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Plastic mulch productivity-sustainability tradeoffs and pathways toward an eco-friendly framework: insights from a global meta-analysis

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Meeting global food demands by 2050 requires a 45–60% increase in agricultural production. Plasticulture has emerged as a pivotal yet controversial solution. Here we perform a meta-analysis synthesizing the findings of global studies and reveal that plastic mulch enhances crop yields by 28.7% and water use efficiency by 48.9% under diversified systems. In China (2015–2024), plasticulture contributed an additional 189 million tons (Mt) of staple food, conserved 33.5 million hectares of arable land, and reduced emissions by 438 Mt CO_2-equivalent. However, persistent plastic residues degrade soils, and nanoplastics infiltrate food chains, posing ecological and health risks. Despite global negotiations (2024–2025), a binding UN treaty on plastic pollution remains stalled due to disparities among players. To reconcile productivity with sustainability, we propose six evidence-based priorities: (1) scaling integrated eco-farming systems with AI-driven precise application of soil mulches; (2) accelerating material innovation, focusing on biodegradable films and organic-based alternatives; (3) deploying blockchain-enabled circular economies for plastic waste; (4) improving reuse and recycling infrastructure; (5) implementing localized incentive mechanisms to support plastic-free farming; and (6) integrating plastic management into UN carbon trading frameworks. These strategies can pivot plasticulture toward a climate-resilient, ecologically sustainable model—balancing food security with environmental stewardship in an era of climate uncertainty.

The global challenge of producing sufficient food, biofuels, and industrial fibers to sustain growing populations and economies remains immense[1,2]. These pressures are more acute in densely populated regions, such as China, India, and many African nations[3,4], where rapid urbanization has led to the loss of fertile agricultural land[5], threatening food security (food supply and shortages). Many countries have relied heavily on synthetic fertilizers to boost agricultural productivity in recent decades. For example, China's fertilizer use rose from 17.8 million tons (Mt) in 1986 to 59.8 Mt in 2016[5], resulting in a 74% increase in crop yields. However, we estimated, based on the Chinese Yearbook datasets, that nitrogen use efficiency—crop yield per unit of applied nitrogen (N)—declined from 21.3 to 11.1 kg of grain per kg of N, representing a 48% decrease and indicating diminishing returns and possible exhaustion of fertilizer-driven productivity gains.

Agriculture has increasingly adopted plastics to intensify production per unit of land, including polyethylene film mulches, drip irrigation systems, industrial abrasives, and agrochemical containers. As a result, agriculture has become a major source of land-based

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plastic pollution. In 2020, China—the largest plastic user in the world[6]—had approximately 25 million hectares (Mha) of plastic-mulched cropland and 1.4 Mha of plastic-covered walk-in greenhouses and crawl-in tunnels—representing roughly 13% of its arable land[5]. Between 1981 and 2020, plastic use in China's agrifood systems increased 420-fold—from 0.006 to 2.5 Mt[5]—and continues to grow.

Plastic residues are now ubiquitous in plasticulture farmlands. In some Chinese cotton (*Gossypium hirsutum* L.) and potato (*Solanum tuberosum* L.) fields with over a decade of plastic mulch use, residue concentrations reach 1200 kg ha^{-1} or 690,000 particles per kg of soil under the specific testing conditions[7–9]. Also, large volumes of plastic debris accumulate in rural landscapes, degrading aesthetics and creating persistent environmental hazards. Through mechanical and oxidative processes, these residues fragment into macroplastics (>5 mm in diameter), microplastics (<5 mm), and nanoplastics (1 nm to 1 µm), exacerbating environmental degradation and potentially entering food chains, raising serious food safety (human and animal health) concerns.

Despite these environmental risks, plastic-assisted farming remains attractive to many farmers in densely populated areas due to its ability to increase agrifood output per unit of land and input. However, plasticulture's long-term sustainability is under society's scrutiny as the general public increasingly questions the tradeoff between productivity gains and environmental costs. Governments worldwide are responding with policy initiatives, such as the European Strategy for Plastics in a Circular Economy[10], China's Opinions on Further Strengthening the Prevention and Control of Plastic Pollution, and the United States' Phase Out Single-use Plastic from Federal Operations. Yet, a fundamental question persists: Can we design innovative farming systems that maintain high yields while protecting the environment?

Numerous studies have examined the effects of polyethylene mulches on crop performance, soil properties, and microbial communities. Many have investigated the ecological risks of nano- and microplastics. However, most studies focused on documenting their impacts rather than proposing actionable solutions. Few have provided integrated strategies that enhance productivity while mitigating environmental damage.

At the fifth Intergovernmental Negotiating Committee meeting in Busan (November 2024), more than 3300 delegates from 170 nations and 440 organizations failed to finalize a global treaty to end plastic pollution[11]. A similar deadlock occurred at the 2025 Geneva meeting[12], partly due to unresolved debates over asymmetries in scientific capacity, regulatory enforcement, and financial commitments, among other reasons. Science-based evidence is key to developing a robust global agreement[13]. Policymakers urgently need science-based frameworks to inform negotiations.

In this study, we provide policy recommendations and actionable strategies and practices aiming at ending terrestrial plastic pollution, based on decades of global research. We identified key soil- and crop-related anthropogenic activities driving plasticulture outcomes. Synthesizing global studies using a second-order meta-analysis (Methods and Supplementary Information) reveals that plastic-assisted agriculture increases crop yields by an average of 28.7%, and enhances water use efficiency and land productivity. In China, this translates to an additional 189 Mt of staple food produced from 2015 to 2024, conserving 33.5 Mha of arable land and preventing 438 Mt of N fertilizer-induced CO_2-equivalent emissions. However, these benefits are counterbalanced by substantial trade-offs. The persistent accumulation of plastic residues leads to soil degradation, including reductions in soil organic carbon (SOC) and disruptions to soil structure and microbial activity. Furthermore, the fragmentation of plastic mulch into micro- and nanoplastics introduces risks to food safety and human health, as these particles could infiltrate crops, enter the food chain, and potentially induce toxicological effects.

By analyzing the biological mechanisms underpinning the benefits and tradeoffs of plasticulture, we propose a suite of interdisciplinary mitigation strategies to reduce or eliminate plastic dependence while maintaining productivity. These include: (1) Developing bioengineered 'smart' mulches that synergize advanced material science with ecosystem health objectives, ensuring biodegradability and minimal ecological disruption, (2) Implementing blockchain-enabled circular economies to enhance traceability, accountability, and efficiency in plastic waste valorization, fostering closed-loop agricultural systems, (3) Strengthening reuse and recycling infrastructure, including waste-to-resource conversion, alongside economic incentives for plastic-free farming practices, (4) Integrating gene-edited, stress-resistant crops with AI-enabled precision mulching to optimize resource efficiency and minimize plastic dependency through site-specific agroecological management, (5) Institutionalizing transboundary governance mechanisms under the UN Environment Program's Global Plastic Treaty, incorporating microplastic emissions into carbon trading frameworks, and (6) Designing market-based instruments—such as plastic taxes, subsidies for sustainable alternatives, and extended producer responsibility (EPR) schemes—embedded within regulatory frameworks at local and farm levels to optimize resource allocation and environmental protection. These strategies can operationalize a "One Health" paradigm, harmonizing agroecosystem resilience, environmental sustainability, and public health to steer global agrifood systems toward long-term sustainability.

Results

Low-density polyethylene films are typically applied to fields weeks before crop sowing to conserve soil moisture (Fig. 1a) and raise soil temperatures in colder regions (Fig. 1b), promoting seed germination and early seedling growth. The films remain on the soil surface throughout the growing season (Fig. 1c), enhancing the soil micro-environment. A second-order meta-analysis (SOMA), synthesizing 70 first-order meta-analyses (Supplementary Data 1), identified key dimensions of plastic mulching in agrifood systems: substantial benefits for crop yield, water use efficiency (WUE), and greenhouse gas (GHG) mitigation; a productivity–sustainability tradeoff involving soil health and environmental risks; and mitigation strategies to decouple production gains from the environmental costs.

Yield benefits

Across 9413 paired comparisons, plastic mulching increased crop yields by an average of 28.7% compared to non-mulched cropping systems, with 98% of trials reporting statistically significant improvements (Fig. 2). Crop-specific gains were 10.4% [95% confidence interval (CI): 2.8–17.9; $n = 92$ paired comparisons] in rice (*Oryza sativa* L.), 18.9% (CI: 11.3–27.7; $n = 10{,}103$) in wheat (*Triticum aestivum* L.), 22.0% (CI: 12.8–33.1; $n = 8952$) in potato, 22.4% (CI: 12.4–32.4; $n = 4911$) in cotton, 22.3% (CI: 14.2–32.4; $n = 12{,}200$) in maize (*Zea mays*), 33.6% (CI: 14.0–52.9; $n = 192$) in legume and oilseed crops, and 34.0% (CI: 24.9–44.1; $n = 2574$) in vegetables, such as cucumber (*Cucumis sativus*), pepper (*Capsicum annuum*), and tomato (*Solanum lycopersicum*) (Fig. 2a).

Yield advantages were consistent across mulch types, thicknesses, and coverage levels (Fig. 2a). Full (75–100%) soil coverage outperformed partial mulching (~50%) by 9.6%, and exceeded straw mulching by 25%. The ridge–furrow configuration or flat mulching patterns resulted in greater yield benefits than the ridge- or furrow-only mulching.

Applying N fertilizer (<200 kg N ha^{-1}) together with film mulching increased staple crop yields by 67.1% (CI: 50.5–103.5; $n = 4054$) relative to mulched fields without fertilizer. In plasticulture, yield responses were strongest in coarse-textured soils, which produced 145.7% higher grain yield than fine- or medium-textured soils.

Fig. 1 | Plastic films applied to the soil surface as physical mulches. a Thin, low-density films (0.008–0.051 mm thick; 0.72 g cm^{-3}) laid before sowing to conserve soil moisture and enhance germination. **b** In colder regions, mulches increase soil temperature during seedling establishment. **c** Throughout the growing season, mulches improve soil microenvironments, promoting microbial and enzymatic activity. (Photo on plastic-mulched terraces in Jingyuan County, Gansu Province, China, taken by local agrologists).

Moderator analyses indicated consistent yield gains across wide environmental gradients: elevation (<500 m to >1500 m), mean annual temperature (<5 °C to >20 °C), annual precipitation (<150 mm to >2000 mm), and growing season rainfall (<200 mm to >400 mm) (Fig. 2b). The greatest benefits occurred in northwestern China, where annual evaporation is nearly ten times greater than precipitation[14].

In parallel with yield gains, plastic mulching enhanced WUE—the biomass or grain yield per unit of water input—across most crop types and environments (Fig. 3). Mean WUE increases were 9.3% (CI: 0.5–19.2; n = 91 pairs) for cotton, 18.6% (CI: 9.7–28.2; n = 1512) for wheat, 21.6% (CI: 12.5–31.8; n = 1608) for vegetables, 25.9% (CI: 13.2–39.3; n = 871) for potato, and 32.0% (CI: 23.0–42.5; n = 2713) for maize. Integrating crop diversification with plastic mulching further improved WUE by 48.9% (CI: 42.0–55.3; n = 285). The highest WUE benefits occurred in arid regions of northwestern China, where annual precipitation is typically <200 mm[14].

Physiochemical mechanisms underpinning productivity gains

The mechanisms responsible for yield increase and WUE improvement associated with plasticulture remain under-documented in the scientific literature. However, our SOMA identified multiple interacting factors driving the productivity outcomes (Fig. 4).

Plastic films significantly reduced soil evaporation, increasing plant-available soil moisture by 33–55% (n = 5300 paired comparisons) (Fig. 4a). The moisture-retaining barrier locks promote seed germination, seedling establishment and WUE (Fig. 4b). Periodic wet–dry cycles under mulch also trigger hormonal signals that induce partial stomatal closure, reducing transpiration and CO_2 exchange with minimal impact on carbon assimilation.

Plastic mulch traps solar radiation, increasing soil temperatures and promoting seed germination and vigorous seedling growth in colder areas. In northwestern China, transparent polyethylene film raised spring soil temperatures (0.1 m depth) by 1.2 °C–6.8 °C (n = 538), equivalent to a 25–56% increase relative to bare soil (Fig. 4c). These warmer conditions extended the growing season by 7–12 days, enabling re-cropping of short-season crops, such as finger millet (*Eleusine coracana*), proso millet (*Panicum miliaceum*), and buckwheat (*Fagopyrum esculentum*). However, leaving mulch on the soil surface during post-crop fallow periods increased soil warming, resulting in a 4–19% SOC loss (more discussions on SOC in the following subsection).

Plastic mulching improved microbial diversity by 18% (n = 370 paired comparisons) and oxidative enzyme activity by 27% (n = 486) (Fig. 4d). These changes enhance autotrophic CO_2 fixation via the ribulose-bisphosphate carboxylase pathway, contributing to soil carbon pools. When combined with fertilization, plastic mulching stimulates carbon mineralization, improving soil fertility. Also, enhanced hydrothermal conditions under mulch promoted root growth, increasing root-to-shoot ratios by 22–65% (n = 1205) and elevating extracellular enzyme production, thereby improving water and nutrient extraction from deeper soil layers.

Plastic mulch applied to the soil surface forms a physical barrier that inhibits weed seedling emergence by 42% (n = 168 paired comparisons) (Fig. 4e). Lacking light and oxygen beneath the mulch causes emerging weed seedlings to suffocate in the unfavored environment under the film. Over time, the seed banks of some problematic weed species decline, reducing overall weed pressure and the need for herbicide applications. These findings support the role of plastic mulching in protecting crop health, reducing chemical input, and maintaining ecosystem health.

Adverse impacts of plastics in agriculture

Plastics in soil and the environment degrade into macroplastics (>5 mm), microplastics (<5 mm), or nanoplastics (1 nm–1 μm). Microplastics originate from various field operations, including the application of plastic film, the fragmentation of residual mulch, and the improper disposal of farm plastics. Over time, microplastics degrade into nanoplastics, which persist in soils, migrate through ecosystems, and enter food chains, posing multiple environmental and human health risks.

Traditional management of agricultural plastic waste, such as incorporation into soil (Fig. S1a) or field-edge burning (Fig. S1b), creates complex interactions with soil physical, chemical, and biological

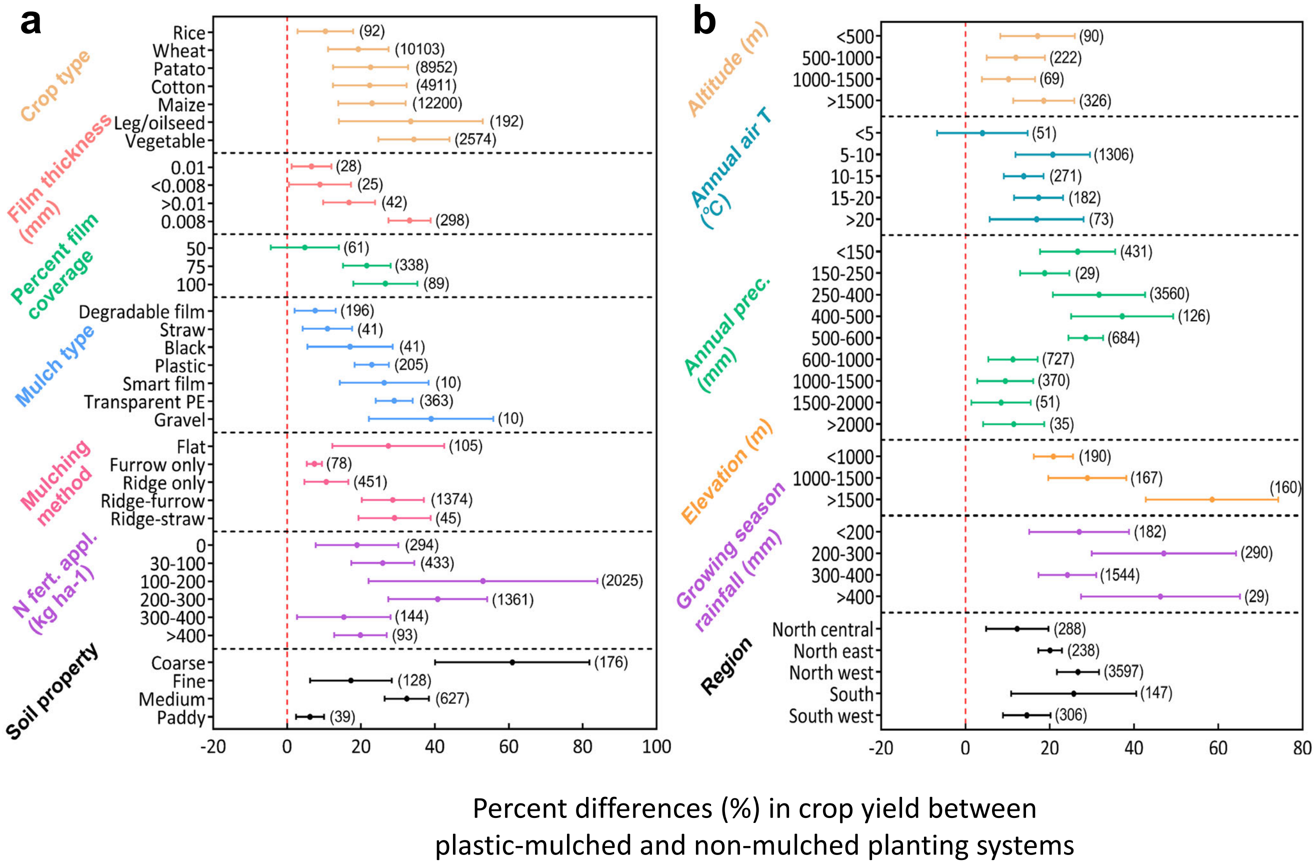


Fig. 2 | Yield advantages of plastic-mulched crops versus non-mulched systems. **a** Forest plots showing percent yield differences analyzed by crop species, mulch thickness, percent film coverage (range 50, 75, and 100% of soil surface covered), mulching type and method, nitrogen fertilization, and soil properties. Ridge–straw mulching: ridges covered with plastic, while furrows covered with crop straw. **b** Yield responses under varying environmental conditions (altitude, temperature, precipitation, growing season rainfall, geographic region). Regional differences highlight key agricultural areas in China. In both (**a**) and (**b**), the number in parentheses beside each error bar represents the sample size of the observed pairs of the two systems (i.e., mulched and non-mulched). The bar length represents the effect size at 95% confidence intervals (CIs). An error bar not overlapping the 0 value on the X-axis (the vertical line) indicates a significant effect between the two systems ($P < 0.05$). Effect sizes were calculated and analyzed using log response ratios, which were back-transformed and converted to percentage differences. Source data are provided in the Source Data file.

properties. Residual plastics increase soil porosity and water transport channels, accelerating water and nutrient losses. Long-term plastic mulching elevates CO_2 and N_2O emissions while reducing methane (CH_4) emissions (Fig. 5a). Nitrogen losses due to plastic use are pronounced in rice, legumes, oilseeds, wheat, and vegetables, but negligible in maize, potato, and cotton (Fig. 5b).

Plastic accumulation disrupts soil structure, decreases permeability, increases bulk density, and reduces root surface areas, collectively diminishing nutrient absorption[15]. Meta-analyses show that soil plastic residues greater than 400–480 kg ha^{-1} reduced the yields of maize, cotton, and potato by 17.5–26.8%[15,16]. High microplastic abundance alters soil aggregate distribution, fosters undesirable microbial taxa (e.g., *Alphaproteobacteria*, *Actinobacteria*), and reduces earthworm and nematode survival[17], while interfering with nutrient cycling, which in turn alters microbial community structure, diversity, and functional abundance[18]. However, the magnitude of the effect varies, depending on nano/microplastic uptake pathways, particle size, type, and shape, the interaction with rhizosphere properties, and climate-soil conditions.

Soil organic carbon is a fundamental indicator of soil health[19]. Our SOMA revealed inconsistent effects of plastic accumulation on SOC (Fig. 5a), with outcomes influenced by climatic conditions, crop management practices, and mulch type and application method. The hydrophobic nature of plastic-covered soils (Fig. 1) can enhance the adsorption of dissolved organic carbon, disrupting carbon cycling processes. Dissolved organic matter can release bioavailable plastic additives (such as plasticizers, colorants, and antioxidants) from polymer degradation, potentially altering soil carbon dynamics. In some dryland regions, however, higher SOC contents have been reported under plastic mulched compared to non-mulched soils, likely due to increased fresh carbon inputs that modify SOC chemical fractions and structure[20]. Plastic mulching can stimulate hydrolytic enzyme activities (β-glucosidase, cellobiohydrolase, β-1,4-xylosidase), enhancing microbial carbon use efficiency and promoting the formation of microbial-derived carbon[21]. Despite these findings, the environmental reactivity of plastic-induced SOC remains poorly understood, limiting insights into how nano- and microplastics influence carbon cycling in soils subjected to long-term mulching.

Nano- and microplastics affect ecosystems via two main pathways: (i) Plant uptake: plastics penetrate plant roots and stems, introducing polyester fibers and polyamide beads into tissues, altering plant structure and elemental composition[22]. Plant-associated nano- and microplastics can disperse widely in the environment. (ii) Environmental dissemination: larger plastic fragments accumulated in farmyards (Fig. S1c) are readily dispersed by wind or water into feedlots (Fig. S1d), marginal or idle lands near villages (Fig. S1e), drainage ditches, and surrounding infrastructure (Fig. S1f). Ingested plastics

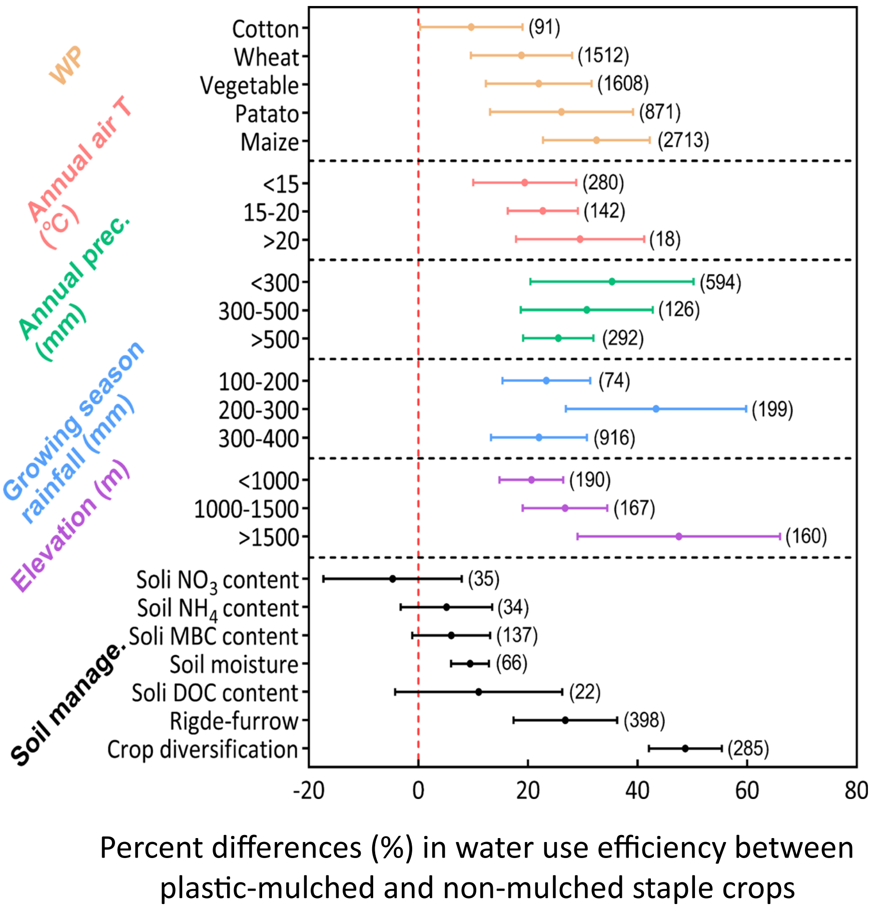


Fig. 3 | Water use efficiency in plastic-mulched versus non-mulched crops. Forest plots showing percent differences in biomass or grain yield per water unit. Analyses include climatic factors (temperature, precipitation, growing season rainfall, and elevation). Soil management practices reflect a subset of key soil properties and cropping practices reported in the original meta-analyses. The number in parentheses beside each error bar represents the sample size for observed pairs of the two systems (i.e., mulched and non-mulched). The bar length represents the effect size at 95% confidence intervals (CIs). An error bar not overlapping the 0 value on the X-axis (the vertical line) indicates a significant effect between the two systems ($P < 0.05$). Effect sizes were calculated and analyzed using log response ratios, which were back-transformed and converted to percentage differences. Source data are provided in the Source Data file.

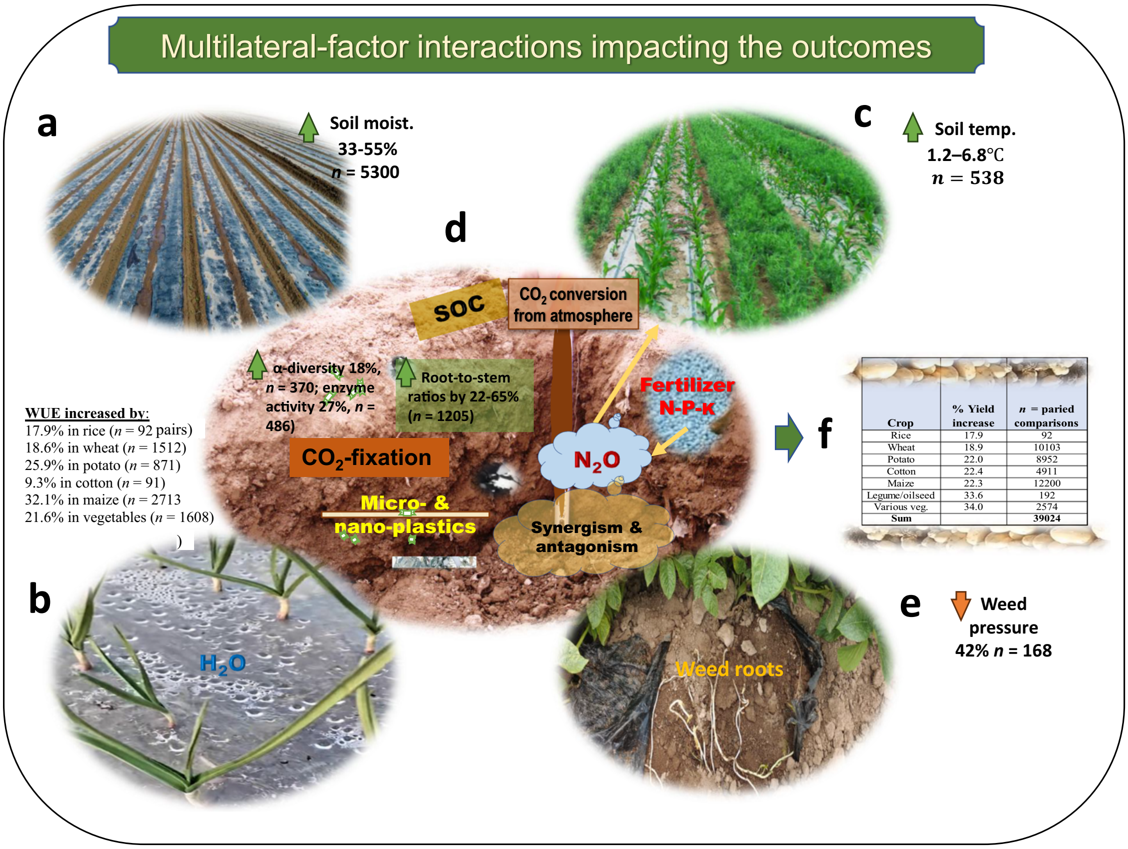
disrupt organisms by altering gene expression, damaging organs, and exacerbating tissue damage[23].

Nanoplastics can infiltrate plant tissues, and chemically active components enter the food chain. Evidence from animal and cell-based studies suggests that nano/microplastics can bind intracellular compounds[24], translocate through tissues, lodge in organs, and interact with cellular structures[25], triggering inflammation, secondary genotoxicity, or inhibiting cell proliferation[24]. The food safety concerns are growing; however, the precise impacts on human health remain difficult to quantify[26], as the pathways from terrestrial plants to human tissues remain unknown, and the influencing outcomes vary with nano/microplastic particle size, shape, chemical composition, exposure route, tissue specificity, and individual susceptibility. Moreover, detection methods—including Fourier transform infrared spectroscopy, scanning electron microscopy, and fluorescence microscopy—often yield inconsistent or controversial results (Table S1). There is a lack of standardized extraction, identification, and quantification protocols, and a threshold has not been established.

Discussion

We propose policy recommendations, actionable strategies, and implementation pathways to transitioning plasticulture toward long-term sustainability. Most of the recommendations are directly supported by our SOMA synthesis (Supplementary Data 2), while a few others are speculative and supported by existing scientific literature; these provide a roadmap to facilitate ongoing intergovernmental negotiations on legally binding instruments to curb global plastic pollution.

Bioengineered 'smart' mulches. Bioengineered and biobased mulches—derived from renewable resources, such as starch, cellulose, and degradable polymers (e.g., polylactic acid)—can naturally degrade through microbial activity. Emerging materials include living mulches, which incorporate active microorganisms into silk-based plastics through plasticizer-assisted thermal molding, enabling microbial degradation in situ. Other materials include (1) photo- and oxy-degradable films, which fragment under sunlight or oxygen exposure, suited to short-term use during crop growth cycles; (2) high-performance composites, combining polyethylene with biodegradable layers—an outer UV-reflective layer and an inner moisture-retentive layer; (3) temperature- and moisture-sensitive films, which adjust permeability to release water vapor according to soil conditions; (4) photodegradable films, incorporating photosensitizers to absorb UV wavelengths, accelerating degradation by altering mechanical properties; (5) starch-based films with aliphatic polyester compounds (e.g., polyvinyl chloride, ethylene/acrylic acid copolymers), which decompose through microbial activity; and (6) bioengineered polyhydroxyalkanoate films, produced by naturally degradable biomass or specific bacterial strains that form biofilms—microenvironments promoting enzymatic breakdown of polymers.



Crop	% Yield increase	n = paried comparisons
Rice	17.9	92
Wheat	18.9	10103
Potato	22.0	8952
Cotton	22.4	4911
Maize	22.3	12200
Legume/oilseed	33.6	192
Various veg.	34.0	2574
Sum		**39024**

Fig. 4 | Key mechanisms of plastic mulch benefits. a conserves soil moisture, increasing availability by 48% in arid/semiarid regions; **b** improves soil hydrothermal conditions, increasing water use efficiency by 32–56%; **c** enables intensified intercropping (strip rotations between cool- and warm-season crops, early- and late-maturing varieties, and cereal–legume combinations) with soil temperature increases of 1.2 °C–6.8 °C; **d** enhances soil microenvironments, boosting enzyme activity by 27% and promoting carbon and nitrogen cycling; **e** suppresses weeds by 42% through opaque coverage; **f** increases overall productivity by 28.7% (n = 39,024 paired comparisons).

Studies have demonstrated that many of these smart mulches perform comparably to, or better than, traditional polyethylene films in conserving soil moisture, increasing soil temperature, and enhancing microbial activity[27,28]. Their incorporation into soils can boost microbial activity and fungal diversity[27] and improve crop yields and WUE. Silk-based plastics can act as long-term carriers for beneficial rhizobacteria, maintaining protease activity and accelerating plastic breakdown upon soil contact[29]. However, the rapid fragmentation of biodegradable mulches may inadvertently release additives with a greater affinity for soil pollutants than polyethene microplastics[30]. Moreover, the seasonal degradation of smart films raises questions about whether they offer equivalent benefits to polyethylene in weed suppression, soil moisture conservation, and surface heat retention. Lacking long-term field trials across diverse soil–climate systems is a key limitation. Production costs remain roughly an order of magnitude higher than those of conventional polyethylene films, constraining broader adoption[31,32].

Achieving global scalability of bioengineered smart mulches will depend on technological innovation and market transformation. We suggest roll-to-roll pattern manufacturing can reduce costs, while 'Functionality-as-a-Service' business models—where farmers pay for outcomes rather than materials—can offset upfront expenses. Co-marketing with sustainable technologies, such as those based on lignocellulosic or waste materials, can enhance environmental appeal and affordability. Initial deployment may focus on high-value horticulture, supported by farm-specific economic calculators that quantify production gains, input savings, labor reduction, and market premiums for sustainable produce. Policy incentives—such as subsidies, carbon credits, and conservation grants—could position smart mulches as essential climate infrastructure.

Current agricultural plastic films are typically 0.004–0.008 mm thick (about 1/300th–1/500th the thickness of a Ziploc® bag), making them highly prone to fragmentation. These micro-fragments can persist in soils, migrate to neighboring fields, or enter waterways (Figure S1a–f). In contrast, thicker films (0.010–0.015 mm) are durable, easier to handle by machinery, achieve higher retrieval rates after use, and can be cleaned and reused multiple times, improving recyclability. Enhancing the elasticity and durability of these thicker materials represents a critical step toward sustainable adoption. Economic viability should be assessed through Life Cycle Assessments (LCA) to evaluate their long-term effectiveness and environmental footprint.

Enhancing plastic use efficiency (PUE). Plastic use efficiency can be improved through several practical approaches: integrating CRISPR-edited crops with AI-driven precision mulching to potentially reduce plastic use by 50–70% without compromising yields[33,34]; partial mulching in row crops; combining plastic mulch with ridge–furrow configurations; deploying photo-sensitive films for high-value crops; replacing plastics in walkways or between crop rows with alternative materials; selecting film color or transparency based on crop requirements; and integrating fertigation systems to optimize soil–plant interactions.

Blockchain-enabled circular economies through recycling and regeneration. Transitioning to a circular economy for plastic mulches is essential to mitigate their transboundary environmental impacts. Mulch's life-cycle traceability, smart contracts, and tokenised incentives can be coordinated in transnational policy frameworks,

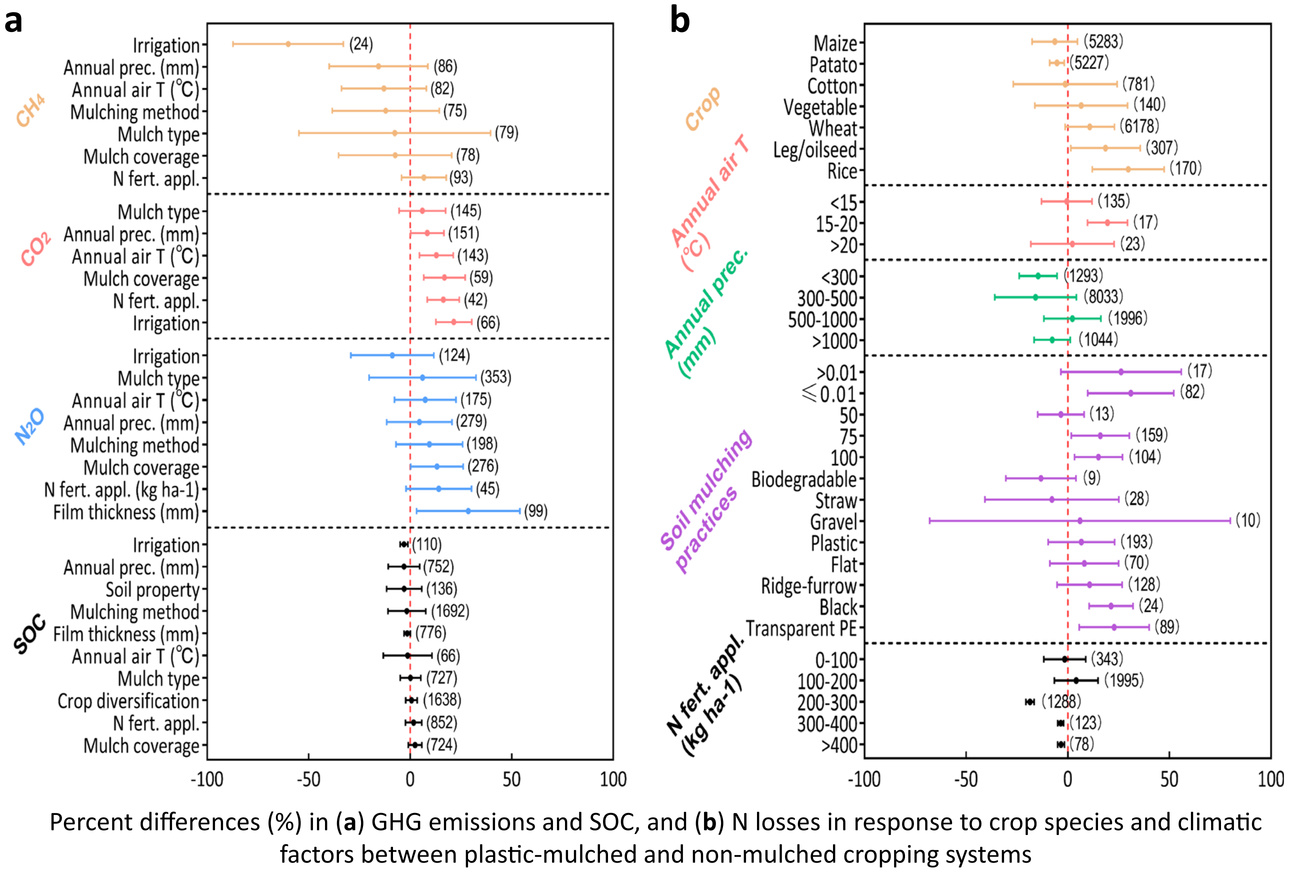


Fig. 5 | Impacts of plastic mulch on the environment vary with anthropogenic activities and climates. Impacts of plastic mulching on (**a**) greenhouse gas (CH_4, CO_2, N_2O) emissions and soil organic carbon (SOC), and (**b**) soil nitrogen loss. Forest plots showing the percentage differences between mulched and non-mulched systems across crop species, climate conditions, mulching practices, and nitrogen fertilization. In both (**a**) and (**b**), the number in parentheses beside each error bar represents the sample size for observed pairs of the two systems (i.e., mulched and non-mulched). The bar length represents the effect size at 95% confidence intervals (CIs). An error bar not overlapping the 0 value on the X-axis (the vertical line) indicates a significant effect between the two systems ($P < 0.05$). Effect sizes were calculated and analyzed using log response ratios, which were back-transformed and converted to percentage differences. Source data are provided in the Source Data file.

supported by technological innovations. Improved and novel approaches to plastic handling are fundamental at every stage—film layout on large commercial farms (Fig. S2a) and smallholder operations (Fig. S2b), waste collection after use (Fig. S2c), post-harvest handling (Fig. S2d), recycling and reuse (Fig. S2e), and the adoption of 'smart' film (Fig. S2f). Integrating blockchain technology with tailored economic instruments can create efficient circular systems to close the gap between policy and economics.

The choice of policy instrument depends strongly on farm-scale economics. Evidence from EU policy responses suggests that small- to medium-sized farms are likely to adopt subsidy-based schemes, whereas large-scale enterprises tend to favor tax-credit mechanisms[35]. This divergence underscores the need for multifaceted policy approaches that reflect regional and operational diversity. Extended Producer Responsibility (EPR) frameworks[36,37], implemented through Producer Responsibility Organizations, are essential to improving recycling efficiency and material quality. Blockchain-enabled smart contracts can enhance EPR systems by automating financial transactions and verifying exchanges among manufacturers, farmers, and recyclers, reducing administrative burdens and fraud risk. In frontrunner countries, digitally monitored EPR models—including multi-stream collection and deposit-return schemes—have demonstrated accountability and transparency[37].

Policy must incentivize participation and ensure verification to operationalize a global circular strategy. The success of local initiatives, such as the "Waste Film Trade-in" program in Dunhuang County, China, where a 5:1 exchange ratio marked improved recovery rates, illustrates the power of direct economic incentives. Blockchain technology offers a scalable solution with an immutable ledger that tracks plastic credits from field-level collection through recycling and new products. Such technology creates a trusted and transparent market for recycled materials.

We advocate for a digitally augmented, locally adapted, and policy-driven framework that aligns technological innovation with regulatory and behavioral interventions. Blockchain-enabled monitoring and verification systems ensure data integrity, helping prevent recycling initiatives from inadvertently increasing energy consumption or greenhouse gas emissions. Such a multidimensional, integrated approach is essential for managing plastic waste, balancing environmental sustainability with economic viability.

Alternative mulching. In regions where the primary goal is soil moisture conservation, organic mulches, such as crop straw, composted manure, and paper-based residues can perform as well as—or better than—plastic films. For cool-season crops like dry pea (*Pisum sativum* L.), spring wheat, and potato, straw mulches (Fig. S2f) improve seedbeds[38] by enhancing soil moisture retention, promoting seed germination under dry conditions, and reducing heat stress during summer emergence. Organic mulches enhance soil water storage at sowing, foster plant–root interactions, boost SOC and N cycling, and stimulate microbial activity, ultimately increasing soil fertility over the long term[39]. Optimizing straw management—including chopping, spreading, and processing residues—maximizes economic and

Fig. 6 | Integrated mitigation strategies to reduce reliance on plastic mulch. **a** alternative mulches (e.g., crop straw) to conserve soil moisture; **b** recycling and reusing plastics and developing thicker and biodegradable films; **c** improved plastic use efficiency via partial mulching or crop-specific application; **d** integrated cropping systems that gradually replace plastic mulch with alternatives, such as organic mulches, or diversified cropping systems, such as cereal–legume intercropping; **e** bioengineered 'smart' mulches; and **f** policy support focusing on subsidies, tax credits, AI-driven smart mulches, CRISPR-edited crops, circular economies (plastic-to-biochar), UN's Plastic Treaty, and local plastic reduction policies. Goal: sustainable agriculture combining food security, soil health, and environmental protection.

environmental benefits. Localized initiatives, such as Brazil's sugarcane-based bio-polyethylene[40] and India's EcoRight and Bio-Green programs, with mulches derived from cassava starch and jute[41], demonstrate the potential of sustainable, high-value alternatives.

Innovative farming systems. Integrated farming systems coordinated under well-designed policy frameworks can reduce or eliminate plastic use while sustaining productivity (Fig. 6). Key strategies include: (i) Advancing microbial tools to enhance beneficial microbiomes[42] that improve soil physicochemical properties, mitigate contaminant effects, and increase SOC storage and ecosystem services. Native rhizosphere microbiomes can also be bioengineered to rehabilitate nutrient-poor or heavy metal-contaminated soils, improving soil health and crop yields; (ii) Integrating nutrient-rich, underutilized crops, such as root crops, pulses, nuts, fruits, and vegetables into diverse systems—particularly in densely populated regions like Southeast Asia—to enhance yields and food security[43]; (iii) Rotating cereals with N-fixing legumes to boost system-wide productivity, reduce synthetic N fertilizer dependence, and strengthen soil resilience[44]; (iv) Combining intercropping, no-till practices, straw mulching, within-field rotations, and precision fertigation to foster beneficial soil–microbe interactions, enhance resource use efficiency, and reduce environmental impacts; (v) Incorporating cover crops, widely adopted in Europe, to increase soil fertility, biodiversity, and overall system productivity, offering a sustainable alternative to plastic mulches[45,46]; (vi) Innovating with biotechnology and AI tools: Bioengineered rhizobacteria embedded in biodegradable mulches could both degrade plastic polymers and fix atmospheric N[47]—simultaneously addressing pollution and fertility. Machine learning can generate site-specific mulch recommendations (e.g., thickness, elasticity, durability, degradability). The real-time biosensors can track microplastic fluxes in soil–plant systems to guide AI-driven risk mapping and remediation. These interdisciplinary strategies can reimagine plastic-assisted agriculture as a convergence of ecological resilience, technological innovation, and social equity, offering a path toward solutions-driven science that supports planetary health.

Policy support. Although plastic mulching has greatly contributed to food security, its risks to soil health, environmental sustainability, and food safety remain unresolved. Our framework advocates for an integrated and inclusive approach centered on education, social and economic incentives, policy reform, and public engagement (Fig. 6).

For policymakers: (i) Introduce a policy framework under the UNEP Global Plastic Treaty to standardize the manufacturing, transport, storage, application, and reuse of plastic films across local, regional, and national levels; (ii) Develop and implement farm-level regulations and a differentiation of market-based tools[36], such as tax credits, pay-back, EPR policy, and a subsidy, among others[35], to incentivize farmers to adopt plastic waste management, control the volume of plastic film usage, and promote higher recovery of waste films; (iii) Invest on recycling infrastructure to improve the efficiency, effectiveness, and economic viability of handling reusable plastics; (iv) Regulate international trade of agricultural products cultivated using plastic cultivation systems, and enforce quality control mechanisms to support adoption of alternative, non-plastic agricultural practices; (v) Establish international 'Plastic-Footprint' standards (e.g., via FAO/UNEP) and certification labels, with mutual recognition agreements to honor each other's certifications; Develop national support programs to subsidize and assist farmers' transition to alternatives and build domestic capacity for certification; Use tiered tariffs for certified goods, mandate sustainable public procurement, and enforce consumer labeling to drive demand; and Provide financial and technical assistance to developing nations to ensure a fair and feasible global transition.

For research communities: (i) Prioritize interdisciplinary research to investigate the biochemical pathways and environmental impacts of long-term plastic residues in soils and develop science-based, real-world solutions to ensure environmental and economic benefits over conventional plastic films; (ii) Develop viable biodegradable alternatives via material innovation; Engineer cost-effective, bio-based polymers designed for addressing SOC-microplastic interactions (Fig. 5a) and biodegradation into non-toxic residues; (iii) Create efficient retrieval machinery for scalable solutions, considering AI-guided harvesters for large-scale farms to low-cost, manual implements for smallholders; Engineer equipment that integrates standard farming operations with efficient on-farm collection and plastic waste stream management; (iv) Establish standardized detection protocols and reproducible methods for sample preparation, purification, and analysis; Establish global standardization through international interlaboratory trials and organizations (e.g., ISO) for formal adoption to enable accurate monitoring and food safety threshold setting.

For farm managers: (i) Adopt AI-driven precise mulching to maintain yields while reducing plastic use, as validated in field studies (Fig. 3); (ii) Transition to alternative mulching solutions, such as crop straw or organic manuals; (iii) Apply soil amendments, including desorbing agents, surfactants, and chelating compound, to facilitate remediation via phytoremediation and bioremediation; (iv) Establish localized policies to overcome higher upfront costs in using smart mulches, such as subsidies, tax credits, cost-sharing programs, and carbon credits for plastic-to-biochar conversion; Explore circular economy mechanisms, such as EPR schemes and deposit-refund systems, to reduce long-term costs by incentivizing plastic recovery and recycling; Provide farm managers with transparent life-cycle cost assessments that compare purchase prices and long-term expenses like retrieval labor, soil health impacts, and end-of-life management. These are essential for farmers to make informed, sustainable, and economically viable decisions in shifting their operations to alternative, diversified, and integrated farming systems.

For the general public and consumers: (i) Recognize that plastic-assisted agriculture has been instrumental in boosting food, feed, and fiber production, helping reduce global hunger. With innovations, such as smart mulches and biodegradable films, plastic-assisted farming can evolve into a sustainable solution rather than a long-term threat; (ii) Understand that recycling and degradation technologies for farm waste are advancing toward standardization, helping minimize environmental harm from agricultural plastic debris; (iii) Be aware current evidence is inconclusive regarding the health risks of nano/microplastics in food, and there is no scientific consensus on the threshold of their concentration in food that may pose a threat to human health; (iv) The governments, researchers, and farm managers communicate actively with society in a transparent way to build coherent public awareness on the issue; Build trust in waste management progress through verifiable actions and traceability (e.g., QR codes) by showing end-of-life management of agricultural plastics and creating trusted certification labels for products grown with responsible practices; Communicate the state of science on health risks responsibly to avoid alarmism by using clear messaging from authoritative bodies (e.g., WHO, FAO) stating that standardized research is actively working to define safe thresholds.

An effective paradigm for public engagement in 'ending terrestrial plastic pollution' can be anchored in the 'One Health' framework, which has a profound interconnection with agricultural systems, environmental sustainability, and public health. Considering agricultural plastics sit at the critical nexus of the triad—the degradation of polymer waste compromises ecosystem health and biodiversity, leaching of additives contaminates water tables, and the trophic transfer of nano/microplastics into the food web—presents a potential vector for human exposure. It is paramount to shift public perception from viewing this as an isolated environmental issue to understanding it as a complex, systemic challenge. The 'One Health' perspective empowers the general public and consumers to recognize that their choices—such as supporting products certified under stringent, verifiable circular economy schemes or derived from systems utilizing validated biodegradable alternatives—directly contribute to a collective mitigation strategy. Fostering an informed citizenry that advocates for and participates in sustainable plastic management is essential in safeguarding the integrated health of our planet, the food systems, and ourselves.

In conclusion, achieving environmental sustainability requires three transformative innovations: (1) Bioengineered materials: Development of 'smart' mulches embedded with beneficial microbial consortia that degrade polymers while enhancing soil fertility. Such materials, derived from lignocellulosic waste or engineered silk proteins, could decompose within a single season while promoting plant growth—an industrially untapped opportunity; (2) Circular agroecosystems: Building on China's 5:1 plastic trade-in model, blockchain-enabled traceability can certify recycled plastic use across supply chains, while decentralized pyrolysis hubs can convert waste into biochar or syngas, closing the loop between waste and resource recovery; (3) Next-generation farming systems: CRISPR-edited crops with enhanced stress tolerance and modified root exudates can promote beneficial microbiomes and reduce the need for plastic mulching. AI-driven precision mulching could optimize placement by applying films only in high-evaporation zones, reducing plastic input cost without yield loss.

We call for a paradigm shift toward a "One Health" framework that coordinates the complex interactions among anthropogenic activities, soil-plant-microbe associations, and various pollutants, at the global, regional, and farm levels. To drive this transition, we advocate for establishing Global Plastic Offset Mechanisms under the UNEP Treaty, where nations adopting plastic-free practices receive credits. This requires harmonized protocols for monitoring, measuring, and evaluating the outcomes. Our residue-yield thresholds (Fig. 5) can guide the setting of UNEP limits as a potential treaty standard. Furthermore, we recommend creating plastic-focused 'living labs' to test and monitor phased-out transition progress and address plastic-induced environmental sustainability frontiers. Such labs can act as a plastic transition accelerator, uniquely combining (i) biodegradable material testing, (ii) agroecological diversification systems to reduce plastic reliance, and (iii) AI-modeled microplastic thresholds in soil systems. The integrated approach enables phased-out, context-specific plastic exit strategies.

Achieving environmental sustainability, moving beyond the end of plastics in agriculture, will take more than replacing polyethylene plastics with alternative materials; it calls for fundamentally reimagining agriculture as a dynamic system grounded in innovation, ecology, and equity. By treating plastics not as an unavoidable burden but as a catalyst for systemic change, we can build resilient farming systems that support both people and the planet—a vision as urgent as it is attainable.

Methods

The policy recommendations and actionable strategies/practices aiming at ending terrestrial plastic pollution are developed based on the second-order meta-analysis (SOMA) that identified the major anthropogenic practices influencing plastic use in agroecosystems. A predefined list of management practices related to plastic mulching, affecting soil water, temperature, crop management, and ecosystem functioning, guided our systematic literature search. We identified and reviewed published first-order meta-analyses that synthesized field experiments examining these factors. This process yielded 70 qualified meta-analyses (Supplementary Data 1), encompassing 11,712 field experiments and 110,809 individual observations worldwide (Fig. S3).

Rationale for using SOMA

Although numerous studies have examined the impacts of agricultural plastics on crop productivity, water use efficiency (WUE), and soil nutrient cycling, most first-order meta-analyses focus on single aspects, often producing variable conclusions due to differences in study scope, experimental design, and environmental conditions[48–51]. A SOMA offers several advantages over first-order analyses: (1) enables evaluation of the quality and consistency of existing meta-analyses[52–54]; (2) enables exploration of broader research questions by quantifying true variance across multiple first-order meta-analyses[55]; (3) enhances methodological rigor by minimizing publication bias at three levels: the SOMA, first-order meta-analysis, and primary study levels[55]; (4) provides more reliable estimates of overall effect sizes by assessing differences between mean effect sizes across studies[55]. Given these strengths, SOMA has emerged as a robust tool increasingly applied across disciplines[52–54,56–61].

Data extraction and analysis

First-order meta-analyses were selected according to PRISMA guidelines (Fig. S4). From each study, we extracted data on effect ratios, percentage changes, confidence intervals, measures of variability (e.g., standard deviations), and sample sizes (the number of studies and observations). All effect metrics—including standardized mean differences and percentage changes—were converted into ratios for cross-study comparison. Log-transformed ratios and confidence intervals were then back-transformed to express percentage changes as:

$$\text{Percent difference} = \frac{M_{\exp} - M_{ctrl}}{M_{ctrl}} \times 100\% \tag{1}$$

where $M_{\exp}$ and M_{ctrl} are the mean effect sizes of the experimental and control groups, respectively. Cohen's d was calculated as:

$$\text{Cohen's } \boldsymbol{d} = \frac{Percent\ difference}{100} x \frac{M_{ctrl}}{SD_{pooled}} \tag{2}$$

The pooled standard deviation was calculated as:

$$SD_{pooled} = \sqrt{\frac{\left(n_{\exp} - 1\right)SD^2_{\exp} + \left(n_{ctrl} - 1\right)SD^2_{ctrl}}{\left(n_{\exp} + n_{ctrl}\right) - 2}} \tag{3}$$

where, $n_{\exp} and n_{ctrl}$ denote the number of replicates in the experimental and control groups, respectively.

Effect sizes were estimated using Comprehensive Meta-Analysis (v3.0) software[62], applying inverse-variance weighting (Hedges and Vevea's estimator) following Sanchez-Meca et al. (1998)[63]. This method reduces the influence of lower-quality studies—defined as those lacking sufficient data to compute effect sizes or measures of dispersion[64]. We also recorded study-specific moderators (e.g., climate zone, crop type, and study duration) and their reported interactions.

A hierarchical analytical framework was employed, and random-effects models were stratified into three thematic pillars (Supplementary notes 1-3), respectively for (1) crop yield, (2) water productivity (WUE), and (3) greenhouse gas emissions and SOC; the results are summarized in Table S2. Forest plots illustrated the variation in effect sizes across various soil and crop management practices and climate conditions. Comparisons between mulched and non-mulched systems were expressed as percentage differences (%) with 95% confidence intervals.

Publication bias was assessed through multiple approaches (Supplementary notes 4-6), including (i) Rosenthal's classic fail-safe *N* (estimating the number of unpublished studies required to nullify the observed effect), (ii) Begg and Mazumdar's rank correlation test, (iii) Egger's regression intercept (quantifying funnel plot asymmetry), and (iv) funnel plots (Figs. S5–S7). Meta-regression analyses were conducted in Comprehensive Meta-Analysis (v3.0) to identify study characteristics that explain variability in reported effect sizes (Figs. S8–S10). Study heterogeneity was addressed through sensitivity analyses (Table S3) and robustness tests (Table S4). Further details on methodology and SOMA limitations are provided in the Supplementary Information.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The datasets generated and analyzed in the current study, including source data for the display items, have been deposited in the Fishare repository [https://doi.org/10.6084/m9.figshare.6025748][65]. Source data are provided with this paper.

Code availability

No new code was generated in the analysis.

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Author contributions

L.W.[1] and G.Y.G. conceptualized the work, analyzed data and wrote original draft; S.G., Y.Z.[9], X.Z., P.L., and W.Y. contributed experimental materials; T.G., K.M.M., M.H., Y.I., J.Z., Y.Z.[15], D.D., Y.Y., S.K., C.H., and M.Z. brought out the critical issues relative to the subject, reviewed the draft and revisions, provided novel ideas to improve the work; S-J.L., S.F., L.W.[1,3], and J.H. contributed subsection materials to the paper; L.W.[1], G.Y.G., D.S., and Z.W. collected data, performed statistics, and constructed graphics; K.H.M.S. reviewed and revised revisions; All authors contributed to the manuscript, agreed on the contents and authorships, and approved the final version. G.Y.G. and L.W.[1] finalized the manuscript for publication.

Competing interests

The authors declare no competing interests as defined by Nature Portfolio or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Additional information

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