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Pollution and Biological Invasions: Two Synergistic Ecological Disruptors!

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Abstract: ***Pollution and biological invasions are two driving forces of ecological disruption to occur though their combined effects are yet to be explored. This review emphasizes how the diverse pollutants viz. heavy metals, pesticides, pharmaceuticals, nutrient enrichment, microplastics, and anthropogenic noise interact with invasion dynamics to remodel ecosystems (Bian et al. 2026; Sousa et al. 2025; Kayode-Afolayan et al. 2022; Cole et al. 2011; Browne et al. 2008). Pollutants eradicate or weaken native species, reduce ecological resilience, and alters habitat in such a way which invasive species can only exploit due to their high phenotypic plasticity and adaptibility (Elliott 2003; Piola and Johnston 2008). Besides, invasive species alters pollutant cycling and various crucial ecological processes, generating control loops that aggravates the habitat deterioration (Camacho-Cervantes and Wong 2023; Alvarez-Aguilar et al. 2022). Many experimental evidences across terrestrial and aquatic systems illustrate how chemical contamination facilitates invasive dominance, eutrophication accelerates algal and macrophyte proliferation, and physical pollutants restructure communities (Crooks et al. 2011). These synergistic and cumulative effects destabilize food webs, reduce biodiversity, and disrupt biogeochemical cycles (Ruhi et al. 2019; Johnston et al. 2017; Ehrenfeld 2010). Traditional management practices which treat pollution and invasion as separate ecological degradative processes, fails to recognize other unintended consequences thus highlighting the need for integrated approaches that addresses both the disruptors simultaneously. So by framing pollution and invasion as two interlinked phenomena, this review advances a holistic approach on conservation of biodiversity and ecological presumption in this ongoing era.***

Keywords: pollution and invasive species, ecosystem disruption, ecological resilience loss, biodiversity decline, pollutant interaction dynamics

1. Introduction

Anthropogenic disturbances and biological invasions together now is an emerging, significant environmental issue of global concern which acts synergistically restructuring ecosystem and ecosystem services thus challenging the decade long conservation management ideas. (Ligocki et al. 2025; Dadhwal et al. 2025; Deslippe and Veenendaal 2025; Chakraborty 2018). In spite of extensive researches on the effects of various stressors individually on our ecosystem the combined effects has not yet been explored. In the context of predicting ecosystem future and conservation strategies of biodiversity in this present scenario, biological invasions and environmental pollution are two of the most high-priority challenges (Simberloff et al. 2013; Hulme 2006; Vitousek et al. 1996) that co-occur and facilitates each other further exacerbating the degradation process (Ventura 2025; Lone et al. 2024; Johnston et al. 2017; Rai 2022).

Pollution encompasses a wide spectrum of stressors, ranging from chemical contaminants such as pesticides, heavy metals, detergents and pharmaceuticals (Bian et al. 2026; Izah and Ogwu 2026; Thakur et al. 2025; Cristiano et al. 2021; Lutts and Lefèvre 2015) to agricultural runoff, untreated sewage, industrial effluents (Izah and Ogwu 2026; Fang et al. 2025; Gunasekara et al. 2025; Rathod et al. 2024), and physical pollutants including microplastics, thermal pollution and anthropogenic noise (Wang et al. 2021; Cole et al. 2011; Francis et al. 2009). The synergistic effects of pollution and invasion on ecosystem can be summarised as:

1) Reduced ecosystem resilience: Pollution is a multifactorial anthropogenic disturbance encompassing a number of stressors differing in their origin, time of exposure in nature as well as their biological impacts which creates a number of constraints for the survival of native inhabitants the condition which invasive species takes advantage of due to their immense physiological tolerances (Kaushik et al. 2025; Khattak et al. 2025). Altered habitat reduces potential of native inhabitants to thrive under such degraded, disturbed conditions which lowers the environmental resistance of the native assemblage. In this way, pollution interacts with invasion pathways by reshaping the environments (Jones and McDermott 2018; Keller et al. 2011). Whatever the cause of invasion may be whether accidental (e.g., ballast water, trade) or intentional, invasion (for eq. aquaculture or agriculture) becomes easier in previously invaded especially polluted habitats as native inhabitants have already been wiped out in such hostile conditions prevailing there (Verna 2021; Hull 2012). Thus, pollution driven invasion helps expand the range of occurrence of invading species into new habitats (Wallingford et al. 2020; Spence and Tingley 2020)

Accumulation of heavy metals such as cadmium, lead, mercury inside soils and sediments sometimes goes beyond the threshold level causing toxicity to the inhabiting flora and fauna (Rahman and Singh 2019; Sardar et al. 2013). But, majority of the invasive plants show phenotypic modifications like changes in vacuoles for metal sequestration, high leaf area index for faster absorption of water, nutrients, sunlight or release of allelochemicals for suppression of native inhabitants etc. (Kumar et al. 2017). In this way, invasive species can explore the polluted areas inhabitable for indigenous one. For instance, metallophyte invaders are excellent competitor in mining sites completely abandoned by sensitive native species. Their tremendous reproductive potential to thrive in degraded soil confers competitive advantage over indigenous species, expanding their habitat range and displacing native vegetation.

Eutrophication is another most significant effects-of-pollution phenomenon directly affecting physiology, feeding, reproduction, communication and resistance of native species (Zhan 2025). Stress-tolerant native species especially algae and aquatic macrophyte can proliferate and takes control of the entire habitat. Pollution affects prey-predator relation, prey behaviour and reduce density of predators by altering their sensory system controlling communication. Such communication disruption reduces their resistance to any further environmental purterbations.

Pesticides designed to decimate pest population has been proved to weaken the resistance to invasion, trophic relationship and thus degrade ecosystem to such an extent irreversible for the survival of native inhabitants again. Due to reduction in the abundance and diversity of native insect species and their predators, the abandoned bare area i.e. agricultural landscape or forest area become the home of millions of stress-tolerant invasive species (Li et al. 2022; Zhang 2018) of which the most abundant phyla being Arthropoda (Wang et al. 2021;). Destruction of the native predators of the invasive species exerts a disrupted top-down effect due to which the invasive prey population escapes the natural predators such as insectivorous birds or amphibians and thus a perfect imbalance is created altering the major food web (Narango et al. 2018; Kats and Ferrer 2003)

2) Habitat degradation: Pollutants in diverse forms alters the hydrodynamics and sedimentation rates of soil thereby altering the nutrient cycling and degrading the quality of habitats. Sensitive indigenous species due to their low resilience cannot withstand such stressful conditions and are outcompeted by highly adapted invasive species (Mori et al. 2025; Wang et al. 2021; Didham 2007) for the sensitive resources like space, food and water.

As evidenced by Li et al. 2022, accumulation of heavy metals decimates the native species populations whereas metallophyte invaders can sustain in such inhabitable situation (Li et al. 2022). Human interferences in the coastline of various continents causes some patches to be devoid of diversity due to multiple, long-term exposure of pollutants. Such patches become occupied by exotic species like *Sargassum muticum*, *Undaria pinnatifida* etc. leading to destruction of dominant macroalgal diversity. Establishment of such dense monocultures and destruction of significant primary producers changes the energy budgets, food web structure which is why shifting in the community structure occurs (Walker and Kendrick 1998). Few introduced species such as monk Parakeet has been known to damage human establishments and several hydrophytes blocks the water ways and affects navigation. Invasive grasses and other plants due to their tremendous proliferation potential increase the frequency and severity of forest fires and modifies their habitat as well as physical environment.

The synergistic effects of pollutants and invaders as a significant contributor of habitat degradation has been documented repeatedly. Rapid proliferation of invasive mussels (*Dreissena polymorpha*, *Corbicula fluminea*) causes filtering of large volumes of water, concentrating heavy metals and organic pollutants in benthic zones thus causing altered pollution cycle. Invaders thriving in excessive polluted conditions acquire many adaptive measures for their sustenance which ultimately causes ecosystem degradation in the long run like invasive macrophytes trapping sediments and nutrients, intensifying eutrophication. (Villamagna and Murphy, 2010). Continuous exposure to combinations of pollutants has cumulative effects on invasion success (Halpern et al. 2008; Crain et al. 2008; Vinebrooke et al. 2004) and causes ecosystem unable to resist invasive pressure (Simberloff 2013; Ehrenfeld 2010; Pyšek et al. 2020). Other than altering the nutrient cycle, alien species has also been reported to manipulate the flow of nutrients among different types of ecosystems thus affecting cross-ecosystem properties. (Ricciardi and MacIsaac 2011; Strayer and Dudgeon 2010).

3) Restructuring of community: Invasions being facilitated by pollution, globalization and trade (Hulme 2021; Thompson 2018; Stoett 2010; Hulme 2009; Galil et al. 2007; Perrings 2005) modifies community establishment rules by disrupting pollination, food web structure and increasing vulnerability of diverse, native floral and faunal assemblage resulting in community homogeneity. Destruction of an assemblage of native species may cause the entire system to collapse what we call as Jenga effect. Uncontrolled use of pesticides in agricultural fields simplifies the food web structure of benthic community. Deposition of harmful contaminants inside soil reduces the population of native predators such as fishes and amphibians thereby posing restrictions on the natural check of their prey population such as Cray fishes etc. Due to reduced predatory pressure and increased tolerance towards pesticides, crayfishes start proliferating enormously with simultaneous decline in another native stress-intolerant crustacean. The effects of reduced predation and pollutant tolerance enables crayfish to expand rapidly, restructure benthic communities, and alter nutrient cycling. This case illustrates how chemical pollution can directly and indirectly promote invasion success, leading to long-term habitat modification.

In sum up, heavy metals, pesticides, and pharmaceuticals demonstrate how chemical pollution interacts with invasion dynamics through multiple pathways (Bian et al. 2026; O'Hea Miller et al. 2024). Pollutants weaken native species, reduce ecological resistance, and create opportunities for stress-tolerant invaders (Zhang 2018). These interactions highlight the importance of considering chemical pollution not merely as an environmental hazard but as a co-driver of biological invasions and habitat homogeneity (Haubrock et al.

2025, Sousa et al. 2025; Ligocki et al. 2025). Understanding these mechanisms is essential for designing integrated management strategies that address both pollution control and invasion prevention (Hulme 2006) as a tool for restructuring of ecosystem.

Alien grasses have been reported to accumulate more nitrogen than their native inhabitants probably due to greater underground masses and efficient decomposition cycles. Some has also been documented to hasten up ammonification process increasing soil ammonia concentration more than that of native vegetation. Nutrient-rich environments inherently favour species with rapid growth and high reproductive output thus conferring competitive advantage on fast-growing invaders. For example, invasive aquatic plants often shows accelerated vegetative growth under high nutrient loads, forming dense mats that causes competitive exclusion of native vegetation (Wang et al. 2021). Similarly, invasive filter feeders may thrive in eutrophic waters by exploring abundant plankton resources, further restructuring community composition (Zhang 2018).

Another significant evidence of the effects of nutrient enrichment on seral changes of community is the proliferation of invasive macrophytes in eutrophic lakes. Species such as *Eichhornia crassipes* (water hyacinth) and *Hydrilla verticillata* rapidly colonize nutrient-rich waters, forming thick surface mats that displace native aquatic vegetation (Sarkar et al. 2016; Tiwari and Pal 2022). These mats reduce oxygen levels, hinder light penetration, and alter habitat availability for fish and invertebrates. Native macrophytes, often adapted to lower nutrient conditions, decline under these competitive pressures. The result is a shift in community composition towards invasive dominance sometimes or sometimes silting up of water bodies with significant implications for biodiversity, fisheries, and water management.

Microplastics impair feeding efficiency and other physiological system of native filter feeders, reducing energy uptake and reproductive success (Galloway et al. 2017; Wright et al. 2013). They accumulate it in tissues which disrupt immune functions and act as vectors for toxic contaminants (Cole et al. 2011). Invasive species with broader tolerances, such as *Dreissena polymorpha* and *Corbicula fluminea*, exploit weakened ecosystems (Sousa et al. 2014).

4) Loss of biodiversity: The intricate association in between pollution and invasion is an emerging environmental issue as presence of different pollutants degrades the quality of soil, air, water creating a hostile, stressful condition for native species to survive which becomes the boon for invasive one. (Sweeney and Mitchell 2019; Godoy 2019; Meyerso and Mooney 2007; Carroll 2007). Invasive species are introduced beyond their native range either naturally or accidentally where they proliferate, establish and outcompete the indigenous co-survivors, (Bharani et al. 2024; Traveset and Richardson 2014). Invaders keep on altering pollutant cycling as has been evidenced in various experimental data - for instance invasive mussels accumulating heavy metals or invader plant altering the nutrient cycle (Schuler et al. 2020) which in turn intensifies destruction of flora and fauna (Li et al. 2022; Rai et al. 2022). In many cases, chemical pollution inadvertently favours invasive species by weakening native populations, altering physiological performance, and disrupting ecological interactions (Cristiano et al. 2025; Scholz and McIntyre 2016; Boyd 2010). Besides, Pollution remediation may also inadvertently favor invaders. (Villamagna and Murphy 2010; Hussner 2012). Dredging to reduce contaminant loads may disturb benthic habitats, facilitating colonization by invasive clams and mussels (Sousa et al. 2008). Pharmaceutical contaminants, including antidepressants, antibiotics, and endocrine disruptors, enter ecosystems through wastewater discharge. These compounds can alter behavior, physiology, and reproductive success in aquatic organisms. For instance, fish exposed to psychoactive pharmaceuticals may exhibit reduced predator efficiency, impaired foraging or altered risk perception. Such behavioral changes weaken native predator populations, indirectly favouring invasive prey species. Invaders that are less sensitive to pharmaceutical exposure can exploit these altered dynamics, establishing themselves in ecosystems where native species are wiped out (Kayode-Afolayan et al. 2022). Other than Pharmaceuticals, nanomaterials, and endocrine disruptors represent novel stressors with potential to reshape invasion dynamics. Their ecological consequences are largely unknown but may alter physiology, reproduction, and competitive interactions (Sharma and Chatterjee 2017; Kidd et al. 2007).

Anthropogenic noise disrupts acoustic communication in native species, impairing mate attraction, prey detection, and territorial defence (Francis et al., 2009). Birds, amphibians, and cetaceans are particularly vulnerable, showing reduced reproductive success and altered migration. Invaders, however, often adapt or exploit altered soundscapes- urban-adapted species like starlings and bullfrogs thrive in noisy habitats. In sum up, pollution causes weakened native species population to wipe out while opening new niches for invader species thus reshaping the entire community. Microplastics and noise has a synergistic relation with eutrophication and climate change, thus paving the way for habitat degradation. Diminishing the sensitive species population like filter feeders performing various ecosystem services like water purification or species with disrupted acoustic communication seriously affects biodiversity and cultural services. Instead of acting independently, pollution and biological invasion interact in complex, nonlinear ways, producing their cumulative effects much more than the sum of their individual's outcomes. Such synergistic and cumulative effects are silently causing the disruption of ecological balance. Excessive nutrient availability promotes the rapid growth of phytoplankton and algae, often leading to dense blooms. While native species may be adapted to moderate nutrient levels, invasive algae and cyanobacteria frequently possess traits like faster growth rates, higher nutrient uptake, greater efficiency and tolerance to fluctuating conditions (Glibert 2015; Thomas and Litchman 2016) so that they can dominate via bloom events, outcompete native phytoplankton altering light penetration, oxygen availability, and overall water quality. The dominance of invasive algal species can cascade through ecosystems, reducing biodiversity and impairing ecosystem services such as fisheries and water purification (Thomas and Litchman 2016; Sukenik et al. 2012).

Pollution-induced environmental stress affects survival of native populations, for which sometimes trophic gap is created which invaders exploit due to their diverse phenotypical modifications. Due to their flexible feeding strategies, invasive species modifies the food webs (Walsh et al. 2016; Ricciardi and MacIsaac, 2011; Strayer, 2010; Shurin et al., 2002) and causes destruction of biodiversity (Pyšek et al. 2020; Strayer & Dudgeon 2010; Dudgeon et al. 2006; Sala et al. 2000). Invasive species causes alteration of nutrients and contaminant flow affecting biogeochemical cycles and reshaping ecosystem functioning. For instance invasive mussel alters as well as concentrates nutrient flow intensifying eutrophication (Scheffer et al. 1993; Sousa et al. 2008; Villamagna and Murphy 2010).

5) Alteration of ecosystem services: Both pollution and invasion degrades the ecosystem functioning exerting pronounced effects on biodiversity, soil stability, pollination, water purification and cultural practices. Acting as pest or weed, invasive species hinders the agricultural activities, clogs waterways, degrades water quality, harbours different pathogens or vectors of pathogens (Sarkar et al. 2023), modify carbon sequestration potential, affects tourism and recreational activities due to diminished fishing, swimming etc. Due to high adaptability and diversified reproductive strategy, invasive species starts to burgeon and lead to profound ecosystem changes. Oxygen depletion from decomposing blooms can cause fish kills, while dense plant mats impede navigation, recreation, and water use. Control or eradication of the alien species and the cause of its sustenance i.e. pollution exerts huge economic burden that challenge restoration and management efforts.

2. Conclusion

Despite these clear linkages, research has traditionally treated pollution and invasion as separate phenomena (Richardson and Pyšek 2006). This segregated approach overlooks the reality that ecosystems are simultaneously exposed to multiple stressors, and that their combined impacts are often nonlinear and synergistic (Dutta 2020). A comprehensive understanding of how pollution interacts with invasion is therefore essential for developing effective conservation strategies (Pyšek and Richardson 2010), designing integrated management approaches (Zhan 2025; Van Rees et al. 2022; Buckley 2008; Hobbs and Humphries 1995; Wang et al. 2021), and forecasting ecosystem futures under such accelerating anthropogenic disturbances (Zhang 2018).

This review synthesizes current knowledge on the multifactorial effects of pollution on biological invasions (Haubrock et al. 2025). It explores how different categories of pollutants influence invasion success, highlights instances across terrestrial and aquatic systems, examines ecosystem level consequences, and discusses the challenges of managing invasions in polluted environments. By framing pollution and invasion as interconnected processes, the review aims to advance a more holistic perspective on biodiversity conservation in the 21st century.

Conventional invasion management often focuses on eradication, containment, or biological control, while overlooking pollution as a co-driver of invasion success. This narrow focus can limit effectiveness of the adopted strategies (Simberloff 2013; Richardson and Pyšek 2006; Lockwood et al. 2013). When adopting particular management strategy suitable for that ecosystem concerned there is often a trade-off between pollution abatement strategy and invasive success. For instance, reduction of nutrient load can decimate algal bloom but often promotes growth of invasive macrophytes under newly available light condition.

Effective management strategy requires an integrative approach with simultaneous consideration of pollution and invasion dynamics. Integrated approaches should encompass coupling of nutrient reduction with invasive macrophyte control, addressing noise and microplastic pollution alongside invasive species monitoring and recognizing feedback loops where invaders alter pollutant cycling, reinforcing degradation (Ehrenfeld 2010; Pyšek et al. 2020). Despite growing recognition of pollution–invasion interactions, there is a lack of long-term, multifactorial experiments that capture cumulative and synergistic effects across ecosystems (Crain et al. 2008; Vinebrooke et al. 2004; Halpern et al. 2008). Most studies remain short-term or single-stressor, limiting predictive power. Future ecological forecasting must incorporate pollution–invasion interactions into predictive models. Integrating multiple stressors into invasion risk assessments will improve management and conservation planning (Wu and Wan 2024; Seebens et al. 2017; Pyšek et al. 2020; Simberloff 2013).

Pollution and biological invasions are not independent stressors but deeply intertwined drivers of ecological disruption. Their interactions produce multifactorial effects that amplify biodiversity loss, destabilize food webs, and reshape biogeochemical cycles. Evidence across aquatic and terrestrial ecosystems demonstrates that pollutants weaken native resilience while invaders exploit and reinforce altered conditions (Simberloff 2013; Ehrenfeld 2010; Pyšek et al. 2020; Strayer 2010). Addressing these challenges requires holistic, interdisciplinary approaches that integrate ecology, toxicology, and conservation biology. Traditional management strategies that treat pollution and invasion separately risk unintended consequences, such as remediation efforts that inadvertently favour invaders. Instead, integrated frameworks must simultaneously consider both drivers, recognizing feedback loops and cumulative impacts (Richardson and Pyšek 2006; Halpern et al. 2008; Crain et al. 2008).

Ultimately, safeguarding biodiversity in the recent scenario depends on acknowledging and addressing the synergy between pollution and invasion. By embedding these interactions into ecological forecasting, management, and policy, we can move toward more resilient ecosystems and sustainable conservation outcomes (Seebens et al. 2017; Sala et al. 2000; Dudgeon et al. 2006).

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