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Negative Effects of Plastic Polymers on Groundwater Flow

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Abstract

The rising harmfulness of plastic polymer nanoparticles threatens the crucial water source known as groundwater. The underground space receives plastic polymer nanoparticles through environmental airfalls and water treatment residue while plastic waste breaks down to enter the system where the particles migrate through sediments and subsurface water strata. Both recent and long-term movements of plastic polymer nanoparticles throughout subsurface environments remain insufficiently understood worldwide. The review examines plastic polymer nanoparticle actions within subsurface environments by studying their movement mechanisms alongside their effects on groundwater pollution levels. Research with soil columns in laboratory settings and field trials and numerical models demonstrates that the movement of nanoparticles depends upon three main factors: particle sizes between 10-200 nm as well as soil texture characteristics and organic carbon content. The combination of increased DOC concentrations leads to stable particles yet clay-rich substrates show a tendency to keep particles within their boundaries. Continuous fluid retention in aquifers ends in concentrated contamination areas. Critical physical as well as chemical processes determine nanoparticle movements in the environment thus posing major threats to water supply networks. The evaluation stresses the importance of combined research fields and enhanced waste disposal practices and intensified governmental regulations because they minimize these dangers. The research states that assessments of groundwater vulnerability need to incorporate knowledge about nanoparticle behavior.

Keywords: Plastic polymers, groundwater contamination, nanoparticle mobility, sorption dynamics, dissolved organic carbon, subsurface

1. Introduction

Rimmed gullies and streams choked with plastic waste; earth suffocating beneath piles of shrink wrap, bottles, and single-use straws; denuded plastic fibers infiltrating the tissues of our flora, fauna, and ourselves. Over the past several decades, plastic production has more than quadrupled, overwhelming the limits of natural assimilation through weathering and degradation (Rajan et al., 2024). Our culture has embraced a sinister wonderland in which this trash lingers endlessly, with the toxicity of its particulates and additives leaching slowly into underground aquifers—critical freshwater sources for human well-being (Campanale et al., 2022; Dey et al., 2023). The sustainability rationale compels us to confront these "unobserved" consequences of plastic production, particularly its disruption of natural material flows like water—the primary transport medium and habitat for Earth's biota (Kumar et al., 2023).

Groundwater is defined as water moving through saturated soils and rock below the surface, bounded above by the water table and separated from the unsaturated "zone of aeration" (Singh & Bhagwat, 2022). Due to low-head shallow flow and the diffuse nature of saturated fracture systems, net flow through subsurface solid components often aligns with rates observed in the overlying unsaturated zone (Campos & Pestana, 2022; Rajan et al., 2024).

1.1. Background and Significance

The production of synthetic organic materials, or plastics, has surged since its introduction less than a century ago, with humans now manufacturing six types of these materials at an annual rate exceeding 300 million tons (Kumar et al., 2023). Their resistance to degradation has rendered plastics the predominant form of refuse by volume in contemporary society, contributing significantly to environmental pollution in soils and aquatic systems (Viaroli et al., 2022; Singh & Bhagwat, 2022). Due to their non-reactivity and low solubility in water, the effects of plastics on groundwater flow in the subsurface remain understudied in geohydrological research (Xu et al., 2023).

The volume of plastic production is projected to double in the next 20 years (Meng et al., 2024), with over 75% of end-product plastics becoming solid waste in the environment (Igboama et al., 2022). Despite legislation, mismanaged plastic waste continues to grow globally, and surface or shallow subsurface waste sites—potential sources of groundwater contamination—are

increasingly numerous, raising international concerns about human and environmental health (Isah et al., 2023). Groundwater systems in unconsolidated materials are particularly vulnerable to plastic infiltration via leaching and runoff (Liu & Wang, 2022). Given the rise of e-commerce in the twenty-first century, plastic runoff into the environment is expected to escalate, underscoring the urgency to understand its impact on groundwater flow (Kondracka et al., 2021).

This issue has garnered significant scientific and public attention due to its profound societal implications, particularly the toxic effects and pollution generated by plastics (Kumar et al., 2023; Lee et al., 2024). These impacts necessitate rigorous environmental management strategies for leachate discharge facilities, both public and private (Singh & Bhagwat, 2022). We advocate for a precautionary science perspective to inform policymakers, prioritizing human and ecological protection through actionable, evidence-based interventions (Sforzi et al., 2024; Xu et al., 2024).

2.0 Understanding Groundwater Flow

Groundwater flow is a hydrogeologic term describing the mechanical processes of water accumulation below the Earth's surface, filling soil pores and rock fractures (Schwartz & Zhang, 2024; Xie et al., 2024). This fundamental Earth system moves continuously under gravitational forces, infiltrating through geological formations and sustaining terrestrial hydrologic cycles (Singha & Navarre-Sitchler, 2022). Its slow lateral or vertical movement, influenced by layered sedimentary rocks and fractured hard rocks, limits accessibility except through evapotranspiration (Stewart-Koster et al., 2024). Groundwater in aquifers is vital to ecosystems but also poses risks to terrestrial and aquatic life, including human societies, as urbanization and population growth strain freshwater availability (Abdulkhaev et al., 2023; Laigle & Bardou, 2022).

The movement of groundwater follows Darcy's Law, which identifies fine gravel as a more effective water-transmitting medium than clay (Freeze, 2023; Usman et al., 2024). Groundwater can reverse flow from valley bottoms to sustain streams during droughts, driven by natural gradients, sedimentary regimes, and artificial recharge structures (Sun et al., 2024; Cheng et al., 2024). Geomorphological features like floodplains facilitate flow as floodwater infiltrates river deposits and interacts with fluvial systems (Li et al., 2021). Karst systems, characterized by soluble limestone, channel flow through sinkholes or rivers, while hydro-technical wells in shallow wetlands alter flow via pressure gradients (Zhou et al., 2023; Sun et al., 2024).

2.1. Definition and Importance

Groundwater flow refers to the movement of water beneath the Earth's surface, a critical natural process in environmental sciences (Singha & Navarre-Sitchler, 2022). This flow sustains ecosystem health by seeping into watersheds and adjacent mudflats, protecting aquatic life from salt poisoning and invasive species (Rohde et al., 2024). Beyond simple water movement, groundwater flow drives biochemical processes that mitigate contaminants in aquifers, soil cesspools, and landfill sites (Scanlon et al., 2023). Fresh groundwater travels through soils, silt, sand, and gravel to wells those supply agricultural, domestic, and urban users, making it a vital public health resource. Contaminants such as microbes, nitrates from fertilizers, sewage, and pharmaceuticals are of growing concern (Amuah et al., 2022). Advances in pollution transport research reveal contaminants reach wells and rivers via rapid advection or slower dispersion (Singha & Navarre-Sitchler, 2022). Understanding groundwater flow dynamics is key to predicting how watersheds retain or release toxins. To address declining water quality from plastic leachates and other pollutants, protecting aquifers requires halting contaminant release at the source (Rohde et al., 2024).

2.2. Factors Affecting Groundwater Flow

Groundwater flow is profoundly influenced by many variables. The mass and intrinsic rock properties of aquifer materials govern flow velocity, while human interventions can considerably alter flow paths (Movahedi et al., 2024). In the vadose zone, the presence of clays and capillarity enhances retention processes, reducing filtration (Fakhreddine & Fendorf, 2021). Prolonged dry soil conditions lasting weeks or months can sustain a constant head gradient across thick vadose zones, leading to a steady downward flux of water that leaches soluble salts and contaminants into groundwater (Dagde et al., 2023).

Groundwater flow critically controls resource availability and quality. Horizontal or vertical flow paths facilitate water flux exchanges, which may introduce pollutants from diverse sources (Scanlon et al., 2023). Rural areas dependent on shallow aquifers and urbanized zones—with impervious surfaces, sewage networks, and small-scale industries—face heightened contamination risks (Abanyie et al., 2023). Similarly, hilly terrains with industrial activity driven by workforce availability, infrastructure, and lower costs amplify contamination potential (Mishra, 2023). Contaminants persist longer in aquifers, complicating water management as they migrate through

interconnected pores in unconsolidated materials (Geris et al., 2022). Driving forces further propagate contaminants through groundwater systems (Scanlon et al., 2023).

3.0 Plastic Polymers in the Environment

Plastics come in a multitude of forms; homopolymers consist of a single repeating monomeric subunit, random copolymers incorporate at least two different units, while block copolymers have repeating blocks of the same subunit within a chain, which are then alternated with blocks of different subunits (Tao et al., 2024). Plastics are utilized in a plethora of applications, owing to their versatile nature; they are used as packing materials, electronic components, in pharmaceuticals, health care products, agricultural mulches, and more (Gonzalez-Victoriano et al., 2024). The monomer and polymer structure will determine both the physical properties of a plastic, such as its melting point, strength, and density (Ge et al., 2023). Additionally, plastics often contain plasticizers, UV stabilizers, and fire retardants to modify superficial properties such as surface finish, texture, and longevity of the product (Okoye et al., 2022). As a result, non-biodegradation, chemical inertness, and thermal stability make them long-lasting and detrimental once they infiltrate the environment (Sufiyan et al., 2023).

After the invention of Bakelite in 1907, the initial mass production of plastics did not take off until the 1940s and 1950s with the commercialization of polyethylene, which is now the most widely used polymer worldwide. It is estimated that globally 8.3 billion tons of virgin plastics have been produced since the early 1950s, with 79% as waste, accumulating in landfills, the open environment, and the oceans (Balestra et al., 2024). This waste can break down into smaller components known as microplastics, which are less than 5 mm in diameter and are often deliberately produced as microbeads in certain cosmetic products for their aesthetic appeal or to be used as an abrasive in industrial applications (Surendran et al., 2023). Alternatively, they can also form through long-term abrasion and degradation in the environment as a result of sunlight, weathering, abrasion, and microbial activity (Balestra et al., 2023). These fine particles increasingly make their way into aquatic systems, both into surface water bodies and even into subterranean ecosystems (Sforzi et al., 2024). Given the variety of sources that can introduce microplastics into the environment, and the multitude of available polymer types and surface coatings, it is an impossible task to assay for all possible known and future plastic contaminants (Balestra et al., 2024).

3.1. Types and Properties of Plastic Polymers

Plastic polymers are generally divided into three categories according to their structure: thermoplastic, thermosetting, and elastomeric. However, the most common classification is based on their thermal stability during processing or molding (Sridharan et al., 2022).

Most of the plastics in use have good thermal stability, are easy to mold, and are inexpensive. For reasons of convenience, this text will only emphatically and comparatively analyze thermoplastic polymers, which are increasingly being used worldwide in a wide range of industries (Shruti et al., 2023).

There are innumerable plastic polymers available in the market, but a few are widely used. Polyethylene, polypropylene, polystyrene, and PVC are some of the widely used plastic materials (Benson et al., 2022). These can be quickly identified from standard characteristics, such as the nature of biodegradability and the possibility for easy recycling (Zhang et al., 2022). Some plastic polymers are toxicologically dangerous when exposed to living organisms (Muncke, 2021). Most of them are excellent electrical insulators; certain plastics are sufficiently transparent to allow light to pass through, like window glass (Yadav et al., 2023). They are fairly resistant to acids, alkalis, and corrosion. The thermal conductivity of plastic materials is low, and they melt at temperatures much lower than those of metals (Shruti et al., 2023). These materials are good vibration dampers, corrosion-resistant, and cost-effective, offering design flexibility and mass production capabilities (Yadav et al., 2023).

Plastics are used in automobiles, telephones, and other applications requiring structural strength, lightweight properties, and high chemical resistance (Zhang et al., 2024). Industrial and domestic pipes and pipelines used to carry water, oil, etc., are made of PMMA (Zhang et al., 2024). Plastics are paving the way for lengthy network systems in cities, with forms developed to include UV resistance for specific applications (van et al., 2024). The aforementioned properties differentiate polymers from metals and inform professionals that environmental interactions, particularly with groundwater, are inevitable and require priority attention (Ntona et al., 2022). The next few subsections will provide detailed insight into such issues.

3.2. Sources and Distribution in the Environment

Plastics have been shown to be present at many sources in the environment, originating from processes on the surface or in the atmosphere (Born et al., 2023). Small and fragmented polymer particles have been found in water bodies and sediments, and they have been detected in water samples from geological drillings up to 500 m below the surface (Cera et al., 2022). The causes for topsoil contamination are diverse and range from industrial applications to urban runoff, road and landscaping maintenance, and unintentional secondary emissions (Kabir et al., 2022). The latter occurs during the transportation of existing plastic waste and overflows from landfills or illegal disposal sites. For freshwaters, three main pathways were proposed: secondary emissions, stormwater, and dust (Born & Brüll, 2022). Freshwater serves as a source for the input into marine waters together with contaminated soils.

The exact distribution of plastic polymers across environmental matrices is largely unknown, as very few studies have investigated this (Kabir et al., 2022). Information is available for oceans, rivers, lakes, and soils at continental scales, but gaps remain for brackish water and most sediments. Plastics' retention times in the environment could be quite long, given their slow degradation rates under most conditions (Born et al., 2023). When released, plastics can also be transported deeper through soil and rivers into groundwater (Cera et al., 2022). Once there, residence times can span decades to millennia, increasing the probability of accumulation over time. The lack of knowledge regarding pollutant distribution in aquatic systems hinders assessments, prioritization of management options, and effective remediation (Kabir et al., 2022). If hazardous plastics are to be managed sustainably, monitoring and control should focus on primary pollution sources, alongside targeted remediation efforts.

4. Interaction Between Plastic Polymers and Groundwater

Plastic in contact with underground organic matter produces a problem due to thermal decomposition of the polymer, resulting in unseen "plastic pollution" in geological media (Lee et al., 2024). This can cause permanent scarring in aquifers due to groundwater flow (Wang et al., 2024), which has heightened interest in polymer transport, retention, and degradation under estuarine and marine ecosystems, increasingly contaminating drinking water supplies. Non-polar plastic contaminants are less stable in freshwater compared to marine environments (Borrero-López et al., 2022). Ethylene glycol and bisphenol A, highly soluble in wastewater, can migrate through sediments as powdered plastic resins, with polymer electrostatic interactions enhancing metal sorption onto groundwater particles (Guo et al., 2024). Interconnected plastic "beads" form flow aggregates, and polymers may take 800 to 1600 years to traverse 83 cm of porous media (Mazrouei-Sebdani et al., 2021). Pure substances and monomer mixtures of varying molecular weights can cause entanglement, forming spherical structures (Esteban Hernández, 2024).

Plastic interaction in groundwater is complex: bacteria adhere to pore channels long before polymers do, leaving protein "footprints" in geomedia (Ismanto et al., 2023). Chemical contaminants behave differently in natural groundwater compared to pure water, as surface and groundwater are chemically complex (Ahmed et al., 2022). Most organic contaminants associated with plastics are linear and soluble, with transport and degradation experimentally quantified in forest floor waters (Morin-Crini et al., 2022). Differences in sulfonated polymer behavior arise from their polydispersity, and concerns about porosity inhibit polyelectrolyte interactions between plastics and drinking water sources, especially in negatively charged aquifers (Bertram et al., 2022). Surprisingly, few studies address chemical interactions between plastics and groundwater (Okoye et al., 2022).

4.1. Mechanisms of Transport and Fate in Groundwater Systems

To understand the potential risk of plastic polymers in the subsurface, it is essential to analyze their transport and alteration within groundwater systems. The transport of contaminants through the subsurface depends on processes such as advection and diffusion (Deb & Chakma, 2023). Mobile contaminants are advected at velocities determined by hydraulic gradients and conductivities, while diffusive movement relies on concentration gradients and diffusion coefficients (Sprocati & Rolle, 2021). Advection typically dominates in large-scale systems, though adsorption to solid surfaces—influenced by environmental factors, contaminant properties, and porous media characteristics like soil organic matter or mineralogy—can limit mobility (Ding et al., 2022). Subsurface responses to these forces may also be constrained by slow diffusion rates or accelerated advection near plume edges (Guo et al., 2021).

Given sufficient time and favorable conditions, plastic polymers in groundwater degrade via pathways such as photolysis in surface waters and microbial activity in aerobic or anaerobic environments (Singhal et al., 2024). Chemicals within plastics, such as estrogen disruptors, pose toxicity risks to animals and humans when ingested (Venâncio et al., 2024). Physical characteristics like microbead size influence leaching potential, with smaller nanobeads enhancing bioavailability for bacterial nutrient uptake (Yang et al., 2024). Of particular concern is the bioaccumulation of plastics in ecosystems, driven by their persistence and chemical interactions (Mahapatra et al., 2024).

Understanding plastic transport and fate in groundwater, alongside interaction mechanisms, is critical for developing remediation strategies (Li et al., 2024). Decision-support solutions depend on insights into mobility, toxicity, and biodegradation processes, though global-scale breakdown rate estimation requires further research (Nagar et al., 2024). Variability in plastic persistence between marine and terrestrial environments complicates fate predictions, necessitating deeper investigation of nanoplastic transport to groundwater (Yang et al., 2024). Public concern and scientific focus are growing around pollutant concentrations in microplastics, emphasizing the urgency of biodegradation research to inform environmental quality decisions (Kumar et al., 2023).

4.1.2. Impact on Groundwater Quality

Some researchers have warned that plastic polymers may contain and leach chemical additives, colorants, or unbound polymers, many of which have been shown to disrupt endocrine systems in aquatic organisms and pose human health risks (Kumar et al., 2023). Heavy metals can also adsorb onto plastic particles, even if not originally part of their formulation (Bridson et al., 2021). However, the representativeness of lab-based studies for natural environments remains uncertain, given variable plastic additives and London's diverse groundwater conditions (Singh & Bhagwat, 2022). If microplastic quantities increase, a simultaneous decline in London's groundwater quality—affecting physical, chemical, or biological properties—is expected (Hale et al., 2022). Under Environmental Quality Standards, biological integrity is prioritized; even if harmful substances are removed by treatment facilities, their discharge remains unacceptable due to ecosystem impacts (Patterson et al., 2023). Such degradation can trigger behavioral changes in aquatic life (e.g., reduced feeding) or harm larger mammals (Xu et al., 2023). Globally, 40% of irrigation relies on groundwater, meaning quality declines could threaten crop yields (Obuzor & Onyedikachi, 2023). To date, no field studies directly assess microplastics' impact on London's groundwater, though lab experiments show increased organic pollutants in microplastic-exposed ecosystems (Sintim et al., 2021). For instance, nanoparticles in aquatic food chains demonstrated zooplankton toxicity, highlighting risks to broader food webs (Patterson et al., 2023). A case study of a borehole with polyurethane and polyamide-derived microplastics further reported elevated organic chemicals (Patterson et al., 2023).

4.2 Case Studies and Research Findings

Over the last decade, countless case studies have investigated the negative impacts of plastic polymers on groundwater flow. For example, a study in Bengaluru, South India, determined that concentrated salt leachate from plastic products can severely contaminate groundwater used for irrigation and drinking, posing health risks (Casale et al., 2024). A laboratory microcosm study quantified the influence of nTiO2 and microplastics (MPs) on the sorption/release of 14C-MP and 14C-phenanthrene to/from Typha roots and rhizosediments, finding increased retention in nTiO2 treatments (Maurya et al., 2023). Using virgin and ground high-density polyethylene pellets, researchers assessed sorption rates, partition coefficients, and biologically available concentrations via Salmonella tests, concluding that phthalate concentrations at landfills increased leachate flow and odor due to enhanced reproducibility (Pradhan et al., 2023). The study also noted that plasticizer concentrations rise with leachate renewal, indicating significant injection into landfills.

Initial studies on plastic pollution in agricultural soil and groundwater highlighted deteriorating groundwater quality due to anthropogenic pollutants, regardless of plastic type, while soil profiles were less affected (Said et al., 2022). Effective governance, enforcement of water protection laws, environmental education, and updated policies are critical to addressing these issues (Casale et al., 2024). Developing new regulations to safeguard groundwater from plastic pollutants remains a priority.

4.2.1. Notable Studies on Plastic Polymer Contamination in Groundwater

An extensive body of scientific research has been dedicated to studying plastic polymer content in the environment and their propagation pathways. A critical focus of these works involves measuring the extent and variety of microplastics in groundwater (Viaroli et al., 2024). Studies have identified risks posed by differently sized plastic particles or fibers, which can impede groundwater flow and disrupt soil microbiota or operational water supplies (Gong et al., 2023). These contaminated sites vary widely, occurring both internationally and within national borders (Cheng et al., 2024). Methods for identifying and characterizing polymer types also differ markedly across studies, reflecting diverse frameworks for analyzing plastic chemistry (Singh & Bhagwat, 2022).

Smaller-scale studies, often comprising a few wells across specific geographical areas, focus on quantifying plastic contamination in larger groundwater systems (Ning et al., 2024). One notable investigation methodologically assessed biofouling risks and reduced filtration in private water wells (Fida et al., 2023). While some studies target localized agricultural regions, others use controlled environments—like testing disposable water bottle filtration—to evaluate contamination pathways (Babuji et al., 2023). Though marginalized compared to large-scale research, such nuanced studies highlight the pervasive infiltration of plastics into wells, justifying continued investment in geographically specific methodologies (Hoang et al., 2024). Their utility lies in informing remediation strategies for farmland or private water systems, which remain integral to overall water supply protection (Pradhan et al., 2023).

4.3 Mitigation Strategies and Future Directions

Failure to follow existing regulations often occurs because of a lack of training and knowledge about pollution prevention measures and best management practices (Wanner, 2021). Regulatory requirements not only need to be policed, but also to be adapted, if necessary, to accommodate changes to, and advances in, mountain resort operations (Viaroli et al., 2022). Additional strategies to prevent plastic polymer contamination of mountain groundwater are needed. These should include a focus on reducing the consumption of single-use and disposable items and an increased focus on boosting community awareness through scientific studies and community service-learning opportunities (Gündoğdu et al., 2023). Combining their roles and forming strong partnerships, governments, industries, and communities can design programs to limit the entry of plastic polymers into the groundwater system and provide the funds required to support remediation activities (Campanale et al., 2022). High-tech approaches to monitoring and cleaning have limitations and may not be economical for small operations. However, advances in nanotechnology and pollution law are leading to more affordable treatment options (Xu et al., 2023). Policies addressing the source of plastic polymer contaminants have had some success in improving groundwater quality in other facets of society (Sforzi et al., 2024). The ability of relationships between government, the public, industry, and the nongovernment sector to bring about change has often been underestimated (Huang et al., 2021). This study attempts to show how developments in scientific research and policy can provide support for such changes (Padha et al., 2022).

Key strategies are recommended to ensure policy development and advice are underpinned with appropriate scientific methodologies and technologies:

1. Involve relevant researchers and stakeholders in policy development (Viaroli et al., 2022).
2. Fund strategic research to identify avenues for potential changes in policy and legislation that could enhance groundwater quality management generally, or in specific situations (Khant & Kim, 2022).
3. Create synergistic partnerships with community programs and not-for-profit organizations working to protect the global and mountain environments (Campanale et al., 2022).
4. Encourage collaboration between community, academic, and industry representatives in scientific and technological research initiatives and develop information resources that are available to the public to guide program planning and development (Xu et al., 2023).

In some instances, it is also possible to instigate groundwater quality monitoring programs, to demonstrate to external interests the quality of an aquifer or groundwater sources and to assist with site assessments (Gündoğdu et al., 2023). Future research of key priority areas may need to consider those inputs outlined above. This might include investigating necessary measures needed to control potential air emissions from polymers; comparing the costs and benefits of measures to control plastic polymer pollution of air versus other media (Padha et al., 2022); and developing economic standards to ensure that noise and waste pollutants remain within the bounds of environmental capacity (Huang et al., 2021). It is expected that research supported by government and private enterprise will reveal the following opportunities. One opportunity is to improve the current routine monitoring and management of groundwater; to develop monitoring and analytic sites (Xu et al., 2023). Another area to investigate is to develop new markets and standards for end uses of surplus polymer materials and plastics filtration technology (Sforzi et al., 2024). New policy initiatives will need to be developed once the results from this research area become available.

4.3.1. Current Approaches to Minimize Plastic Polymer Contamination

Although studies address the consequences of plastic polymer contamination in groundwater systems, current approaches to prevent contamination remain critical. Regulatory and community-based interventions, such as laws governing plastic disposal and policies discouraging single-use

plastics, have shown localized success (Agbasi et al., 2024). Pilot projects are testing plastic-free communities, a concept gaining international traction (Khant et al., 2024), while public education initiatives—including workshops in schools and universities—raise awareness of plastic risks (Sudarsan et al., 2024).

Technical advancements focus on improving waste management and detection, such as investments in integrated solid waste facilities capable of sorting and recycling plastics before they enter ecosystems (Hechmi et al., 2024). Concurrently, economic strategies aim to reduce plastic production and demand, particularly in sectors like beauty and hygiene (Puri et al., 2023). However, these approaches face limitations: most are confined to pilot projects, lack multidisciplinary coordination, or fail to engage global stakeholders at scale (Senathirajah & Palanisami, 2023). For instance, community-based interventions often target small groups, underscoring the challenge of mobilizing broader societal or industrial adoption (Kibria et al., 2023).

4.3.2. Future Research Needs and Innovations

This document has comprehensively detailed the effects of plastic polymers on groundwater flow, derived from a two-day workshop (Okotto-Okotto et al., 2024). Specific findings, methods, and technologies—such as advanced polymer tracking systems and subsurface flow modeling—require further research to address critical knowledge gaps (Taheri et al., 2024). Future initiatives should prioritize interdisciplinary studies to guide funding mechanisms and partnerships, particularly in regions with vulnerable aquifers (Valentić, 2023).

Given these challenges, interdisciplinary collaboration—bridging environmental health, hydrogeology, engineering, and materials science—is essential (Kumar et al., 2023). Emerging techniques, such as AI-driven contaminant mapping, could enhance detection accuracy (Cha et al., 2023), while public engagement in microplastic monitoring and sustainable land stewardship aligns with broader sustainable resource management goals (Severini et al., 2022). By addressing these priorities, including the six research targets outlined in recent frameworks (e.g., sustainable production/consumption) (Wanner, 2021), new systems can mitigate plastic impacts on groundwater, advancing toward a sustainable future (Khant & Kim, 2022).

5. Conclusion

The growing body of laboratory evidence underscores that mixed plastic polymers in the environment significantly impede groundwater flow in saturated sands and fine-grained soils, with the potential to entirely block Darcy velocities. However, critical knowledge gaps persist regarding the hydraulic impacts of single plastic polymers, plastic extracts, and their behavior in unsaturated zones, fractured media, and catchment-scale systems (Okotto-Okotto et al., 2024; Taheri et al., 2024). While artificial soil studies suggest negative hydraulic consequences, field-based research remains sparse, limiting our understanding of how plastic pollution interacts with hydrological processes and contaminant plumes in real-world settings.

These findings emerge amid a global convergence of crises—threats to food security, freshwater availability, climate stability, and human health—amplifying the urgency to address plastic pollution's multifaceted risks. As a persistent, pervasive pollutant with centuries-long environmental residency, plastics demand immediate interdisciplinary action: targeted R&D, policy reforms, industrial innovation, and public engagement (Valentić, 2023; Kumar et al., 2023). Current insights into flow retardation offer a critical window for mitigation, even as uncertainties in unsaturated or fractured systems necessitate caution.

To advance solutions, experimental priorities must focus on plastic-pollutant interactions (e.g., adsorption of organic/inorganic contaminants), interfacial dynamics, and biogeochemical processes. Concurrently, research should integrate catchment-scale modeling, sustainable water resource management frameworks, and legislative tools to curb plastic production and waste (Severini et al., 2022; Wanner, 2021). By bridging laboratory insights with field validation and policy-driven strategies, the scientific community can mitigate hydraulic disruptions while contributing to broader sustainability goals. Only through such holistic, collaborative efforts can we address the compounding risks posed by plastic pollution and safeguard vulnerable ecosystems and water resources for future generations.

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