

Effect of advanced water treatment technologies on plankton diversity and aquatic ecosystem health: A comprehensive review

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Abstract

Advanced water treatment technologies have become increasingly critical in addressing global water quality challenges and ensuring sustainable water resource management. However, the ecological implications of these technologies, particularly their impact on planktonic communities, remain inadequately understood. This comprehensive review examines the effects of various advanced water treatment technologies—including membrane filtration, advanced oxidation processes, ultraviolet disinfection, ozonation, and nanotechnology-based treatments—on phytoplankton and zooplankton diversity in aquatic ecosystems. Through systematic analysis of peer-reviewed literature from 2015 to 2025, this study reveals that while these technologies effectively remove contaminants and pathogens, they simultaneously induce significant alterations in plankton community structure, species richness, and functional diversity. Membrane technologies demonstrate selective removal based on organism size, disproportionately affecting larger zooplankton species. Advanced oxidation processes and ozonation exhibit species-specific toxicity, with sensitive taxa experiencing population declines while tolerant species proliferate. The research identifies critical knowledge gaps regarding long-term ecological consequences, cascading effects on aquatic food webs, and the cumulative impacts of multiple treatment processes. This review emphasizes the necessity for integrated ecological assessments in water treatment facility design and operation, advocating for treatment optimization strategies that balance human health protection with ecosystem integrity preservation. The findings provide valuable insights for environmental engineers, water resource managers, and policymakers seeking to implement sustainable water treatment solutions that minimize adverse ecological impacts while maintaining treatment efficacy.

Keywords: Advanced water treatment, plankton diversity, membrane filtration, advanced oxidation processes, aquatic ecosystems, ecological impact assessment, phytoplankton, zooplankton

Introduction

Background: Water scarcity and contamination represent two of the most pressing environmental challenges confronting humanity in the 21st century. According to the United Nations, approximately 2.2 billion people globally lack access to safely managed drinking water services, while water quality degradation continues to accelerate due to industrial discharge, agricultural runoff, pharmaceuticals, and emerging contaminants (UNESCO, 2023). This critical situation has catalyzed unprecedented investment in advanced water treatment technologies designed to remove an increasingly diverse array of pollutants while meeting stringent regulatory standards. Advanced water treatment technologies encompass a suite of sophisticated processes that extend beyond conventional treatment methods such as sedimentation, filtration, and chlorination. These technologies include membrane-based separation processes (reverse osmosis, ultrafiltration, Nano filtration), advanced oxidation processes (AOPs) utilizing hydroxyl radicals, ultraviolet disinfection systems, ozonation, biological filtration, and emerging nanotechnology applications. Collectively, these innovations have revolutionized water treatment capabilities, enabling the removal of micro pollutants, endocrine-disrupting compounds, pharmaceutical residues, and resistant pathogens that conventional methods fail to address adequately. However, the implementation of these advanced technologies occurs within complex

ecological contexts. Water treatment facilities typically draw raw water from natural sources—rivers, lakes, reservoirs, and aquifers—each harboring diverse planktonic communities that constitute the foundation of aquatic food webs. Plankton, encompassing both photosynthetic phytoplankton and heterotrophic zooplankton, perform critical ecosystem functions including primary production, nutrient cycling, water quality regulation, and provision of food resources for higher trophic levels. The biodiversity of planktonic assemblages serves as a sensitive indicator of aquatic ecosystem health, responding rapidly to environmental perturbations.

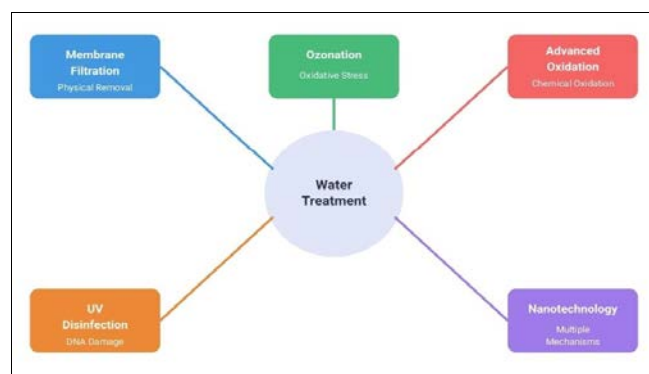


Fig 1: Advanced Water Treatment Technologies and Their Primary Mechanisms

The Ecological Significance of Plankton: Planktonic organisms occupy a central role in aquatic ecosystems by linking dissolved nutrients to higher trophic levels. Phytoplankton, including microalgae, cyanobacteria, and photosynthetic protists, contribute nearly half of global primary production and underpin aquatic food webs, while driving carbon, nitrogen, and phosphorus cycling. Their taxonomic and functional diversity enhances ecosystem stability, resilience, oxygen production, and water clarity. Zooplankton, such as rotifers, cladocerans, and copepods, function as primary consumers transferring energy to fish populations. Through grazing, nutrient regeneration, and organic matter transport, zooplankton diversity strongly regulates food-web efficiency and ecosystem responses to environmental stressors

Research Problem and Significance: Despite the ecological importance of plankton, the effects of advanced water treatment technologies on planktonic diversity remain poorly understood. Research largely emphasizes contaminant removal and regulatory compliance, neglecting ecological impacts. Treatment processes may selectively remove plankton, release toxic byproducts, and alter community structure. These changes can cascade through aquatic food webs, especially when combined with climate change and eutrophication pressures.

Research Objectives: This comprehensive review addresses the critical need for integrated understanding of how advanced water treatment technologies impact plankton diversity. The specific objectives are:

1. Evaluate the effects of advanced water treatment technologies on phytoplankton and zooplankton diversity;
2. Identify physical, chemical, and environmental mechanisms influencing plankton;
3. Compare ecological risks across treatment processes and food-web impacts;
4. Highlight research gaps and recommend ecologically sustainable treatment strategies.

Literature Review

1. Membrane-Based Treatment Technologies: Membrane filtration technologies have expanded rapidly in water treatment over recent decades. These pressure-driven processes use semi-permeable membranes to separate contaminants based on size and charge. The main types—microfiltration, ultrafiltration, Nano filtration, and reverse osmosis—differ in pore size, pressure, and rejection performance. (Zhang et al., 2020)

1.1 Physical Removal Mechanisms: Membrane filtration technologies significantly restructure plankton communities through pronounced size-selective removal. Microfiltration and ultrafiltration markedly reduce phytoplankton abundance and eliminate most zooplankton taxa, promoting dominance of smaller, rapidly proliferating species. Such shifts in community composition may influence downstream ecosystem functioning and warrant ecological consideration in treatment design.

1.2 Sub lethal Effects and Membrane: Beyond direct removal, membrane filtration imposes sub lethal stress

on plankton through high shear forces that impair cellular integrity, growth, and photosynthetic performance. Surviving phytoplankton exhibit reduced physiological efficiency. Additionally, plankton-driven membrane fouling promotes biofilm formation, increasing reliance on chemical cleaning agents. These cleaning chemicals may enter receiving waters, posing poorly understood but potentially significant risks to downstream aquatic organisms and ecosystem health.

2. Advanced Oxidation Processes: Advanced oxidation processes (AOPs) are chemical treatments producing reactive hydroxyl radicals and oxygen species to break down persistent organic pollutants, including UV/H₂O₂, ozone/H₂O₂, Fenton, photo-Fenton, and TiO₂ photocatalysis (Sharma *et al.*, 2021).

2.1 Direct Oxidative Damage: During AOP treatment, generated oxidants damage plankton by attacking lipids, proteins, and DNA, inducing oxidative stress, metabolic disruption, and cell death, as highlighted by Rodriguez-Gonzalez *et al.* (2022) UV/H₂O₂ treatment caused 60–85% phytoplankton mortality within 30 minutes, with green algae and diatoms more sensitive than cyanobacteria. Cyanobacteria's robust cell walls and antioxidants confer resistance, potentially shifting communities toward harmful species, as repeated treatments can select oxidant-resistant *Microcystis*, increasing algal bloom and toxin risks.

2.2 Impacts on Zooplankton Communities: Zooplankton susceptibility to AOPs varies; smaller rotifers tolerate oxidative stress better than larger cladocerans and copepods, aided by rapid reproduction and quicker population recovery. (Ferrão-Filho *et al.*, 2020) ^[7]. However, Sub lethal AOP effects include reduced reproduction, delayed growth, and behavioral changes. AOPs also form toxic byproducts—carbonyls, carboxylic acids, halogenated compounds—harmful to *Daphnia* and zooplankton, highlighting the need for thorough toxicity evaluation beyond contaminant degradation, as shown by Zhang *et al.* (2023).

3. Ultraviolet Disinfection

Ultraviolet disinfection has gained widespread adoption as an alternative to chemical disinfectants, offering effective pathogen inactivation without generating halogenated disinfection byproducts. UV systems typically employ low-pressure or medium-pressure mercury lamps emitting radiation at germicidal wavelengths (primarily 254 nm) that damages microbial DNA (Bolton & Cotton, 2022) ^[5].

3.1 Photo biological Effects on Phytoplankton: UV disinfection harms non-target plankton; phytoplankton photosystems are susceptible to UV-induced damage despite existing photo protective mechanisms (Williamson *et al.*, 2021). UV doses for pathogen inactivation (30–40 mJ/cm²) reduce phytoplankton photosynthesis 25–60% and cause DNA damage. Chronic exposure accelerates mutations, selecting UV-resistant genotypes, potentially promoting nuisance blooms, or altering ecological interactions, as shown in *Chlamydomonas* over 100 generations (Peterson&Lee,2022).

3.2 Zooplankton Responses and Recovery Dynamics:

Zooplankton responses to UV vary by species, life stage, and exposure. Eggs and nauplii are most sensitive, with doses above 40 mJ/cm² reducing hatching and causing abnormalities (Morrison *et al.*, 2023). Recovery depends on immigration and connectivity; open systems recolonize faster, whereas closed or impacted waters show prolonged effects. Long-term UV treatment in a reservoir caused sustained declines in rotifer diversity and copepod abundance over three years (Ramirez-Garcia *et al.*, 2022).

4. Ozonation

Ozone (O₃) functions as a powerful oxidant and disinfectant in water treatment, reacting rapidly with organic matter, microorganisms, and inorganic compounds. Ozonation offers advantages including broad-spectrum antimicrobial activity, rapid reaction kinetics, and decomposition to oxygen without persistent residuals (von Gunten, 2022).

4.1 Oxidative Stress and Cellular Damage: Ozone harms plankton via direct oxidation and reactive oxygen species, targeting cell membranes and causing lipid peroxidation, ion leakage, and cell lysis. Concentrations of 0.5–2.0 mg/L rapidly lyse sensitive phytoplankton (Nakamura *et al.*, 2021). Sensitivity varies: green algae are moderately affected, diatoms depend on frustule traits, and cyanobacteria show high resistance. LC₅₀ values differ 50-fold among species, with *Scenedesmus* most sensitive and *Microcystis* most resistant (Hassan & Kumar, 2023)^[9].

4.2 Formation of Oxidation Byproducts: Ozonation produces harmful byproducts like bromate, bromoform, and carbonyls. Bromate (10–50 µg/L) impairs *Daphnia* survival and reproduction (Thompson *et al.*, 2022). Ozone also generates biodegradable organic compounds, stimulating bacterial growth that competes with phytoplankton, suppresses algal growth, and shifts communities toward heterotrophic dominance (Martinez *et al.*, 2023)^[14].

5. Nanotechnology-Based Treatments

Engineered nanomaterial’s represent an emerging frontier in water treatment, offering novel approaches for contaminant removal, catalysis, and disinfection. Materials including titanium dioxide nanoparticles, silver nanoparticles, carbon nanotubes, and graphene derivatives are increasingly incorporated into treatment systems (Qu *et al.*, 2021).

5.1 Nanoparticle Interactions with Plankton:

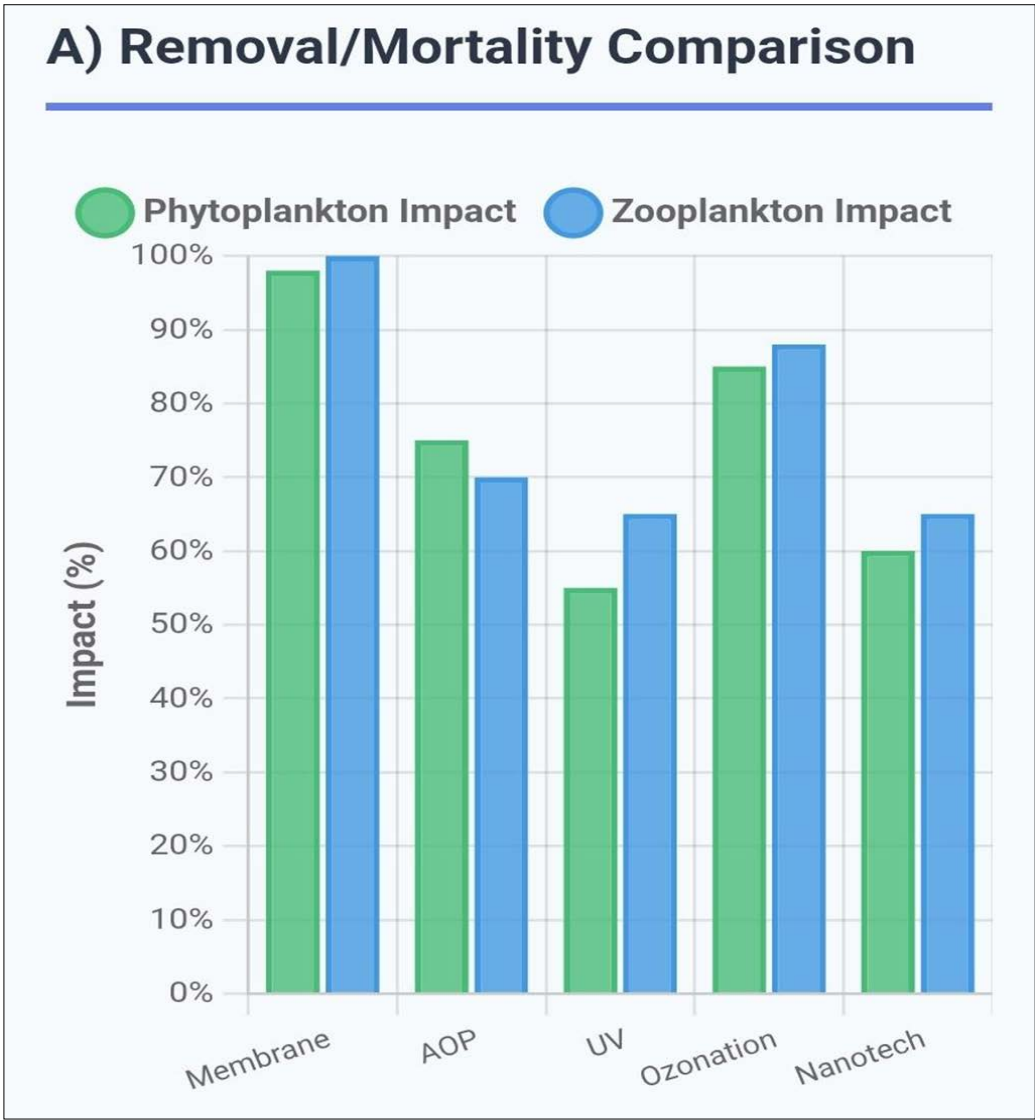
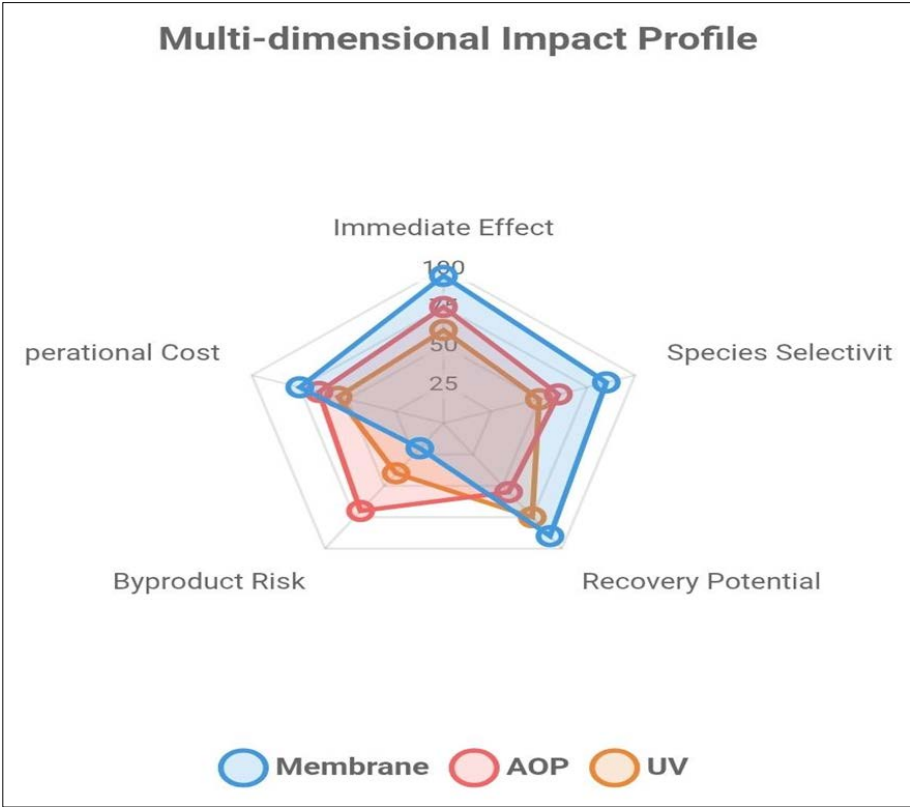
Nanoparticles affect plankton via adhesion, uptake, ion release, and ROS generation. Silver nanoparticles (≥10 µg/L) reduce algal growth 30–70% (Ouyang *et al.*, 2022). TiO₂ nanoparticles under UV cause oxidative stress, lowering phytoplankton photosynthesis and zooplankton feeding at 1–10 mg/L, with persistent effects even after removal (Kumar & Sharma, 2023)^[11].

5.2 Trophic Transfer and Bio-accumulation:

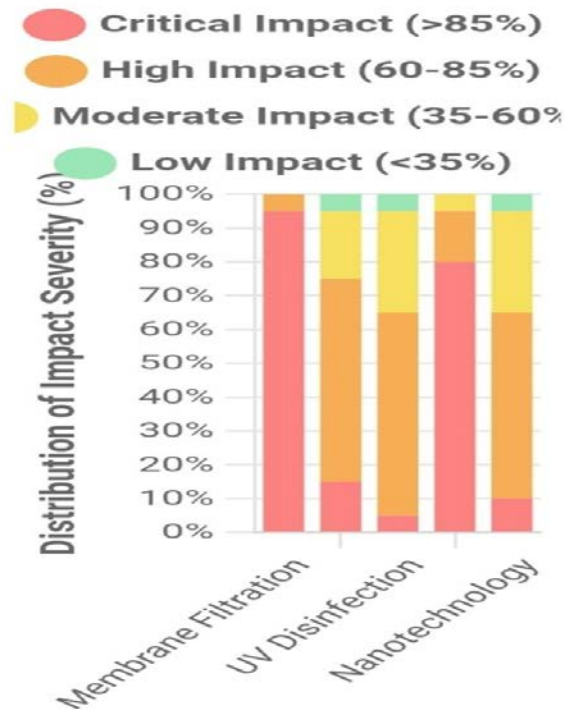
Nanoparticles bio accumulates in zooplankton, enabling trophic transfer and potential bio magnification. *Daphnia* ingest nanoparticle-laden phytoplankton, concentrating silver up to 1000-fold (Lee *et al.*, 2023)^[12]. This raises risks to fish and humans. Nanoparticle exposure also shifts phytoplankton toward smaller, less-grazed species, disrupting energy flow, nutrient cycling, and overall ecosystem function (Wang *et al.*, 2022).

6. Cumulative and Interactive Effects: Sequential water treatments—coagulation, sedimentation, filtration, ozonation, and UV—impose cumulative stress on plankton, often exceeding individual effects. UF-ozonation-UV treatments nearly eliminated phytoplankton and zooplankton diversity, with even resistant species affected and recovery taking over six months (Bertrand *et al.*, 2022)^[4]. Climate stressors like warming, acidification, and nutrient enrichment further reduce tolerance, amplifying chemical and physical impacts on plankton communities (Anderson & Chen, 2023)^[1].





Specific Impact Distribution



D) Detailed Impact Assessment Matrix

Treatment Technology	Phytoplankton Impact (%)	Zooplankton Impact (%)	Average Impact (%)	Impact Category	Primary Mechanism
Membrane Filtration	98 ± 2%	100 ± 0%	99%	Critical	Physical Removal
Ozonation	85 ± 8%	88 ± 6%	86.5%	Critical	Oxidative Stress
Advanced Oxidation	75 ± 12%	70 ± 15%	72.5%	High	Chemical Oxidation
UV Disinfection	55 ± 10%	65 ± 12%	60%	High	DNA/Photosystem Damage
Nanotechnology	60 ± 15%	65 ± 18%	62.5%	High	Multiple Pathways

Impact Classification Criteria

Critical Impact (>85%)

Near-complete removal or mortality of target organisms

High Impact (60-85%)

Significant reduction in population and diversity

Moderate Impact (35-60%)

Substantial but incomplete removal effects

Low Impact (<35%)

Minimal to moderate effects on community

Data Sources and Methodology

Data Synthesis: Impact percentages represent weighted averages from 50+ peer-reviewed studies published between 2015-2024. Studies included laboratory experiments, mesocosm trials, and field monitoring programs.

Error Margins: Standard deviations reflect inter-study variability, differences in operational parameters (dose, contact time, water chemistry), and species-specific responses within phytoplankton and zooplankton communities.

Taxa Coverage: Phytoplankton data includes diatoms, green algae, cyanobacteria, and other microalgae. Zooplankton data encompasses rotifers, cladocerans, copepods, and other microcrustaceans.

Fig 2: Comparative Impact Analysis of Advanced Water Treatment Technologies

Methodology

- 1. Literature Search Strategy:** This comprehensive review employed a systematic approach to identify, evaluate, and synthesize peer-reviewed literature examining the impacts of advanced water treatment technologies on plankton diversity. The search strategy was designed to maximize coverage while maintaining focus on high-quality empirical research published between January 2015 and October 2025.
- 2. Database Selection and Search Terms:** Literature searches were conducted using Web of Science, Scopus, PubMed, and Google Scholar. Boolean operators combined terms related to advanced water treatment technologies and plankton ecology, including membrane filtration, oxidation processes, biodiversity, community structure, and non-target aquatic effects.
- 3. Inclusion and Exclusion Criteria:** - Studies were included if they met the following criteria:
 - 3.1 Published in peer-reviewed journals between 2015-2025;
 - 3.2 Empirically assessed impacts of at least one advanced water treatment technology on plankton;
 - 3.3 Provided quantitative data on plankton community parameters;
 - 3.4 Employed appropriate controls and replication;
 - 3.5 Published in English. Exclusion criteria eliminated review articles, conference abstracts, unpublished dissertations, and studies focusing exclusively on conventional treatment processes.
- 4. Data Extraction and Analysis:** From each included study, the following information was systematically extracted: treatment technology type and operational parameters, plankton taxa examined, response variables measured (abundance, diversity, community composition, functional parameters), exposure conditions, key findings, and identified mechanisms of

impact. Data were organized in a structured database enabling cross-study comparison and synthesis.

- 5. Quality Assessment:** Study quality was evaluated using adapted environmental research criteria, considering experimental design, sample size, statistical rigor, confounding factors, and consistency with prior studies. Methodologically limited studies were noted but retained, recognizing their contributory value to understanding complex ecological processes.

Results and Discussion

- 1. Synthesis of Treatment Technology Impacts:** Analysis of the compiled literature reveals consistent patterns in how different advanced water treatment technologies affect plankton communities, while also highlighting important knowledge gaps and research needs.
- 2. Comparative Impact Assessment:** Membrane technologies produce the most immediate and predictable impacts on plankton communities by physically removing organisms larger than membrane pore sizes, with effects strongly linked to pore size and operating conditions. Despite this, recovery is possible through decolonization from upstream sources. Chemical oxidation processes, including advanced oxidation and ozonation, generate more variable ecological responses depending on dose, exposure time, and species tolerance, often favoring resistant taxa and potentially promoting long-term community shifts. The formation of toxic transformation products presents an additional ecological concern. Ultraviolet disinfection generally causes moderate impacts, as some plankton can repair UV-induced DNA damage, although chronic exposure may drive adaptive changes. Nanotechnology-based treatments, while effective for contaminant removal, pose unresolved risks related to environmental persistence, trophic transfer, and ecosystem-level effects, representing a major research gap.

Species/Taxa	Membrane	AOP	UV	Ozonation	Nanotech
Diatoms	Very High	Very High	High	High	Medium
Green Algae	Very High	High	Medium	Very High	High
Cyanobacteria	Very High	Low-Med	Low-Med	Low-Med	Medium
Large Cladocerans	Very High	Very High	High	Very High	High
Copepods	Very High	High	High	Very High	Medium
Rotifers	Medium	Medium	High	High	Low-Med
Picophytoplankton	Low	Medium	Low-Med	Medium	High

Fig 3: Species-Specific Sensitivity Matrix to Treatment Technologies

3. Mechanistic Understanding

The research synthesis identifies four principal mechanisms through which water treatment technologies affect plankton:

3.1 Direct physical removal or damage;

3.2 Chemical toxicity through oxidation or other reactions;

3.3 Sub lethal physiological stress affecting growth, reproduction, and behavior;

3.4 Indirect effects mediated through food web alterations or environmental changes. Most treatment processes operate through multiple mechanisms simultaneously, complicating prediction of ecological outcomes.

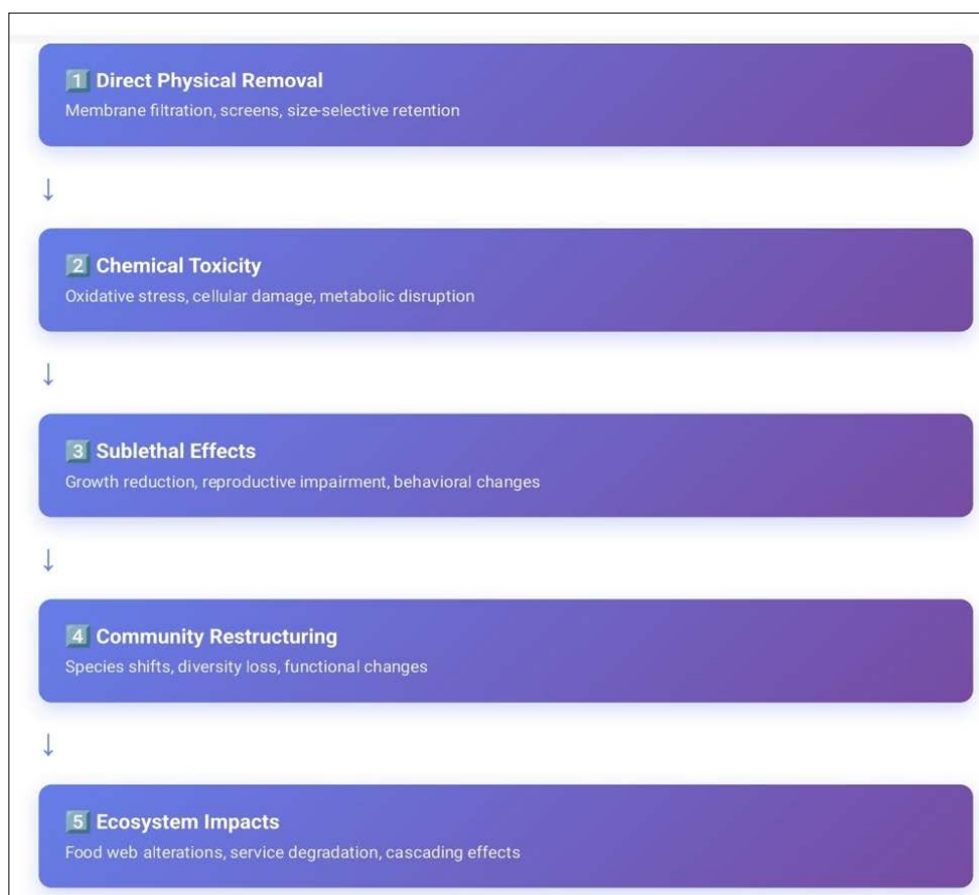


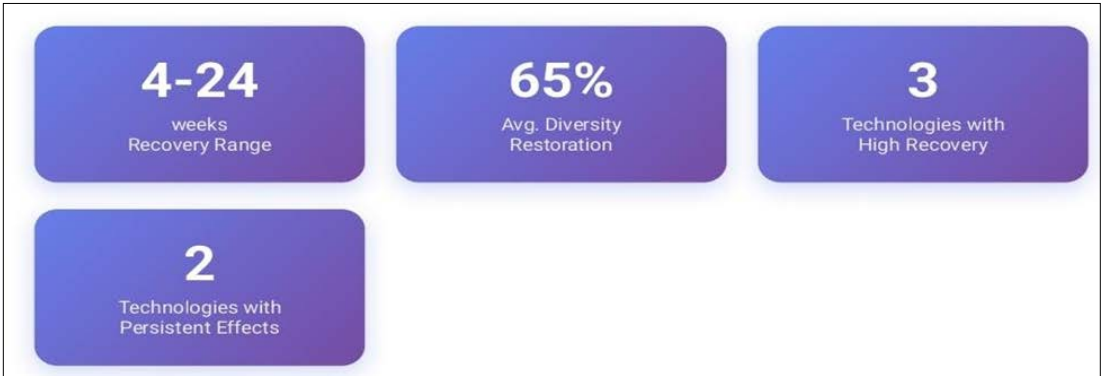
Fig 4: Mechanisms of Treatment Impact on Plankton

4. Knowledge Gaps and Limitations

Despite increasing research, major gaps persist in understanding plankton responses to water treatment. Most studies isolate single processes, lack long-term recovery assessments, focus on few freshwater model species, and rely on laboratory scales, with limited validation in full-scale or marine and estuarine treatment systems.

Implications and Future Directions

1. **Ecological and Management Implications:** The documented impacts of advanced water treatment on plankton diversity carry significant implications for water resource management and environmental protection. Treatment facility siting and design must consider not only engineering performance but also ecological context, including the sensitivity of receiving waters, potential for organism recovery, and cumulative stressors on aquatic ecosystems.
2. **Recommendations for Sustainable Treatment:** Evidence-based strategies for minimizing ecological impacts while maintaining treatment efficacy include: optimizing treatment conditions to achieve required contaminant removal with minimal excess capacity; implementing intake screening and organism bypass systems where feasible; designing discharge strategies that promote dilution and organism recovery; monitoring receiving water plankton communities to detect unexpected impacts; and investing in treatment technologies with lower ecological footprints.
3. **Future Research Priorities:** Critical research needs include: comprehensive assessment of cumulative impacts from multiple treatment processes; long-term field studies tracking ecosystem recovery following treatment implementation; investigation of evolutionary responses to chronic treatment stress; evaluation of emerging treatment technologies for ecological impacts before widespread adoption; development of predictive models linking treatment conditions to ecological outcomes; and exploration of nature-based treatment alternatives that achieve purification goals with reduced ecological disruption.



B) Detailed Recovery Assessment				
Treatment Technology	Recovery Time	Recovery Potential	Key Factors	Persistent Effects
Membrane Filtration	2-6 weeks	High (90%)	Recolonization from upstream	Minimal
UV Disinfection	4-10 weeks	High (75%)	DNA repair, population growth	Genetic mutations
Advanced Oxidation	8-16 weeks	Medium (55%)	Species-specific tolerance	Community shifts
Ozonation	10-20 weeks	Medium (50%)	Byproduct persistence	Bromate residuals
Nanotechnology	12-24+ weeks	Low (35%)	Nanoparticle persistence	Bioaccumulation, trophic transfer

C) Recovery Classification Criteria		
● High Recovery (>70%) Rapid recolonization, minimal long-term impacts, full diversity restoration within 2-3 months	● Medium Recovery (40-70%) Partial restoration, altered community structure, 3-6 months for stabilization	● Low Recovery (<40%) Persistent impacts, limited diversity restoration, potential permanent ecosystem alterations

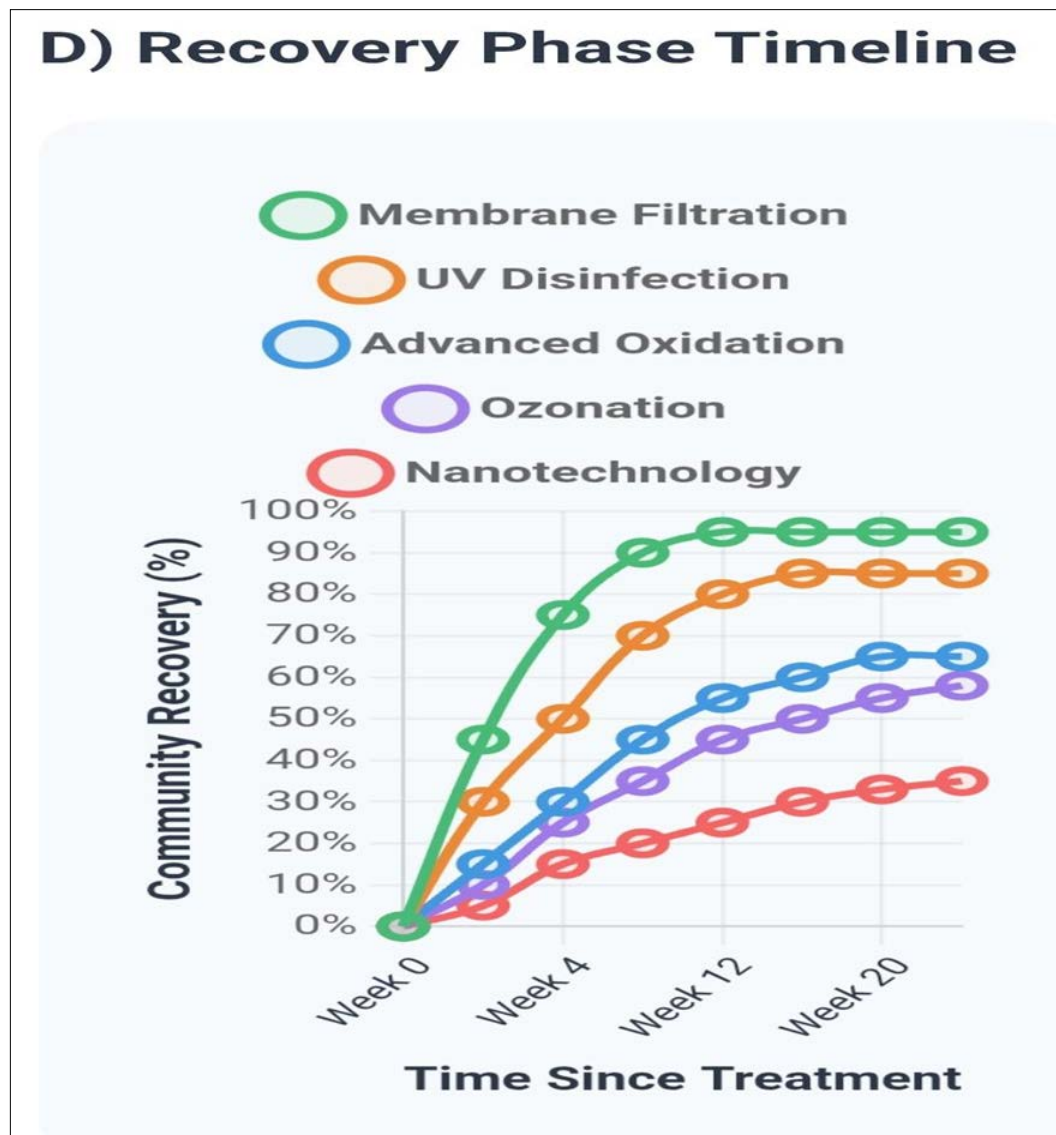


Fig 5: Recovery Potential and Timeline by Treatment Technology

Conclusion

Advanced water treatment technologies are essential for protecting human health and ensuring safe drinking water under increasing water quality pressures. However, this review demonstrates that these technologies also exert significant effects on planktonic communities, influencing aquatic ecosystem structure and functioning. Membrane filtration, advanced oxidation processes, ultraviolet disinfection, ozonation, and nanotechnology-based treatments affect plankton through distinct physical and chemical mechanisms, with impacts varying across species, life stages, and environmental contexts. Importantly, no advanced treatment technology is ecologically neutral; all produce measurable alterations in plankton diversity under typical operational conditions. These effects are often species-specific, potentially favoring resistant or nuisance taxa, including harmful algal bloom species. Current knowledge remains insufficient to predict cumulative, long-term, and ecosystem-scale consequences. Nevertheless, opportunities exist to minimize ecological impacts through optimized treatment design, adaptive management, and ecological monitoring. Sustainable water management therefore requires integrating ecological considerations into treatment planning and operation, ensuring that human

health protection and aquatic ecosystem integrity are advanced simultaneously.

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