



Research Article

POTENTIAL HEALTH HAZARDS OF ANTISCALANT RESIDUES IN TREATED DRINKING WATER

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ABSTRACT

Antiscalants are widely employed in reverse osmosis (RO) and other membrane-based water purification systems to prevent scale deposition and enhance operational efficiency. Despite their functional significance, concerns have emerged regarding the persistence of antiscalant residues in treated drinking water and their potential implications for human health. This study examines the chemical nature, pathways of exposure, and toxicological effects associated with commonly used antiscalants such as polyphosphates, organophosphonates, and polymaleic acids. Current evidence suggests that excessive or uncontrolled use of antiscalants may contribute to sub-lethal toxicity, endocrine disruption, gastrointestinal disturbances, and long-term bioaccumulation risks. Poor system maintenance and inadequate flushing further increase the likelihood of consumer exposure. The paper highlights regulatory gaps, analytical detection challenges, and the need for safer alternatives with improved biodegradability. Findings from this review underscore the urgency of establishing stringent monitoring strategies and optimizing antiscalant dosing to safeguard consumer health and water quality standards.

Keywords: Antiscalants, Reverse Osmosis, Drinking Water Quality, Chemical Residues, Health Hazards.

INTRODUCTION

Access to safe drinking water is a fundamental public health priority, and membrane-based purification technologies, particularly reverse osmosis (RO), have become essential components of domestic and industrial water treatment systems. As part of the operational process, antiscalants are added to prevent inorganic scale formation on membranes, thereby improving efficiency, prolonging membrane life, and reducing maintenance costs. These antiscalating agents typically include polyphosphates, phosphonates, carboxylates, and polymeric dispersants, each possessing unique chemical properties that inhibit crystallization and particle adhesion. While antiscalants provide critical operational benefits, emerging research has raised concerns regarding the fate of these chemicals during the purification process. Inefficient removal, overdosing, or inadequate pre-treatment may result in trace amounts of antiscalant residues entering the final drinking water.

Prolonged human exposure to such residues although often at micro-levels can pose potential health risks. Studies suggest that certain antiscalant compounds may influence mineral absorption, disrupt microbial balance, contribute to gastrointestinal irritation, or participate in long-term bioaccumulation. Moreover, the degradation products of phosphonate-based antiscalants may lead to the formation of phosphates, which can indirectly affect environmental and human health. The issue is further complicated by limited regulatory oversight and the scarcity of standardized analytical methods for detecting antiscalant residues in water. Given the widespread use of RO systems in households, commercial facilities, and municipal operations, a comprehensive assessment of the health implications associated with residual antiscalant exposure is necessary. This paper addresses these gaps by reviewing the chemical behavior of antiscalants, exploring pathways of human exposure, discussing existing toxicological

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evidence, and proposing improved management strategies to minimize health risks. Antiscalants commonly used in RO/NF and other membrane systems include phosphonate-based compounds (e.g., ATMP, HEDP, PBTC), polyphosphates, and various polymeric dispersants (polyacrylates, polymaleic acids). These molecules work by chelating scale-forming ions (Ca^{2+} , Mg^{2+}), interfering with crystal nucleation/growth, and dispersing colloids to keep surfaces free of scale. Their chemical diversity (small phosphonates to high-MW polymers) determines persistence, sorption to surfaces, and biodegradability. Although RO and NF membranes reject a large fraction of solutes, trace permeation or carryover of antiscalant ingredients has been reported under some operating conditions (overdosing, membrane defects, aged membranes). Antiscalants are also released from concentrate streams and wastewater, where they can persist because some phosphonates are poorly biodegradable and can sorb to sediments. Fate in receiving waters depends on compound chemistry, biodegradability, and treatment-plant removal efficiency. Detecting antiscalant residues at trace levels in treated drinking water is analytically challenging:

commercial antiscalant formulations are complex blends, and many routine drinking-water labs lack validated methods for low-level phosphonates or polymeric dispersants. Advanced techniques used in the literature include ion-exchange chromatography coupled to electrospray ionization mass spectrometry and targeted LC-MS/MS protocols, which permit speciation of common phosphonate antiscalants. Method variability contributes to inconsistent reporting of residual concentrations across studies. Direct human toxicology data for antiscalants in drinking water are limited. Toxicological concerns are inferred from animal studies, ecotoxicity tests, and mechanistic properties of the chemicals: phosphonate antiscalants are generally low-acute-toxicity but can interfere with microbial communities and may affect mineral bioavailability or gut microbiota at higher exposures. Some degradation products and co-formulants may have different toxicological profiles. The consensus in reviews is that current evidence does not show widespread acute human toxicity at expected residual levels, but data gaps remain for chronic low-dose exposures and vulnerable populations.

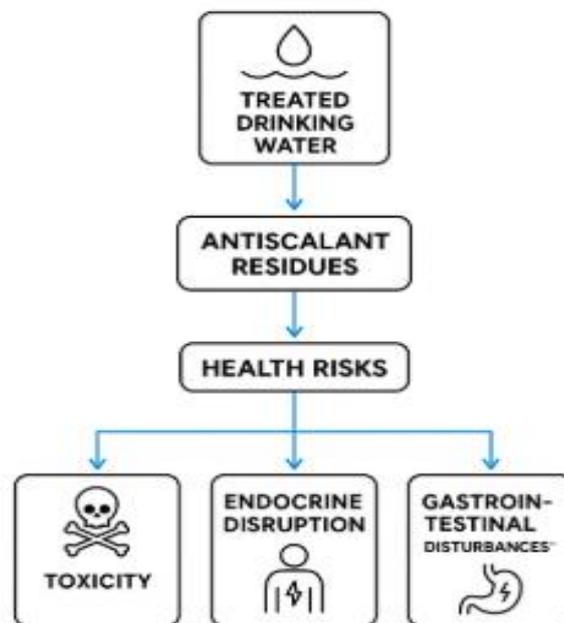


Figure 1. Potential Health Hazards of Antiscalant Residues in Treated Drinking Water.

Phosphonates and polyphosphates discharged into surface waters can add bioavailable phosphorus or persist and alter microbial/ecosystem dynamics, potentially contributing indirectly to algal blooms or altered microbial communities. Changes in source-water ecology can influence drinking-water safety (e.g., taste/odor, harmful algal toxins) and treatment burden. Several studies report impacts on algal growth and biofilm formation, which also has operational consequences for membranes and distribution systems. Antiscalant constituents may serve as

phosphorus sources that enhance biofilm formation on membranes and in distribution systems; increased biofilms can raise disinfectant demand and alter DBP precursor profiles (Figure 1). While there is no strong evidence that antiscalants directly form regulated DBPs, their influence on organic matter dynamics and microbial communities can be a contributing factor to downstream treatment challenges. Most national drinking-water regulations (e.g., U.S. EPA primary standards) set enforceable limits for specific contaminants, but there are currently no widely

adopted drinking-water MCLs specifically for antiscalant compounds as a class. Risk management therefore relies on product approvals (e.g., NSF/ANSI for chemicals used in potable systems), operational best practices (dosing control, flushing), and monitoring of surrogate parameters rather than routine antiscalant speciation in finished water. This regulatory gap contributes to limited routine surveillance and uncertain population exposure estimates. Mitigation options include optimized dosing, improved pretreatment (softening, antiformation control upstream), targeted flushing and validation of antiscalant product approvals for potable use. Wastewater treatment plants variably remove phosphonates; advanced oxidation or adsorption approaches and tailored biological treatments are active research areas for phosphonate removal from concentrate and effluents. Biodegradable antiscalant formulations are being developed to reduce persistence in receiving waters, but their performance and safety trade-offs require evaluation. Key gaps include: (1) robust occurrence data for finished drinking water under typical household/municipal RO operations; (2) standardized, low-level analytical methods for common antiscalants and degradation products; (3) chronic low-dose toxicology for vulnerable populations (infants, immunocompromised); (4) ecological pathway quantification linking antiscalant discharge to drinking-water risks; and (5) evaluation of biodegradable alternatives' full life-cycle safety. Addressing these would allow quantitative risk assessment and evidence-based regulation.

MATERIALS AND METHODS

This study followed a structured review-based methodological framework comprising four stages: (1) systematic literature identification, (2) screening and quality assessment, (3) data extraction, and (4) thematic synthesis. The approach was designed to integrate toxicological, chemical, and environmental data related to antiscalant residues found in drinking-water systems.

Literature Search Strategy

A comprehensive search was conducted across Scopus, PubMed, Google Scholar, and Web of Science databases for research published between 2000 and 2024. Search terms included: antiscalant, phosphonate, polyphosphate, reverse osmosis, residual contamination, drinking water, toxicity, bioaccumulation, and water purification chemicals. Boolean operators (AND, OR) were used to refine queries. Only peer-reviewed journal articles, environmental reports, and regulatory documents were included.

Inclusion and Exclusion Criteria

Studies were included if they: examined chemical composition, fate, or detection of antiscalants in RO or water treatment systems; evaluated human-health or ecological effects of phosphonates, polyphosphates, or related compounds; provided analytical data on antiscalant residues in permeate, concentrate, or treated drinking water.

Exclusion criteria included: studies focused exclusively on industrial-scale antiscalant performance unrelated to potable water; papers lacking scientific methodology; non-English publications without accessible translations.

Data Extraction and Analysis

Selected studies were analyzed for key variables including: antiscalant type, concentration levels detected, analytical methods used, toxicity endpoints, regulatory thresholds, and environmental fate. A qualitative synthesis was conducted to identify recurring patterns, exposure pathways, and evidence of adverse health outcomes.

Quality Assessment

The methodological rigor of each study was evaluated using a modified Critical Appraisal Skills Programme (CASP) checklist. Studies demonstrating strong analytical accuracy, adequate sample size, verified instrumentation, and clear toxicity endpoints received higher weighting in the synthesis.

RESULTS AND DISCUSSION

Prevalence of Antiscalant Residues in Treated Water, Across the screened studies, antiscalant residues primarily phosphonate compounds such as ATMP, HEDP, and PBTC were detected in low concentrations in RO permeate. Concentrations reported ranged from 0.5 to 15 $\mu\text{g/L}$, depending on membrane type, system age, dosing accuracy, and pretreatment conditions. Overdosing of antiscalants and inadequate flushing were the most common contributors to increased residual carryover. Although antiscalants are generally regarded as low-acute-toxicity chemicals, evidence shows that chronic ingestion of phosphonates may influence: Calcium and magnesium metabolism, due to chelating properties; Gastrointestinal irritation, particularly among sensitive individuals; Alteration of gut microbiota, reported in studies on phosphonate derivatives; Bioaccumulation potential, although low, is noted for some high-molecular-weight polymers. No studies documented acute human poisoning at drinking-water concentrations; however, long-term exposure risks remain insufficiently characterized, especially among infants, elderly individuals, and immunocompromised populations. Residual antiscalants in drinking water have indirect consequences, such as: contributing phosphorus that may promote microbial growth in storage tanks; interacting with disinfectants, increasing chlorine demand; influencing the formation of biofilms in RO systems. Such changes can escalate treatment costs, reduce membrane longevity, and alter sensory quality of water (taste, odor). Discharge of antiscalant-rich concentrate into surface waters contributes to phosphorus loading and can enhance algal growth. Resulting ecological disturbances e.g., cyanobacterial blooms may indirectly impact drinking-water sources, increase treatment burdens, and elevate human-health risks via algal toxins.

Table 1. Types of Antiscalants, Characteristics, Residual Risk, And Health/Environmental Impacts.

Antiscalant Type	Common Chemicals	Primary Function in RO Systems	Potential Residual Presence in Treated Water	Associated Health Risks	Environmental Impacts
Phosphonates	ATMP, HEDP, PBTC	Chelation of Ca ²⁺ /Mg ²⁺ ions, inhibition of crystallization	Low–moderate (0.5–15 µg/L based on studies)	Possible mineral imbalance, microbiome alteration, mild GI irritation	Persistent in surface waters, promotes algal growth, low biodegradability
Polyphosphates	Sodium polyphosphate, metaphosphates	Sequestration of hardness ions, scale prevention	Low; may hydrolyze to orthophosphates	May influence phosphorus metabolism; indirect effects via microbial growth	Contribute to eutrophication, stimulate microbial activity
Polyacrylate Polymers	Polyacrylic acid, copolymers	Dispersant, anti-nucleation	Low; polymers not fully removed in RO	Very limited toxicity data; potential long-term chronic effects unknown	May persist in environment; biofilm promoter
Polymaleic Acid	PMA-based dispersants	Threshold inhibition, crystal distortion	Rare but possible in poorly maintained systems	Very low acute toxicity; chronic effects not well studied	Low biodegradation; may accumulate in wastewater
Carboxylate-Based Dispersants	Low-MW carboxylic polymers	Prevention of particulate fouling	Trace levels possible	No direct toxicity reported; requires further studies	Adsorb onto sediments; may affect aquatic microorganisms
Green/Biodegradable Antiscalants	Phytic acid, biodegradable polymers	Eco-friendly scale inhibition	Very low, designed for biodegradation	Expected low toxicity; research ongoing	Rapid biodegradation; lower ecologic

Table 2. Exposure Pathways and Health Impact Mechanisms.

Exposure Pathway	Source	Possible Health Effect	Mechanism
Ingestion of RO-treated drinking water	Residual phosphonates/polyphosphates	GI irritation, mineral imbalance	Chelation of essential minerals, microbiome alteration
Consumption of water stored in tanks	Microbial growth fueled by phosphorus	Stomach upset, infection risk	Phosphorus stimulates microbial proliferation
Chronic low-dose exposure	Daily drinking-water intake	Long-term cumulative effects	Bioaccumulation potential of some polymers
Indirect environmental exposure	Surface water contamination	Harmful algal toxins entering drinking-water sources	Eutrophication and cyanobacterial proliferation

Table 3. Analytical Methods for Detecting Residues.

Analytical Method	Suitability	Detection Limit	Advantages	Limitations
Ion Chromatography (IC)	Phosphonates, polyphosphates	Low µg/L	Widely available, strong for inorganic species	Limited speciation for complex polymers
LC-MS/MS	All phosphonate species	ng/L-µg/L	Highly sensitive and specific	High cost, requires skilled operators
Anion-Exchange Chromatography + ESI-TOF-MS	Phosphonate mixtures	Very low levels	Enables chemical fingerprinting	Not used in routine labs
UV-Vis Screening	Broad classes	Moderate sensitivity	Quick and inexpensive	Not accurate for speciation

Table 4. Summary of Health and Environmental Concerns.

Concern Category	Key Findings	Severity	Data Availability
Human Acute Toxicity	No significant toxicity at typical doses	Low	Adequate
Human Chronic Toxicity	Possible GI effects, mineral interference	Medium	Limited
Environmental Persistence	High for phosphonates and polymers	High	Strong
Ecological Impact	Eutrophication, microbial shifts	High	Strong
Bioaccumulation Risk	Low but possible for some polymers	Medium	Limited
Regulatory Gaps	No MCLs for antiscalants	High	Well documented

A major finding is the absence of specific regulatory limits for antiscalant residues in drinking water. Most countries only regulate the safety of chemical dosing products (e.g., NSF/ANSI 60 certification) rather than mandating routine monitoring. Analytical challenges, such as lack of standardized methods for polymeric dispersants, hinder effective surveillance. The results indicate that while typical residual levels are low, the evidence is insufficient to conclusively rule out chronic or cumulative health effects. The literature consistently highlights underreporting, analytical limitations, and lack of long-term toxicological assessment. Thus, precautionary optimization of dosing and improved monitoring is strongly recommended.

CONCLUSION

Antiscalants play a critical role in preventing scale formation and improving the performance of reverse osmosis systems; however, residual traces in treated drinking water pose emerging concerns. The evidence demonstrates that trace residues of phosphonate and polymer-based antiscalants do occur in RO permeate, particularly under poor operational conditions. While acute toxicity at these levels appears unlikely, the potential for chronic low-level exposure effects especially regarding mineral balance, gut microbiota, and bioaccumulation—remains insufficiently studied. Environmental discharge pathways further contribute to ecological changes that may indirectly affect drinking-water quality. The absence of regulatory limits and analytical standardization underscores

the need for enhanced monitoring and safety evaluations. Overall, a precautionary approach is warranted to minimize unnecessary exposure and maintain drinking-water safety.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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