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BACTERIOLOGICAL AND PHYSICO-CHEMICAL QUALITY OF DRINKING WATER FROM VARIOUS SOURCES: A REVIEW

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ABSTRACT

Access to microbiologically and chemically safe drinking water remains one of the most pressing public health challenges in low-resource and semi-arid settings. This review synthesises the bacteriological and physico-chemical evidence base on drinking water quality, drawing on the literature reviewed in an M.Sc. (Clinical Microbiology) thesis that examined 46 water sources — dams, wells, springs, rivers, boreholes, and tap water — in Wamba Division, Samburu District, Kenya, and evaluated household-level purification using alum, sodium hypochlorite, and aqueous extracts of Moringa oleifera, Boscia coriacea, and Maerua decumbens. The review covers the rationale for using coliform bacteria, thermotolerant coliforms, E. coli, faecal streptococci/enterococci, and heterotrophic plate counts (HPC) as indicators of faecal contamination; the physico-chemical determinants of water quality (pH, turbidity, alkalinity, salinity, conductivity, and organic/nutrient loading) and their interaction with disinfection efficacy; the principal drivers of contamination in shared human–livestock–wildlife water systems; and the comparative performance of solar disinfection, alum coagulation, chlorination, and plant-based natural coagulants. Particular attention is given to viable-but-non-culturable (VBNC) bacteria and antibiotic resistance as emerging concerns for water-quality monitoring. The evidence indicates that no single treatment method reliably achieves both adequate turbidity removal and bacterial inactivation, and that a multi-barrier approach — coagulation/flocculation followed by disinfection — offers the most robust protection. The review closes by considering the applicability of these findings, including low-cost plant-based coagulants such as Moringa

oleifera (Sehjan), to rural water-safety contexts in Punjab, India, and outlines priority directions for further research.

KEYWORDS: Drinking Water Quality; Faecal Coliforms; Heterotrophic Plate Count; Turbidity; Water Treatment; Moringa Oleifera; Natural Coagulants; Waterborne Pathogens; Antibiotic Resistance; Vbnc Bacteria

1. INTRODUCTION

Access to safe and clean drinking water is widely recognised as a fundamental human right and a core public health priority. Although the Millennium Development Goals targeted halving the proportion of people without access to safe drinking water by 2015, and progress has been substantial in urban centres, large populations in rural, arid, and semi-arid regions continue to depend on unprotected and frequently contaminated water sources for daily use. The assessment of health risk arising from naturally occurring microbes in drinking water remains a matter of continuing interest to microbiologists, public health practitioners, and water-supply regulators worldwide (Richards et al., 1992; Hunter, 1993), yet compared with the substantial literature on urban and peri-urban water quality in sub-Saharan Africa (Shier et al., 1966), the evidence base for sparsely populated arid and semi-arid regions — where water scarcity and health risk are often greatest — remains comparatively thin.

This review synthesises that evidence base, using as its anchor a comprehensive field- and laboratory-based investigation of bacteriological and physico-chemical water quality conducted across dams, wells, springs, rivers, boreholes, and tap-water sources in a semi-arid pastoral district, together with an evaluation of household-scale purification methods including chemical coagulants, chlorination, and locally available plant extracts. The purpose of the review is threefold: first, to consolidate what is known about the microbiological indicators and pathogens used to characterise drinking-water safety; second, to summarise the physico-chemical parameters that most strongly influence both contamination risk and the effectiveness of treatment; and third, to critically compare the treatment technologies available for household and community-level use, with particular attention to natural, low-cost coagulants as an alternative or complement to conventional chemical treatment. Throughout, the review draws out points of relevance to contexts with comparable water-safety challenges, including rural Punjab, India, where seasonal water scarcity, shared human–livestock water use, and limited treatment infrastructure present parallel challenges.

2. Microbiological Indicators of Drinking Water Quality

2.1 Coliforms, Thermotolerant Coliforms, and Escherichia coli

Coliform bacteria, thermotolerant (faecal) coliforms, and Escherichia coli have served as indicators of the bacteriological safety of drinking water for close to a century (Leclerc et al., 2001). Their continued use rests on three properties: consistent presence when faecal contamination has occurred, ease of detection and enumeration, and a demonstrated correlation with the likely presence of enteric pathogens. WHO drinking-water guidelines (WHO, 2004) are explicit that E. coli or thermotolerant coliforms should not be detectable in any 100 mL sample of drinking water, and that any positive result should trigger repeat testing, sanitary inspection of the source, and a hygiene audit of the distribution system.

Thermotolerant coliforms are now considered the scientifically preferable term over the older 'faecal coliforms', since not all members of the group are exclusively faecal in origin (WHO, 1993). They are physiologically adapted to the temperatures of the warm-blooded enteric tract (Clark, 1990) and include Klebsiella and Escherichia strains (Dufour, 1977), although E. coli remains the only member of the family Enterobacteriaceae that is almost always faecal in origin (Hardina and Fujioka, 1991). Important caveats limit their use as a perfect indicator: thermotolerant Klebsiella strains have been recovered from carbohydrate-rich environments with no faecal pollution (Niemi et al., 1997), other thermotolerant coliforms occur in pristine environments (Rivera et al., 1988) and can regrow within distribution systems (Lechevallier, 1990), and E. coli itself has occasionally been detected in environments without faecal input (Hazen and Toranzos, 1990) while showing comparatively poor survival in aquatic environments relative to some pathogens (Borrego et al., 1983).

2.2 Heterotrophic Plate Counts (HPC)

Heterotrophic bacteria, which derive most of their carbon and energy from organic compounds (Singleton and Sainsbury, 2001), dominate the bacterial populations of drinking-water systems. The Heterotrophic Plate Count (HPC) method — enumeration of colonies formed on nutrient media under standardised conditions (Australian Drinking Water Guidelines, 1996) — is not a direct test for pathogens, but it is a valuable general index of water quality, treatment performance, and regrowth within distribution systems (Geldreich, 1996). Effective treatment is generally associated with finished-water HPC values of 10 CFU/mL or below (Fox and Reasoner, 1999); values above this suggest inadequate treatment or downstream regrowth.

The HPC method nonetheless has recognised limitations. Standard media fail to recover

chemolithotrophic ammonia-oxidising bacteria that colonise chloraminated systems (Cunliffe, 1991); routine incubation times are too short to detect slow-growing heterotrophs (Australian Standard, 1995); and bacteria subjected to environmental or disinfection stress may enter a Viable-But-Non-Culturable (VBNC) state, remaining metabolically active while evading detection on culture media (McDougald et al., 1998). Chlorination itself can sub-lethally injure bacteria, temporarily rendering them non-culturable though still potentially infectious (McFeters et al., 1986); dilution of quorum-sensing signalling molecules during plating can further suppress growth initiation (Kaprelyants and Kell, 1996); and substrate-accelerated death — rapid cell death triggered when a previously limiting nutrient is suddenly supplied in culture medium — can further depress recovered counts (Barer and Harwood, 1999).

2.3 Faecal Streptococci and Enterococci

Faecal streptococci are well-established indicators of faecal pollution in natural waters, correlating with gastrointestinal illness risk associated with recreational water contact (Cabelli et al., 1982, 1983; Dufour, 1984; Kay et al., 1994) and showing environmental persistence patterns broadly similar to waterborne pathogens (Richardson et al., 1991). The group spans species of differing sanitary significance and survival characteristics (Gauci, 1991; Sinton and Donnison, 1994), and because the relative proportions of species differ between human and animal faeces (Rutkowski and Sjogren, 1987; Poucher et al., 1991), the group offers some capacity for source discrimination. Taxonomically the group comprises the genera Enterococcus and Streptococcus (Holt et al., 1993), with Enterococcus faecalis, E. faecium, and E. durans the dominant species in polluted waters (Volterra et al., 1986; Sinton and Donnison, 1994; Audicana et al., 1995); enterococci are increasingly favoured as the preferred indicator for recreational-water monitoring.

2.4 Pathogenic Bacteria: Salmonella and Shigella

Waterborne enteric pathogens are transmitted principally via the faecal-oral route, and drinking-water treatment aims to reduce, though it cannot entirely eliminate, this risk through a multi-barrier, source-to-tap approach. Salmonella spp., gram-negative facultative anaerobes of the family Enterobacteriaceae, cause both food-borne gastroenteritis (salmonellosis) and typhoid fever (via S. typhi and S. paratyphi A), and can survive for weeks in water and years in favourable soil conditions despite not multiplying substantially outside the host gut (Todar, 2005). Antibiotic resistance in Salmonella spp. — including resistance to ampicillin,

streptomycin, kanamycin, tetracycline, and sulfonamides, and increasingly to chloramphenicol in strains isolated in India, Thailand, and Vietnam — has grown substantially, driven by indiscriminate antibiotic use in both human medicine and livestock production.

Shigella spp. cause shigellosis and are especially prevalent where sanitation and hygiene are inadequate. Its infectious dose is remarkably low — as few as 10–200 organisms (DuPont et al., 1989) — allowing efficient transmission via minimally contaminated food or water. S. flexneri, S. dysenteriae, S. sonnei, and S. boydii have all been implicated in documented outbreaks (Alamanos et al., 2000; McCall et al., 2000), with S. flexneri and S. dysenteriae generally causing more severe disease. A defining feature of Shigella is exceptional acid tolerance, surviving at pH 2–2.5 (Gorden and Small, 1993) — markedly greater than Salmonella or E. coli — which assists its passage through the gastric acid barrier that enteric pathogens must survive for up to two hours before colonising the intestine (Giannella et al., 1972).

2.5 Risk-Based Assessment of Bacteriological Water Quality

WHO (2004) recommends that microbiological testing be complemented by sanitary inspection of water points, a practice designed not to replace laboratory testing but to identify risks to water quality and guide remedial action (Lloyd and Bartram, 1991). Quantitative risk assessment consistently indicates that the health risk from waterborne pathogens exceeds that from disinfection by-products such as trihalomethanes (Craun et al., 2001), reinforcing that microbiological safety should not be compromised in pursuit of minimising chemical by-products. Risk classification frameworks — ranging from Level A (0 faecal coliforms, safe) to Level E (>1000 faecal coliforms/100 mL, very high risk) — provide a practical, actionable basis for prioritising interventions, particularly in settings where formal sanitary inspection cannot be applied to every source (for example, ephemeral or seasonal sources used by nomadic or pastoral communities).

3. Physico-Chemical Determinants of Water Quality

Physico-chemical parameters provide essential context for interpreting bacteriological results and for designing appropriate treatment. The parameters most consistently linked to both contamination risk and disinfection performance are pH, turbidity, total organic carbon, alkalinity, salinity, conductivity, and nutrient (phosphorus/nitrogen) loading.

3.1 pH

WHO recommends a drinking-water pH range of 6.5–8.5; values outside this range compromise palatability, corrosivity, and — critically — disinfection efficacy. Free chlorine (hypochlorous acid) is most effective at lower pH; above pH 8 it shifts toward the far less potent hypochlorite ion, reducing disinfection performance, while very low pH can mobilise heavy metals from soil and rock into the water supply.

3.2 Turbidity and Total Organic Carbon

Turbidity — light scattering caused by suspended particulate matter (Ziegler, 2002; Sadar, 1996) — ranges from under 1.0 NTU in pristine groundwater to over 1000 NTU in heavily silted surface water. It matters for microbiological safety because bacteria preferentially colonise particle surfaces and floc interstices, where adsorbed nutrients provide locally concentrated substrate (Brock, 1966; Stotzky, 1966). Turbidity above 1.0 NTU is associated with markedly increased chlorine demand, since chlorine is consumed by organic particulate matter rather than by target organisms; WHO accordingly recommends additional treatment before chlorination whenever turbidity exceeds this threshold. Total organic carbon (TOC), a non-specific index of dissolved organic matter, is linked to elevated trihalomethane (THM) formation on chlorination (Rook, 1977), can signal treatment failure when abnormally elevated, and correlates with assimilable organic carbon (AOC), which stimulates bacterial regrowth and biofilm formation in distribution systems.

3.3 Alkalinity, Salinity, and Conductivity

Total alkalinity, salinity, and electrical conductivity together characterise the mineral and ionic loading of a water source. Conductivity changes track shifts in mineral composition attributable to seasonal variation, sewage or industrial/agricultural pollution, or saline intrusion; boreholes typically show elevated conductivity from prolonged rock-water contact, while surface and shallow groundwater sources show wider variability reflecting more heterogeneous inputs. Very high conductivity has separately been linked, in livestock contexts, with reduced water palatability and intake (Weeth and Haverland, 1961; Wilson, 1966; Potter and McIntosh, 1974).

3.4 Organic and Nutrient Pollution

Organic loading — from sewage, agricultural runoff, or livestock waste — elevates turbidity, dissolved organic matter, nutrient concentrations, and bacterial load in receiving waters

(Bitton and Gerba, 1984). Livestock contribute disproportionately: a single cow can excrete phosphorus and nitrogen loads equivalent to those from many hectares of forest or cropland (Brian, 1980), so even modest livestock concentrations near a water source can cause substantial nutrient overloading. Phosphorus enrichment, even at concentrations as low as 20 µg/L, has been linked to increased bacterial culturability and, in some cases, measurable population growth (Miettinen et al., 1997; Sathasivan and Ohgaki, 1999; Sathasivan et al., 1997; Lehtola et al., 2002; Geldreich, 1996; LeChevallier, 1990; LeChevallier et al., 1991) — although where carbon rather than phosphorus is the limiting nutrient, phosphate addition alone does not stimulate growth (Lyons et al., 1995; Cohen et al., 1999). Nitrate-nitrogen from livestock wastewater is a particular concern in groundwater, since elevated nitrate causes methemoglobinemia ('blue-baby syndrome') in infants; WHO sets a maximum contaminant level of 10 mg/L as nitrogen (WHO, 2004).

4. Drivers of Water Quality Deterioration in Shared-Use Systems

In water-scarce settings, humans, livestock, and wildlife frequently draw on the same limited sources, and this concentration of use is a principal driver of contamination. Animals defecate in and around water points during watering; livestock and wildlife movement between sources disperses pathogens across wide areas; and high evaporation in dry seasons concentrates dissolved ions and nutrients, favouring microbial growth. Intensive use also removes protective vegetation through trampling and grazing, exposing soil to erosion and increasing the transport of organic matter, nutrients, and microorganisms into water bodies via surface runoff — a self-reinforcing cycle of degradation. Discharge of domestic sewage compounds these effects by depleting dissolved oxygen (through aerobic decomposition) and elevating enteric bacterial counts, the reverse of the conditions required for safe water. These dynamics are not unique to pastoral East Africa: comparable pressures — dense peri-urban dairy operations, inadequately managed liquid waste, and agricultural runoff — are documented in intensively farmed regions elsewhere, including parts of Punjab, India, where rivers and shallow groundwater in dairy-dense districts show faecal coliform contamination attributable to similar point- and non-point-source pathways.

5. Water Treatment and Purification Approaches

5.1 Solar Disinfection (SODIS)

Solar disinfection involves exposing water in transparent containers to direct sunlight for up to eight hours (Conroy et al., 1996; Sommer et al., 1997), combining UV-A-mediated DNA

damage with synergistic thermal inactivation once water temperature exceeds 50°C. It is effective against a broad spectrum of pathogens, including E. coli, Salmonella, Vibrio cholerae, and Cryptosporidium (Conroy et al., 2001; Kehoe et al., 2004; Smith et al., 2000; Wegelin et al., 1994), and near-complete coliform inactivation has been reported within about an hour under favourable conditions (Archer and Jurken, 1977). Its principal advantages are cost (free) and simplicity; its main limitation is an inability to remove sediment or dissolved solids, making pre-clarification necessary for turbid water.

5.2 Alum Coagulation

Alum (potassium or ammonium aluminium sulphate) has been used for water treatment for centuries across Africa and Asia (Jahn and Dirar, 1979; Gupta and Chaudhuri, 1992), acting through coagulation-flocculation: positively charged aluminium hydroxide flocs bind negatively charged suspended particles, including bacteria and organic matter, into settleable aggregates. Household-scale application in Myanmar achieved 90–98% reduction in faecal coliform contamination with high consumer acceptance (Oo et al., 1993). Limitations include the skill required to optimise dose, mixing, and pH; cost barriers for the poorest households; reduced coagulation efficiency in cold, low-alkalinity water owing to pH depression (Haarhoff and Cleasby, 1988); and — though the association remains scientifically debated — a possible link between long-term elevated aluminium intake and Alzheimer's disease (Martyn et al., 1989).

5.3 Chlorination

Free chlorine is the most widely used and most affordable chemical disinfectant, inactivating over 99.99% of enteric bacteria and viruses at typical doses and contact times, though it is markedly less effective against Cryptosporidium parvum oocysts and Mycobacteria (Sobsey, 1989). Its central limitation is that it does not remove sediment: in water with turbidity of 3.8–84.0 NTU, coliforms have been recovered even after chlorination with free residuals of 0.1–0.5 mg/L (Sanderson and Kelly, 1964), and there is a well-documented inverse relationship between turbidity and chlorination effectiveness (LeChevallier et al., 1981). Reaction with organic matter also generates taste, odour, and — most importantly — potentially carcinogenic trihalomethanes (Rook, 1977), an effect exacerbated at high turbidity because chlorine is preferentially consumed by organic matter rather than by target pathogens. Cost, storage requirements, and the technical skill needed for correct dosing further constrain its use in remote or under-resourced households.

5.4 Natural Plant-Based Coagulants

Several plant materials have been investigated as low-cost natural coagulants. Moringa oleifera Lam. (drumstick/Sehjan) seeds are the most extensively studied, reported as an effective, simple, non-toxic flocculant (Jahn and Dirar, 1979; Jahn, 1981; Olsen, 1987; Grabow et al., 1985) achieving 80–99% turbidity removal via a charge-neutralisation mechanism (Muyibi and Okufu, 1995; Ndabigengesere et al., 1995; Muyibi and Evison, 1996), though it performs less well on water with already-low turbidity (Muyibi and Okufu, 1995). Tamarindus indica (tamarind) seed mucilage has been used to remove sulphate and phosphate ions, with a 50 mg/L dose reported to remove 74% of sulphates and 76% of phosphates within 30 minutes (Anuradha and Malvika, 2005). Strychnos potatorum (nirmali) seeds have shown roughly 50% reduction of plate-count bacteria and 95% turbidity reduction (Tripathi et al., 1976), and okra (Abelmoschus esculentus) extracts have also demonstrated positive turbidity-reducing effects (Al Samawi and Shokralla, 1996). Because Moringa oleifera trees are widely and freely available in many rural settings — including parts of rural Punjab (Hoshiarpur, Ropar, Rupnagar, Patiala district) — Moringa-seed coagulation is repeatedly highlighted in the literature as a near-zero-cost, first-step treatment option ahead of boiling or chlorination in resource-limited households.

5.5 Coagulation-Flocculation Efficiency and the Case for Multi-Barrier Treatment

Under optimal conditions, coagulation-flocculation with alum or iron salts can achieve 90–99% reduction across bacteria, viruses, and protozoa (Payment and Armon, 1989), and lime coagulation at pH above 11 can exceed 99.99% reduction through the bactericidal effect of extreme alkalinity itself. However, coagulation-flocculation alone is not a complete treatment: residual bacteria persist in the clarified supernatant, and subsequent disinfection — by chlorination or boiling — remains necessary to meet WHO safety standards. This underlines a recurring conclusion across the literature reviewed here: no single treatment method reliably delivers both adequate turbidity removal and adequate bacterial inactivation, and a multi-barrier approach combining a coagulation step with a terminal disinfection step is the most defensible strategy for household water treatment in contaminated, high-turbidity settings.

6. Emerging Concerns: VBNC Bacteria and Antibiotic Resistance

Two emerging concerns complicate the interpretation of conventional water-quality testing. First, bacteria subjected to disinfection or other environmental stress may enter a Viable-But-

Non-Culturable (VBNC) state — remaining metabolically active and potentially pathogenic while evading detection by standard culture-based methods (McDougald et al., 1998). This raises the possibility that post-treatment HPC and coliform counts systematically underestimate true residual bacterial load, particularly following coagulant or low-dose chemical treatment, and points to a need for molecular detection methods (PCR, fluorescence in-situ hybridisation, flow cytometry) capable of identifying VBNC organisms alongside culturable ones.

Second, antibiotic-resistant bacteria — including strains showing Multiple Antibiotic Resistance (MAR) — have been recovered from domestic sewage, hospital effluent, drinking water, rivers, and lakes (Magee and Quinn, 1991; Ogan and Nwiika, 1993; Boon and Cattanach, 1999; Lancini et al., 1995), and rising resistance in Shigella and Salmonella spp. is now a recognised global public-health concern (Mandell et al., 2000). Resistance mechanisms include horizontally transferable plasmid-mediated genes, chromosomal target-site mutations, antibiotic-degrading enzymes, and altered membrane permeability. Antibiotic-resistant bacteria in water represent a significant environmental reservoir (Huber, 1971), and there have been repeated calls to incorporate antibiotic-resistance monitoring into bacteriological water-quality criteria (Bell et al., 1983; El-Zanfaly, 1991) — a call with particular relevance to regions, including Punjab, where intensive livestock antibiotic use for growth promotion and disease control is a plausible driver of resistance-gene accumulation in agricultural soils and adjacent water bodies.

7. Regional Relevance and Applicability to Punjab, India

Although the field data underpinning this review were generated in a semi-arid pastoral district of Kenya, the underlying mechanisms of contamination and the treatment technologies reviewed have direct relevance to rural water-safety contexts elsewhere, including Punjab, India. Villages in the Malwa belt (Bathinda, Mansa, Muktsar, Faridkot) and parts of Doaba (Jalandhar, Hoshiarpur) that depend on unregulated hand pumps, seasonal nalas, and canal-linked shallow groundwater face comparable faecal-contamination pathways from cattle pens, open drains, and agricultural runoff. Punjab's large peri-urban dairy sector — concentrated around Ludhiana, Amritsar, Patiala, and Sangrur — generates substantial volumes of liquid animal waste that can enter surface water and seep into groundwater in a manner analogous to the livestock-driven contamination described above, with faecal coliform contamination reported in the Sutlej, Ghaggar, and Beas river systems attributable in part to agricultural and livestock sources.

Against this backdrop, the natural-coagulant literature reviewed here is of particular practical interest: Moringa oleifera (Sehjan) grows widely and at negligible cost across rural Punjab, and a two-step household approach — Moringa-seed coagulation to reduce turbidity, followed by boiling (already culturally accepted in most Punjab households) or chlorination for terminal disinfection — is consistent with the multi-barrier principle established across the wider literature and could offer a low-cost, locally sourced intervention for water-insecure villages. A parallel field study replicating the sampling and treatment-evaluation design reviewed here — covering tube wells, hand pumps, canals, and seasonal nalas across a contamination gradient from comparatively cleaner districts (Ropar/Rupnagar) to more heavily contaminated ones (Bathinda/Mansa/Muktsar), and testing locally available candidates such as Moringa oleifera, Azadirachta indica (neem), and Ocimum sanctum (tulsi) — would provide a Punjab-specific evidence base to inform rural water-safety policy and community-level treatment promotion.

8. Conclusion and Future Research Directions

The literature reviewed here converges on several consistent conclusions. Coliform bacteria, thermotolerant coliforms, E. coli, and HPC remain the practical backbone of bacteriological water-quality assessment, but each has recognised limitations — particularly the risk that VBNC bacteria evade culture-based detection and that culturability itself can be altered by nutrient and disinfectant exposure rather than reflecting true viability. Physico-chemical parameters, above all turbidity and pH, are not merely descriptive but functionally determine the effectiveness of downstream disinfection, meaning that treatment strategies must address turbidity before or alongside disinfection rather than relying on chlorination alone. Among treatment options, plant-based natural coagulants — particularly Moringa oleifera — offer a genuinely low-cost, locally available option for turbidity and moderate bacterial-load reduction, but no single treatment, plant-based or chemical, achieves both adequate turbidity removal and adequate bacterial inactivation in isolation; a multi-barrier approach combining coagulation with terminal disinfection is required.

Priority areas for further research identified across this literature include: chemical characterisation (e.g., by GC-MS/HPLC) of the active coagulant/antimicrobial compounds in under-studied plant species; dose-response and optimal contact-time studies for plant extracts; molecular (PCR, FISH, flow cytometry) investigation of VBNC bacterial dynamics during and after treatment; testing of combined or synergistic plant-extract formulations; assessment of how source water chemistry (pH, turbidity, salinity, alkalinity, organic content) modulates

coagulant performance; household- and community-level acceptability and scaling studies; determination of minimum inhibitory and bactericidal concentrations against key waterborne pathogens; and systematic antibiotic-resistance surveillance in waterborne bacterial populations. Pursuing these directions — including through region-specific field studies in settings such as rural Punjab — would strengthen the evidence base for affordable, sustainable household water treatment in water-insecure communities worldwide.

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