenowitz et al. [38] reported comparable protective effects of magnesium-rich water in Sweden. These epidemiological findings, however, warrant cautious interpretation: most are ecological studies that cannot fully account for dietary, socioeconomic, and lifestyle confounders.

Diets in Iraq and much of the wider Arab region may already run short of certain micronutrients, raising the question of whether the further removal of minerals from drinking water compounds this shortfall. This question has not, to date, been directly examined in the region: a search of the indexed literature identified no Iraqi or regional study tracking mineral status, whether through urinary magnesium excretion or dietary intake surveys, among populations relying primarily on RO water relative to those consuming municipal tap water. The underlying concern rests on solid ground, as the international literature on mineral depletion discussed above supports it; what is absent is the regional human data required to confirm or rule it out, and Section 10 lists targeted cross-sectional or cohort studies among the priorities this gap identifies.

6.2. Remineralization: The Missing Step

Given these concerns regarding mineral depletion, remineralization of RO permeate constitutes a logical post-treatment step, and several commercial approaches are available. Calcite contactors, in which water flows through a bed of calcium carbonate, represent the simplest and most common method, raising calcium levels to 40 to 80 mg/L and pH to 7.0 to 8.0 depending on contact time and bed dimensions [39]. Blending a small proportion of feedwater back into the permeate constitutes an alternative approach, although this reintroduces a fraction of the contaminants previously removed. More sophisticated systems combine calcite with magnesium-rich media, such as dolomite or corosex, to restore both calcium and magnesium [40].

Despite the availability of these technologies, most household RO units sold across the Middle East and South Asia continue to ship without a remineralization stage as standard; only a limited number of manufacturers offer it as an optional feature. The extent of consumer awareness of the mineral-depletion issue remains a further open question. Awareness is widely presumed to be low, although no quantitative regional survey capable of establishing a specific figure was identified in this review. The gap between what the technology is capable of and what actually reaches households is treated here as a plausible but unquantified blind spot in the household RO market, and a regional consumer-awareness survey is carried forward as a priority in Section 10.

6.3. Microbial Re-Contamination

RO membranes themselves constitute highly effective barriers against microorganisms, but the household system built around them does not necessarily share this property. The pressurized storage tank, dispensing faucet, and connecting tubing all provide surfaces and stagnant water in which bacteria can proliferate, a mechanism documented for household water storage generally [9] warm climates exacerbate this tendency, as higher temperatures accelerate biofilm formation.

Payment [9] and Payment et al. [24] sampled the storage reservoirs of 300 household RO units and found bacterial counts that, in many cases, substantially exceeded those in the incoming feedwater, a counterintuitive result that underscores the importance of post-membrane hygiene. The organisms most commonly isolated, *Pseudomonas* (non-aeruginosa), *Alcaligenes*, *Moraxella*, *Acinetobacter*, *Flavobacterium*, and *Chromobacterium* species, are not necessarily pathogenic in themselves but indicate conditions favorable to opportunistic pathogens.

Whether a comparable pattern occurs in Baghdad or other Iraqi cities remains unknown, as no published study has examined the question. The underlying mechanism, biofilm formation in storage tanks, is well established internationally [9, 24], which is precisely why Iraq-specific field monitoring belongs on the research agenda set out in Section 10. Documented instances of microbial contamination in household RO systems, drawn from the studies discussed above, are summarized in Table 3.

Table 3: Documented Microbial Contamination Issues in Household RO Systems

Location	Finding	Organism(s)	Reference
Laval, Quebec, Canada	300 units sampled; HPC typically 10^4 - 10^5 CFU/mL in storage reservoirs (range 0 - 10^7)	<i>Pseudomonas</i> (non-aeruginosa), <i>Alcaligenes/Moraxella</i> , <i>Acinetobacter</i> , <i>Flavobacterium</i> , <i>Chromobacterium</i>	Payment [9]; Payment et al., [24]
Various (review)	Biofilm formation in tanks and tubing; bacterial counts often exceeded incoming feedwater counts	Mixed heterotrophic communities	Payment, [9]; Payment et al., [24]

6.4. Brine Disposal and Water Waste

The brine generated by household RO systems represents both an environmental and an economic concern. In a typical household unit operating at 25% recovery, four liters of water are consumed for every liter of purified water produced, with three of those liters discharged as concentrate carrying rejected salts and contaminants at elevated concentrations [8]. This water loss is a serious issue in water-scarce regions, which include much of the Middle East, North Africa, and parts of South Asia: a household consuming 10 liters of RO water per day may discharge 30 liters of brine daily, typically directly into the municipal sewer system.

Voutchkov [41] reviewed the environmental impacts of brine discharge from both industrial and household RO operations, noting that the increased salinity of the reject stream can stress aquatic ecosystems where discharged without adequate dilution. In the context of household systems, the cumulative brine load from millions of individual units represents a non-trivial contribution to municipal wastewater salinity, which can in turn affect the performance of wastewater treatment plants and the quality of treated effluent used for irrigation [42]. To date, no jurisdiction has implemented regulations specifically targeting household RO brine discharge, although the issue has received increasing attention in the academic literature. Figure 5 illustrates how brine TDS increases with recovery ratio for both low- and high-TDS feedwater.

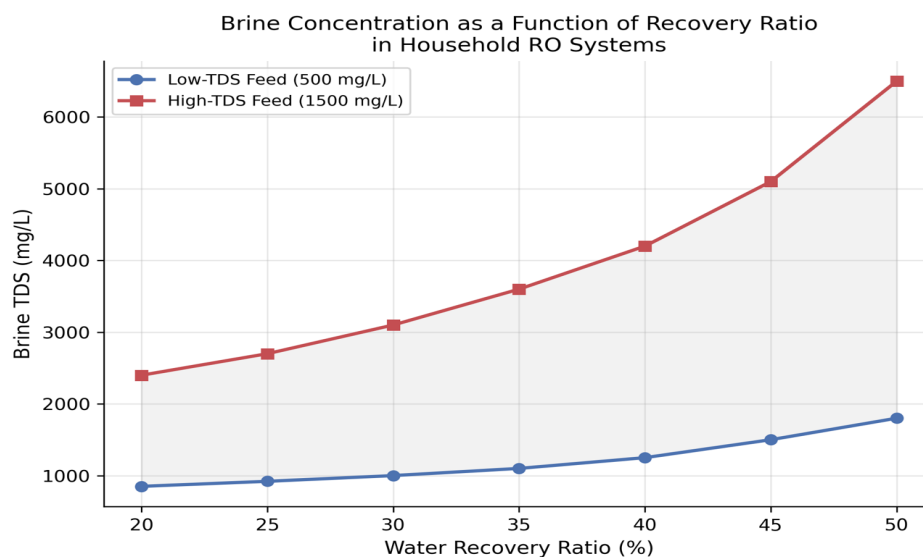


Figure 5: Brine TDS concentration as a function of water recovery ratio for household RO systems operating on low- and high-TDS feedwater. Illustrative values consistent with the relationships described by [41] and [8] not extracted point-by-point from a single dataset

7. Performance of Household RO Systems in Arab and Iraqi Contexts

The Middle East and North Africa (MENA) region faces some of the world's most acute water scarcity challenges, and household RO systems have become a critical component of domestic water management in many countries within it. Iraq presents a particularly complex case at the intersection of water quality, infrastructure, and consumer behavior.

Iraq's freshwater resources are dominated by the Tigris and Euphrates river systems, both of which have experienced declining flows and increasing salinity as a result of upstream damming in Turkey and Syria and reduced precipitation associated with climate change [5]. The Shatt al-Arab waterway in southern Iraq, which serves as the primary water source for Basra, has experienced a marked increase in salinity, with TDS levels at times exceeding 3,000 mg/L, well above potability thresholds [28] household RO adoption in Basra has consequently become nearly ubiquitous among households able to afford the initial investment. One genuine Iraqi data point exists in this context: Al-Obaidi et al. [43] evaluated RO membranes treating spent cooling water from a power station in Iraq and found that rejection performance was sensitive to pre-filtration quality and maintenance history. As an industrial rather than a household setting, this finding does

not speak directly to conditions in domestic contexts, but it does support the general principle that maintenance affects RO performance. A published multi-city household RO field study covering Baghdad, Basra, Mosul, and Erbil, by contrast, does not appear to exist; this absence is carried forward as one of the gaps consolidated in Section 10.

Other Arab countries facing similar groundwater conditions likely face comparable challenges, although the strength of the evidence base varies considerably. Jordan illustrates the point: over 90% of the population depends on groundwater that is often brackish, yet a household-level survey of RO user awareness and satisfaction, of the kind referenced earlier in Section 6.2, could not be independently verified here and should be read as a gap rather than a confirmed finding. Egypt offers firmer ground. Abdel-Shafy and Mansour [44] studied RO system performance in rural communities relying on groundwater contaminated with iron and manganese; they documented effective removal of both parameters but found that inadequate maintenance caused performance to deteriorate within 12 to 18 months of installation. Saudi Arabia represents a distinct case. In most major cities there, the municipal supply already consists of desalinated seawater with naturally low mineral content, such that passing this water through a household RO unit strips it further still. On general chemical principles, a compounding reduction in dissolved calcium and magnesium in the permeate appears likely, although no published study measuring this double-demineralization effect in Saudi Arabia or the other GCC countries was identified in this review. Absent such measurement, this remains a biologically plausible concern rather than a documented one, and it joins the research priorities set out in Section 10.

A recurring theme within the Arab-region literature concerns the gap between what RO systems can technically achieve and how effectively their owners maintain them, a pattern well documented internationally [9, 24]. No published household-level maintenance survey specific to Baghdad or other Iraqi cities, however, confirms that this pattern holds locally. Cost and lack of awareness are the barriers most commonly cited in the broader point-of-use literature and constitute reasonable hypotheses for Iraq as well, but no dedicated regional survey covering filter and membrane replacement behavior, its drivers, and its consequences for water quality appears to have been conducted to test them. Section 10 lists this among its recommended priorities. The regional studies discussed above are summarized in Table 4.

Table 4: summarizes the regional studies discussed in this section

Country	Study	Key Finding	Sample Size	Year
Iraq	Shubbar et al. [28]	Basra water salinity exceeding 3,000 mg/L TDS in the Shatt al-Arab waterway	Water-quality survey	2017
Iraq	Al-Obaidi et al. [43]	RO membrane rejection sensitive to pre-filtration quality and maintenance history (industrial cooling-water application)	Case study, Iraqi power station	2018
Egypt	Abdel-Shafy & Mansour [44]	Effective iron/manganese removal in rural groundwater; performance declined within 12-18 months without maintenance	Rural communities	2013

Additional claims about RO adoption, awareness, and maintenance behavior in Iraq and Jordan could not be corroborated and are discussed as evidence gaps in Sections 7 and 10.

8. Economic, Environmental, and Sustainability Considerations

The economics of household RO systems involve both capital and recurring costs that vary substantially by geography. Initial purchase prices for a standard under-sink five- or six-stage RO unit vary considerably by country, from approximately \$80 to \$100 in India and Egypt to \$200 to \$250 in the United States and the European Union average, with intermediate prices reported for Saudi Arabia, Jordan, and Iraq, reflecting differences in manufacturing costs, import duties, and market positioning [4]. Annual maintenance costs, driven primarily by filter and membrane replacement, typically amount to \$40 to \$100 per year, although many users defer these expenses by extending replacement intervals beyond manufacturer recommendations. Figure 6 compares initial purchase and annual maintenance costs for household RO systems across selected countries.

When evaluated against alternative household water treatment options, RO systems occupy a middle ground in terms of cost-effectiveness. Simple chlorination is considerably cheaper but does not remove dissolved chemical contaminants. Activated carbon filters are effective against chlorine, certain organic chemicals, and taste or odor issues but offer limited rejection of dissolved salts and inorganic contaminants. Boiling is effective against pathogens but consumes energy and does not address chemical contamination. RO provides the broadest spectrum of contaminant removal among commonly available household technologies, which justifies its higher cost for consumers facing complex water quality challenges [45]. From an environmental perspective, the primary concerns relate to water waste, discussed in Section 6.4, and the disposal of spent filter cartridges and membranes. A typical household RO system generates four to six spent filter cartridges per year and one membrane every two to three years; these are generally disposed of as solid waste, contributing a modest but non-trivial volume of plastic and activated carbon to landfills. Life-cycle assessment studies comparing household RO with bottled water consumption have generally found that RO carries a smaller environmental footprint per liter of water consumed, primarily because bottled water production involves additional plastic packaging, transportation, and energy-intensive manufacturing processes [46]. Table 5 summarizes this comparison across the main household water treatment technologies discussed above.

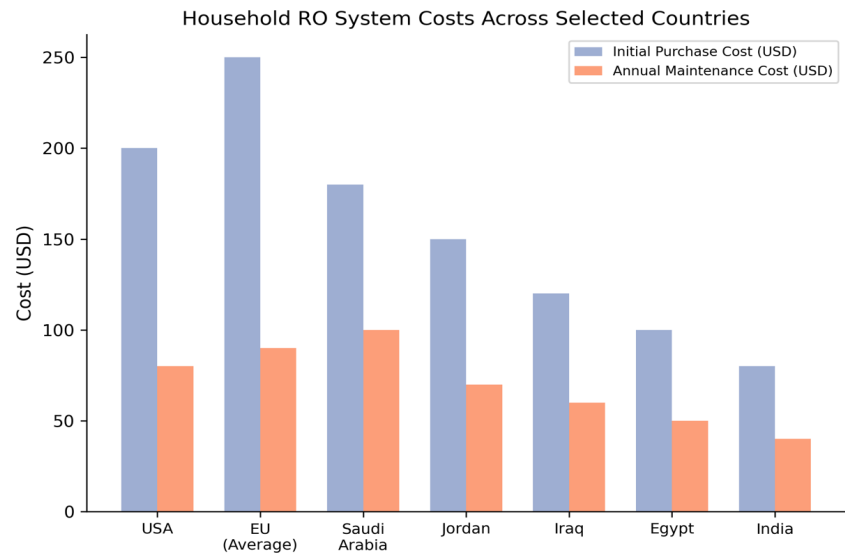


Figure 6: Household RO system costs (initial purchase and annual maintenance) across selected countries. Illustrative values consistent with the cost ranges reported by [4] and general market reporting; country-level figures are approximate and not drawn from a single verified survey dataset

Sustainability considerations also extend to energy consumption. Household RO systems are typically connected to the municipal water supply and rely on line pressure, supplemented in some cases by a small booster pump, to drive the separation process. Energy consumption is modest for systems relying on line pressure alone, with essentially no additional electrical draw, and low for systems employing a small booster pump; manufacturer specifications and independent estimates generally place booster-pump electricity use at well under 0.01 kWh per liter of permeate for typical household units, although this review did not identify a peer-reviewed source reporting a precise, representative figure, and the value should accordingly be treated as an approximate, order-of-magnitude estimate rather than an established one. This modest household energy draw represents a small fraction of the energy required for large-scale desalination, which ranges from 3 to 5 kWh per cubic meter for state-of-the-art seawater RO plants [47]. The cumulative energy footprint of millions of household units nonetheless warrants consideration in national energy planning, particularly in countries such as Saudi Arabia and Kuwait, where household desalination adds to an already high per-capita energy consumption associated with large-scale desalination [48].

Table 5: Comparison of Household Water Treatment Technologies

Technology	Pathogen Removal	Chemical Removal	TDS Removal (USD)	Annual Cost	Water Waste
Reverse Osmosis	Very high	Very high	90–99%	\$40–100	High (50–80%)
Activated Carbon	Low	Moderate	Minimal	\$30–60	None
UV Disinfection	High	None	None	\$20–50	None
Chlorination	High	None	None	\$5–15	None
Boiling	Very high	None	Increases TDS	Variable (fuel)	Evaporation loss
Water Waste = 100% – Recovery Ratio (Section 2.2). At a typical household RO recovery of 20%–50% [4], this yields the 50%–80% range shown.					

9. Regulatory Frameworks and WHO Guidelines

The regulation of household water treatment devices varies considerably across jurisdictions, and the absence of a universally adopted performance standard for POU RO systems constitutes a notable gap in the global regulatory landscape. In the United States, the NSF/ANSI Standard 58 provides the most widely recognized testing and certification protocol for RO drinking water treatment systems, specifying minimum rejection requirements for TDS (75%) alongside performance benchmarks for specific contaminants, including arsenic, barium, cadmium, chromium, copper, fluoride, lead, nitrate, radium, and selenium [49]. Systems meeting NSF 58 carry certification marks that afford consumers a reasonable basis for confidence in their performance claims.

In Europe, no single EU-wide standard equivalent to NSF 58 exists for household RO devices. The EU Drinking Water Directive (Council Directive 98/83/EC, as amended) sets quality standards for water at the tap but does not regulate the performance of household treatment devices per se. Individual member states may maintain their own certification schemes, though compliance is generally voluntary. In the United Kingdom, the Water Regulations Advisory Scheme (WRAS) provides approvals for water fittings, including certain POU devices, but comprehensive performance testing comparable to NSF 58 is not mandated [50].

In the Arab region, regulatory frameworks for household RO devices remain even less developed. The Gulf Standardization Organization (GSO) has issued standards for bottled water and general drinking water quality, but specific performance standards for POU treatment devices are largely absent. Iraq’s national drinking water standard (IQS 417) sets quality parameters for treated water but does not mandate or regulate the performance of household treatment equipment. Jordan and Egypt have begun developing product standards for imported water treatment devices, although enforcement capacity remains limited. The WHO Guidelines for Drinking-Water Quality, currently in their 4th edition with addenda, provide the overarching framework within which most national standards are developed; the WHO does not endorse specific treatment technologies but instead sets health-based guideline values for individual contaminants and encourages the adoption of

Water Safety Plans as a comprehensive risk-management approach [29]. The Guidelines note that POU treatment can serve as an effective interim measure where centralized treatment is inadequate, while emphasizing that it should not be regarded as a substitute for improving the public water supply. The 2005 WHO publication on nutrients in drinking water specifically addressed the health risks of demineralized water and recommended that RO permeate intended for drinking should ideally be remineralized to restore minimum calcium and magnesium levels [7] this recommendation, however, has not been incorporated into binding regulatory requirements in any jurisdiction reviewed.

The absence of mandatory remineralization requirements constitutes a significant regulatory gap. In practice, consumers purchasing household RO units in Iraq, Jordan, Saudi Arabia, and most other countries in the region can and typically do consume water well below the WHO's recommended minimum mineral levels, with no regulatory mechanism requiring manufacturers to disclose this fact or to include remineralization as a standard feature.

10. Gaps in the Literature and Future Research Directions

Despite the extensive body of literature on RO membrane technology and its applications, several important gaps remain when the focus is narrowed to household-level systems and their public health implications. First, longitudinal epidemiological studies tracking health outcomes in populations consuming RO-treated water over extended periods are strikingly scarce. Most of what is known regarding the health effects of demineralized water derives from ecological studies comparing disease rates across regions with differing water hardness, a design inherently susceptible to confounding. Randomized controlled trials, while ethically and logistically challenging, would provide substantially stronger evidence concerning the nutritional and cardiovascular consequences of long-term RO water consumption.

Second, field-level data on the actual performance of household RO systems as operated by consumers, as distinct from laboratory data on membrane performance under controlled conditions, remain surprisingly sparse. Most published studies test a relatively small number of units within a limited geographic area. Large-scale surveys assessing membrane rejection rates, the microbiological quality of dispensed water, filter replacement compliance, and system age across hundreds or thousands of households would provide a considerably more representative picture of how these systems perform in practice. Figure 7 presents this trend schematically.

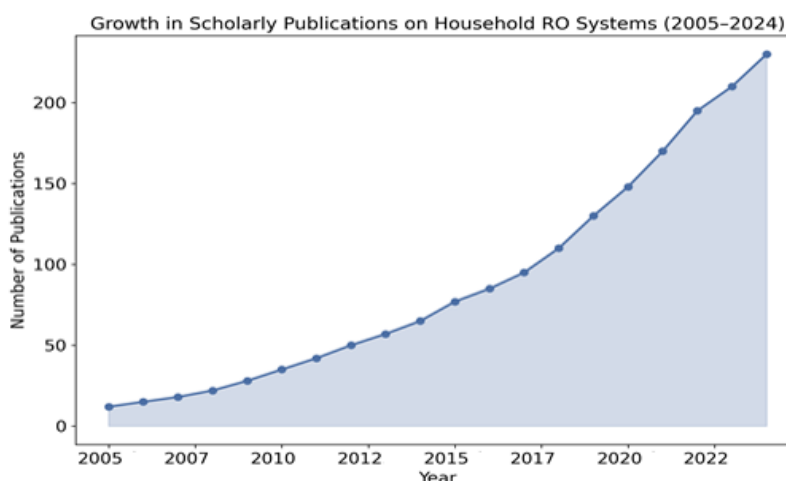


Figure 7: Illustrative trend consistent with the general growth in scholarly attention to household RO systems described qualitatively in this review's literature search (2005–2024); presented schematically, as no specific Scopus query and result count are reported here

Third, the environmental and hydrological implications of brine discharge from household RO systems at scale remain poorly characterized. Although the brine generated by an individual household unit is small in volume, the aggregate discharge from millions of units in a city such as Baghdad or Riyadh represents a measurable input of concentrated salt water into the municipal sewer system. Research is needed to quantify this cumulative effect and to evaluate strategies for household-level brine management, including its use for non-potable purposes such as toilet flushing or the irrigation of salt-tolerant plants.

Fourth, the development and evaluation of cost-effective remineralization technologies suitable for integration into household RO systems merits greater attention. While calcite contactors are well understood in general terms, their sizing and performance within a compact household unit, where water flow is intermittent and contact times variable, remain poorly characterized. Novel approaches, such as magnesium-containing ceramic media or the controlled blending of mineral concentrates, warrant systematic evaluation.

Fifth, research is needed on consumer behavior and awareness, particularly within the Arab region. Studies examining how users make decisions regarding filter replacement, how they perceive the quality of RO-treated water, and what information, if any, they receive from installers concerning maintenance requirements and nutritional implications would inform the design of public health messaging and could guide regulatory action.

Finally, the interaction between RO treatment and specific regional water quality challenges, such as the extremely high salinity encountered in Basra, elevated nitrate levels in the agricultural areas of the Nile Delta, or arsenic contamination in parts of the Arabian Peninsula, merits targeted investigation. Generic studies of RO performance may not adequately capture the specific challenges and opportunities presented by these regional contexts.

Taken together, the gaps identified throughout this review indicate four priorities currently unaddressed by published Iraqi data: household RO adoption rates at the city or national level; mineral-status outcomes, such as urinary or dietary magnesium and calcium, among populations relying on RO-treated water; consumer awareness of mineral depletion and remineralization uptake; and post-membrane microbial re-contamination in storage tanks and dispensing components. None of these priorities represents a substantial departure from established findings; each extends well-documented international results [6, 9, 24, 31] to a setting in which they have not yet been examined.

In the authors' assessment, addressing these four gaps through primary field research constitutes the single highest-value next step for this literature.

Limitations of This Review

This review carries its own methodological limitations, distinct from the gaps in the underlying field described above. It is a narrative review, not a systematic one: sources were identified through non-systematic keyword searching and citation chasing rather than a pre-registered protocol, a fixed date range, or independent dual screening, such that the reference set should be understood as illustrative of the evidence base rather than exhaustive of it (see Section 1.1). Several claims specific to Iraq and the wider Arab region could not be corroborated against a verifiable, indexed source; each such claim is explicitly framed here as an evidence gap rather than an established finding, and readers should treat the Iraq and Arab-region sections as identifying plausible, biologically and technically reasonable hypotheses grounded in the international literature, rather than as a confirmed regional evidence base. The illustrative figures presented in this paper Figures 1-7 warrant a similar caveat: they present schematic values consistent with the ranges reported in the cited literature rather than point-by-point extractions from a single dataset, as disclosed in each caption. As with any narrative synthesis, moreover, the selection and emphasis of sources reflects the authors' judgment and is not immune to selection bias; a systematic review or meta-analysis, where feasible, would provide a stronger evidentiary basis for the quantitative claims summarized here.

11. Conclusion

Household reverse osmosis systems have established themselves as among the most effective and broadly applicable point-of-use water treatment technologies available to consumers. Their capacity to reduce TDS, heavy metals, nitrates, fluoride, pathogens, and a range of trace organic contaminants from drinking water is supported by a substantial body of laboratory and field evidence. For households in settings where the municipal supply is unreliable, where groundwater salinity is high, or where specific chemical contaminants pose documented health risks, a well-maintained RO unit can provide a meaningful layer of protection.

This review has, however, also documented a pattern of unresolved concerns that tempers such enthusiasm. The systematic removal of essential minerals from drinking water produces permeate that is nutritionally impoverished and chemically aggressive, with potential long-term health consequences that remain insufficiently characterized by the existing epidemiological evidence. The practical reality of household RO operation, characterized in many settings by inconsistent maintenance, degraded membranes, and microbial re-contamination of storage components, means that the idealized performance observed under laboratory conditions is not always realized at the point of consumption. The environmental cost of brine discharge, while modest per unit, becomes significant when millions of systems are in operation. The regulatory landscape, particularly in the Arab region and Iraq, has not kept pace with the technology's adoption, leaving consumers without adequate guidance regarding either the capabilities or the limitations of the systems on which they rely.

The path forward requires action on multiple fronts. Manufacturers should be encouraged, or required, to incorporate remineralization stages as standard components rather than optional extras. National regulatory bodies, in Iraq and other countries where RO adoption is widespread, should develop and enforce performance standards for household RO devices, modeled on frameworks such as NSF 58 but adapted to local water quality conditions. Public health agencies should invest in consumer education that communicates both the benefits and the limitations of household RO, with specific guidance on maintenance schedules and the importance of balanced dietary mineral intake. The research community, finally, should prioritize longitudinal studies of health outcomes associated with RO water consumption, large-scale field assessments of system performance as actually practiced, and the development of cost-effective solutions for brine management and remineralization.

The evidence reviewed here does not support the conclusion that household RO systems are either unambiguously beneficial or unambiguously harmful. Rather, the picture that emerges is one of a technology with demonstrated strengths and acknowledged weaknesses, deployed in settings where the trade-offs between contaminant removal and mineral depletion, between water purification and water waste, and between consumer protection and regulatory inaction play out in complex and context-dependent ways. A more mature and evidence-based approach to household RO, one that addresses the full spectrum of public health implications rather than focusing solely on contaminant removal, is both achievable and overdue.

Article Information

Data Availability: Data sharing is not applicable to this article as no new datasets were generated or analyzed during the current study. Data analyzed in this review were extracted from the published studies cited in the reference list.

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References

- [1] *Drinking-water: Key facts*. World Health Organization, 2019. URL <https://www.who.int/news-room/fact-sheets/detail/drinking-water>.

- [2] K. Onda, J. LoBuglio, and J. Bartram. Global access to safe water: Accounting for water quality and the resulting impact on MDG progress. *International Journal of Environmental Research and Public Health*, 9(3):880–894, 2012. URL <https://doi.org/10.3390/ijerph9030880>.
- [3] C. Fritzmann, J. Löwenberg, T. Wintgens, and T. Melin. State-of-the-art of reverse osmosis desalination. *Desalination*, 216(1-3):1–76, 2007. URL <https://doi.org/10.1016/j.desal.2006.12.009>.
- [4] A. Subramani and J. G. Jacangelo. Emerging desalination technologies for water treatment: A critical review. *Water Research*, 75: 164–187, 2015. URL <https://doi.org/10.1016/j.watres.2015.02.032>.
- [5] N. Al-Ansari, A. A. Ali, and S. Knutsson. Present conditions and future challenges of water resources problems in Iraq. *Journal of Water Resource and Protection*, 6(12):1066–1098, 2014. URL <https://doi.org/10.4236/jwarp.2014.612102>.
- [6] F. Kozisek. Health risks from drinking demineralised water. In *Nutrients in drinking water*, pages 148–163. World Health Organization, 2005.
- [7] *Nutrients in drinking water*. 2005. URL <https://www.who.int/publications/i/item/9241593989>.
- [8] A. Panagopoulos, K.-J. Haralambous, and M. Loizidou. Desalination brine disposal methods and treatment technologies—A review. *Science of the Total Environment*, 693:133545, 2019. URL <https://doi.org/10.1016/j.scitotenv.2019.07.351>.
- [9] P. Payment. Bacterial colonization of domestic reverse-osmosis water filtration units. *Canadian Journal of Microbiology*, 35(11): 1065–1067, 1989. URL <https://doi.org/10.1139/m89-178>.
- [10] L. F. Greenlee, D. F. Lawler, B. D. Freeman, B. Marrot, and P. Moulin. Reverse osmosis desalination: Water sources, technology, and today's challenges. *Water Research*, 43(9):2317–2348, 2009. URL <https://doi.org/10.1016/j.watres.2009.03.010>.
- [11] R. W. Baker. *Membrane technology and applications*. John Wiley Sons, 3rd edition, 2012.
- [12] J. Kucera. *Reverse osmosis: Design, processes, and applications for engineers*. Wiley-Scrivener, 2nd edition, 2015.
- [13] R. J. Petersen. Composite reverse osmosis and nanofiltration membranes. *Journal of Membrane Science*, 83(1):81–150, 1993. URL [https://doi.org/10.1016/0376-7388\(93\)80014-0](https://doi.org/10.1016/0376-7388(93)80014-0).
- [14] R. Y. Ning. Discussion of silica speciation, fouling, control and maximum reduction. *Desalination*, 151(1):67–73, 2002.
- [15] R. A. Al-Juboori and T. Yusaf. Biofouling in RO system: Mechanisms, monitoring and controlling. *Desalination*, 302:1–23, 2012. URL <https://doi.org/10.1016/j.desal.2012.06.016>.
- [16] A. Antony, J. H. Low, S. Gray, A. E. Childress, P. Le-Clech, and G. Leslie. Scale formation and control in high pressure membrane water treatment systems: A review. *Journal of Membrane Science*, 383(1-2):1–16, 2011. URL <https://doi.org/10.1016/j.memsci.2011.08.054>.
- [17] *Guidelines for drinking-water quality*. World Health Organization, 4th edition, 2011.
- [18] M. Hanna-Attisha, J. LaChance, R. C. Sadler, and A. Champney Schnepf. Elevated blood lead levels in children associated with the Flint drinking water crisis: A spatial analysis of risk and public health response. *American Journal of Public Health*, 106(2):283–290, 2016.
- [19] Y. Sato, M. Kang, T. Kamei, and Y. Magara. Performance of nanofiltration for arsenic removal. *Water Research*, 36(13):3371–3377, 2002.
- [20] M. H. Ward, T. M. deKok, P. Levallois, J. Brender, G. Gulis, B. T. Nolan, and J. VanDerslice. Workgroup report: Drinking-water nitrate and health—Recent findings and research needs. *Environmental Health Perspectives*, 113(11):1607–1614, 2005.
- [21] J. J. Schoeman and A. Steyn. Nitrate removal with reverse osmosis in a rural area in South Africa. *Desalination*, 155(1):15–26, 2003. URL [https://doi.org/10.1016/S0011-9164\(03\)00235-2](https://doi.org/10.1016/S0011-9164(03)00235-2).
- [22] M. Mohapatra, S. Anand, B. K. Mishra, D. E. Giles, and P. Singh. Review of fluoride removal from drinking water. *Journal of Environmental Management*, 91(1):67–77, 2009. URL <https://doi.org/10.1016/j.jenvman.2009.08.015>.
- [23] K. Hu and J. M. Dickson. Nanofiltration membrane performance on fluoride removal from water. *Journal of Membrane Science*, 279 (1-2):529–538, 2006. URL <https://doi.org/10.1016/j.memsci.2005.12.047>.
- [24] P. Payment, E. Franco, L. Richardson, and J. Siemiatycki. Gastrointestinal health effects associated with the consumption of drinking water produced by point-of-use domestic reverse-osmosis filtration units. *Applied and Environmental Microbiology*, 57(4):945–948, 1991. URL <https://doi.org/10.1128/aem.57.4.945-948.1991>.
- [25] K. Kimura, G. Amy, J. E. Drewes, T. Heberer, T.-U. Kim, and Y. Watanabe. Rejection of organic micropollutants (disinfection by-products, endocrine disrupting compounds, and pharmaceutically active compounds) by NF/RO membranes. *Journal of Membrane Science*, 227(1-2):113–121, 2003.
- [26] Y. Yoon, P. Westerhoff, S. A. Snyder, E. C. Wert, and J. Yoon. Removal of endocrine disrupting compounds and pharmaceuticals by nanofiltration and ultrafiltration membranes. *Desalination*, 202(1-3):16–23, 2006.

- [27] E. Steinle-Darling, M. Zedda, M. H. Plumlee, H. F. Ridgway, and M. Reinhard. Evaluating the impacts of membrane type, coating, feed water chemistry, and flux on the rejection of trace organic compounds by nanofiltration and reverse osmosis membranes. *Journal of Membrane Science*, 290(1-2):1–9, 2007.
- [28] R. M. Shubbar, D. Lee, and H. A. Gzar. Water quality deterioration of the Euphrates River and Shatt Al-Arab waterway, Iraq. *Civil Engineering Journal*, 3(9):793–808, 2017.
- [29] *Guidelines for drinking-water quality: Fourth edition incorporating the first addendum*. World Health Organization, 2017. ISBN: 978-92-4-154995-0.
- [30] M. R. Schock and D. A. Lytle. Internal corrosion and deposition control. In American Water Works Association, editor, *Water quality and treatment: A handbook on drinking water*, page 20. McGraw-Hill, 6th edition, 2011.
- [31] L. A. Catling, I. Abubakar, I. R. Lake, L. Swift, and P. R. Hunter. A systematic review of analytical observational studies investigating the association between cardiovascular disease and drinking water hardness. *Journal of Water and Health*, 6(4):433–442, 2008. URL <https://doi.org/10.2166/wh.2008.054>.
- [32] S. Monarca, F. Donato, I. Zerbini, R. L. Calderon, and G. F. Craun. Review of epidemiological studies on drinking water hardness and cardiovascular diseases. *European Journal of Cardiovascular Prevention Rehabilitation*, 13(4):495–506, 2006.
- [33] A. H. Smith, E. O. Lingas, and M. Rahman. Contamination of drinking-water by arsenic in Bangladesh: A public health emergency. *Bulletin of the World Health Organization*, 78(9):1093–1103, 2000.
- [34] T. Clasen, W.-P. Schmidt, T. Rabie, I. Roberts, and S. Cairncross. Interventions to improve water quality for preventing diarrhoea: Systematic review and meta-analysis. *British Medical Journal*, 334(7597):782, 2007. URL <https://doi.org/10.1136/bmj.39118.489931.BE>.
- [35] R. Rajamohan, V. P. Venugopalan, D. Mal, and U. Natesan. Efficiency of reverse osmosis in removal of total organic carbon and trihalomethane from drinking water. *Research Journal of Chemistry and Environment*, 18(12):1–6, 2014.
- [36] H. F. Al-Mudhaf, A. I. Abu-Shady, and M. I. Selim. Drinking water quality in Kuwait: Current status and future perspectives. *Desalination and Water Treatment*, 11(1-3):213–221, 2009.
- [37] A. Kousa, E. Moltchanova, M. Viik-Kajander, M. Rytönen, J. Tuomilehto, T. Tarvainen, and M. Karvonen. Geochemistry of ground water and the incidence of acute myocardial infarction in Finland. *Journal of Epidemiology and Community Health*, 58(2):136–139, 2004.
- [38] E. Rubenowitz, G. Axelsson, and R. Rylander. Magnesium and calcium in drinking water and death from acute myocardial infarction in women. *Epidemiology*, 10(1):31–36, 1999.
- [39] L. Birnhack, N. Voutchkov, and O. Lahav. Fundamental chemistry and engineering aspects of post-treatment processes for desalinated water—A review. *Desalination*, 273(1):6–22, 2011. URL <https://doi.org/10.1016/j.desal.2010.11.011>.
- [40] D. Hasson and O. Bendrihem. Modeling remineralization of desalinated water by limestone dissolution. *Desalination*, 190(1-3):189–200, 2006.
- [41] N. Voutchkov. Energy use for membrane seawater desalination—Current status and trends. *Desalination*, 431:2–14, 2018.
- [42] E. Jones, M. Qadir, M. T. H. van Vliet, V. Smakhtin, and S. Kang. The state of desalination and brine production: A global outlook. *Science of the Total Environment*, 657:1343–1356, 2019. URL <https://doi.org/10.1016/j.scitotenv.2018.12.076>.
- [43] M. A. Al-Obaidi, R. H. A. Zubo, F. L. Rashid, H. J. Dakkama, R. Abd-Alhameed, and I. M. Mujtaba. Evaluation of reverse osmosis membranes in the treatment of spent cooling water from power station: A case study in Iraq. *Journal of Cleaner Production*, 190:413–425, 2018.
- [44] H. I. Abdel-Shafy and M. S. M. Mansour. Overview on water reuse in Egypt: Present and future. *Sustainable Sanitation Practice*, 14:17–25, 2013.
- [45] M. D. Sobsey, C. E. Stauber, L. M. Casanova, J. M. Brown, and M. A. Elliott. Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environmental Science Technology*, 42(12):4261–4267, 2008.
- [46] M. Garfi, E. Cadena, D. Sanchez-Ramos, and I. Ferrer. Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. *Journal of Cleaner Production*, 137:997–1003, 2016.
- [47] M. Elimelech and W. A. Phillip. The future of seawater desalination: Energy, technology, and the environment. *Science*, 333(6043):712–717, 2011. URL <https://doi.org/10.1126/science.1200488>.
- [48] N. Ghaffour, T. M. Missimer, and G. L. Amy. Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination*, 309:197–207, 2013. URL <https://doi.org/10.1016/j.desal.2012.10.015>.
- [49] NSF International. NSF/ANSI 58: Reverse osmosis drinking water treatment systems. Technical report, 2022.
- [50] J. Fawell and M. J. Nieuwenhuijsen. Contaminants in drinking water. *British Medical Bulletin*, 68(1):199–208, 2003. URL <https://doi.org/10.1093/bmb/ldg027>.