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Beyond the binary: context matters in the plastic pollution crisis

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An Editorial on the Frontiers in Science Lead Article

[Plastic pollution under the influence of climate change: implications for the abundance, distribution, and hazards in terrestrial and aquatic ecosystems](#)

Key points

- Climate change is transforming plastic pollution from a reversible to a poorly reversible problem by accelerating fragmentation into nanoplastics and enhancing mobilization across ecosystems, however, our analytical methods cannot adequately detect or characterize these smallest particles, leaving critical uncertainties in risk assessment.
- Methodological flaws in microplastic research, including the use of unrealistically high concentrations, pristine plastics, and inadequate controls, are undermining scientific credibility and driving policy responses that may be inappropriate for contexts where plastics deliver critical benefits such as food security.
- Effective regulation of agricultural plastics requires shifting from “zero-use” to “zero-leakage” approaches grounded in rigorous source attribution, realistic exposure scenarios, transparent additive disclosure, and clear consideration of trade-offs across multiple Sustainable Development Goals.

The rapid expansion of global plastic production over the past seven decades has delivered substantial societal benefits but also generated persistent and pervasive environmental contamination. The intersection of plastic pollution and climate change represents one of the greatest environmental challenges currently facing society, yet our policy responses often treat these issues with overly reductive simplicity. In their Frontiers in Science lead article Kelly et al. (1) highlight this complexity, showing how climate change exacerbates plastic pollution across terrestrial, freshwater, and marine ecosystems, with synergistic effects that intensify at higher trophic levels. Similarly, Wang et al. (2) reveal a

critical paradox in agricultural systems, where plastic film mulching has fed 100 million additional people while simultaneously raising concerns about microplastic accumulation in soil, potential entry into food chains, and downstream transfer to aquatic ecosystems. Together, these studies exemplify why the plastic pollution crisis demands context-specific solutions rather than blanket legislation, particularly when pursuing multiple, and sometimes competing, Sustainable Development Goals (e.g., food security versus environmental protection).

The agricultural exception: when plastics feed billions

Within the global discourse on plastic pollution, agricultural systems introduce a complex set of trade-offs, as plastics are integral to numerous farming practices, from mulch films, irrigation pipes and polytunnels to the packaging of pesticide, fertilizers and vegetables. Modern agriculture is deeply reliant on plastics, a dependence unlikely to diminish in the foreseeable future. Determining how their use can be made sustainable remains a key challenge (1). Agricultural plastic film mulching, which covers approximately 50 million hectares of the Earth's surface, illustrates the tension between technological benefit and environmental concern (Figure 1). As Wang et al. (2) document, this technology has revolutionized farming in arid and semi-arid regions, increasing crop yields by 45%, improving water use efficiency by 58% (saving approximately 35 billion m³ of water), and reducing herbicide applications by approximately 16,000 tons annually in China alone. These are not marginal gains but transformative impacts that directly contribute to food security, economic prosperity and rural livelihoods in many regions of the world, while also reducing greenhouse gas emissions and promoting soil carbon sequestration. Bans on plastic film mulching to prevent environmental pollution would likely trigger cascading negative impacts: reduced crop yields in water-limited regions (with increased risk of land degradation), compromised rural livelihoods, increased pressure on remaining agricultural land, and potential displacement of farming communities—outcomes potentially more environmentally and socially damaging than the microplastic contamination they aim to prevent.

Research on microplastic impacts in soil has often generated alarming headlines. However, these concerns are frequently based on studies with fundamental methodological flaws that overstate real-world risks (3, 4). This disconnect between laboratory experiments and field reality threatens to erode confidence in rigorous scientific assessment, hampers evidence-based policymaking, and risks driving inappropriate regulatory responses. First, many experiments employ unrealistically high contamination loads (>1% by volume), using plastic concentrations orders of magnitude above field conditions (<0.01 of the soil volume in agricultural soils). Such artificial conditions typically generate negative soil-health outcomes, but the responses bear very little relation to real-world scenarios. Second, most studies

use pristine, virgin plastics rather than weathered materials, failing to account for the leaching of chemical additives (plasticizers, UV stabilizers) that may be primary drivers of toxicity (5). Third, degradation rates are often estimated using mass loss, which primarily reflects additive leaching rather than polymer breakdown. Fourth, experimental designs frequently lack appropriate controls, making it impossible to attribute observed effects specifically to microplastics. Finally, many studies assume any measurable change represents environmental harm, without contextualizing the magnitude of effects relative to standard agricultural practices such as tillage, fertilization, or pesticide application. Collectively, these methodological inconsistencies undermine our ability to develop effective, science-based policy interventions.

Emerging evidence also indicates that most microplastics detected in soil do not necessarily originate from plastic mulch films but are introduced via atmospheric deposition or other sources. While particle counts provide useful baseline information, meaningful risk assessment requires detailed characterization of particle type, size, and morphology. These factors highlight the need for rigorous source-apportionment studies to ensure that regulatory interventions are accurately targeted and scientifically defensible. Effective regulation of agricultural plastics must balance environmental protection with food security by grounding policies in realistic contamination levels, transparent additive disclosure, and accurate source attribution.

The climate-plastic nexus: amplifying environmental risks

Climate change is intensifying the environmental impacts of plastic pollution. Elevated temperatures, increased UV irradiation, and the increasing frequency and magnitude of extreme weather events (e.g., storms, floods) accelerate physicochemical degradation and dispersal, transforming plastics from a predominantly reversible contaminant, removable as intact material, into a poorly reversible pollutant that fragments into smaller, more persistent, and more biologically hazardous particles. For example, Kelly et al. (1) predict that a 10 °C temperature rise could double plastic degradation rates, while intensifying storms and floods can remobilize plastic debris at unprecedented scales, as evidenced by the large increase in beach sediment microplastic concentrations following typhoons in Hong Kong (6). Such accelerated fragmentation and dispersal increase the likelihood of microplastics entering aquatic food webs and soil systems, potentially amplifying ecological toxicity and human exposure risks.

The ecological consequences appear especially severe at higher trophic levels. Kelly et al. (1) report that large, long-lived aquatic organisms face the greatest vulnerability to combined climate-plastic stressors, experiencing synergistic toxicity through multiple pathways including bioaccumulation, altered metabolism under warming, and compromised immune function. In contrast, species at lower trophic levels often show resilience or even



FIGURE 1
Plastic film mulching in Chinese agriculture. This practice has transformed farming productivity in water-limited regions while also raising concerns about microplastic accumulation in soils. Image credit: © Imago/Alamy. Images used under license and not included in the article's Creative Commons license.

positive responses, creating complex food-web dynamics that challenge simplistic risk assessments. This differential sensitivity across organizational levels, from individuals to ecosystems, highlights why context-specific approaches are essential.

The nanoplastic knowledge gap: our greatest uncertainty

One of the greatest uncertainties in evaluating the biological impact of plastic pollution concerns nanoplastics, particles smaller than 1 μm that remain largely invisible to current analytical methods. These nanoplastics can cross biological membranes, accumulate in tissues, and interact with cellular processes in ways that larger microplastics cannot. Yet our understanding of these interactions remains in its infancy, and we lack standardized methods to reliably extract, quantify, and assess their environmental fate and toxicity (7). The methodological challenges are even more severe than those

associated with microplastic research with nanoplastic experiments typically employing concentrations that far exceed plausible environmental exposure, lacking adequate particle characterization, and rarely accounting for aggregation behavior or interactions with natural colloids. In the context of climate change, it is likely that warming will accelerate nanoplastic generation through enhanced fragmentation of larger particles, creating a feedback loop in which warming produces progressively smaller and more mobile plastic particles. This still requires critical evaluation. Overall, the combination of methodological limitations and climate-driven acceleration mean we are likely underestimating nanoplastic contamination by orders of magnitude. A critical contextual question remains largely unexplored: whether nanoplastics, at realistic environmental concentrations, exert biological effects that are qualitatively distinct from those of naturally occurring recalcitrant nanoparticles such as biochar, clay minerals, or iron oxides that are ubiquitous in soil systems. Establishing this distinction is essential for determining whether nanoplastics warrant regulatory attention as a novel environmental hazard.

From zero-use to zero-leakage: reframing policy approaches

There is growing consensus that the policy goal should be “zero-leakage” rather than “zero-use” of plastics, particularly in sectors where plastics deliver substantial benefits. Kelly et al. (1) emphasize that addressing plastic pollution at source, by rapidly reducing emissions into the environment, represents the most rational response to prevent poorly reversible negative impacts. However, they also acknowledge that achieving this will require major societal, economic, and commercial shifts. For agriculture, Wang et al. (2) advocate for evidence-based approaches that optimize plastic film management through thicker, more durable films that resist fragmentation, mandated collection programs with farmer incentives, mechanical removal equipment, and traceability systems to track films from production through disposal. Such approaches recognize that agricultural plastics have enabled food-production gains that cannot simply be reversed without threatening food security for millions of people.

Conclusion: embracing complexity in environmental policy

The plastic pollution crisis resists simple solutions because plastics have become integral to modern life, delivering benefits from food security to medical devices to renewable energy infrastructure. Plastics’ ability to substitute for other materials has supported advances across multiple sectors, while their lightweight properties reduce greenhouse gas emissions in vehicle manufacturing and food packaging (1). In agricultural systems, plastic films have enabled farming in water-scarce regions while reducing pesticide applications and irrigation demands (2).

This does not negate environmental concerns. Climate change is amplifying plastic pollution through accelerated degradation, increased mobility, and synergistic toxicity in ecosystems. However, the scientific community must move beyond binary thinking that frames plastics as simply “good” or “bad”. Context matters: agricultural applications differ fundamentally from single-use consumer packaging, industrial processes, or medical uses, each presenting distinct risk-benefit profiles that require tailored solutions. The future lies not in precautionary bans that could threaten food security and development goals, but in evidence-based approaches that minimize environmental leakage while preserving beneficial applications. This requires standardized research using real-world conditions, comprehensive life cycle assessments, robust material flow analyses, and policy frameworks that accommodate regional differences in farming practices, economic conditions, and environmental priorities. Only by embracing this complexity can we develop effective responses to the plastic-climate nexus that protect both environmental health and human well-being.

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Author contributions

DLJ: Writing – review & editing, Writing – original draft, Visualization, Project administration, Funding acquisition, Conceptualization.

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