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Plastics can be used more sustainably in agriculture

Thilo Hofmann[1✉], Subhasis Ghoshal[2✉], Nathalie Tufenkji[3✉], Jan Franklin Adamowski[4], Stéphane Bayen[5], Qiqing Chen[6], Philip Demokritou[7], Markus Flury[8], Thorsten Hüffer[9], Natalia P. Ivleva[10], Rong Ji[11], Richard L. Leask[3], Milan Maric[3], Denise M. Mitrano[12], Michael Sander[13], Sabine Pahl[14], Matthias C. Rillig[15], Tony R. Walker[16], Jason C. White[17] & Kevin J. Wilkinson[18]

Plastics have become an integral component in agricultural production as mulch films, nets, storage bins and in many other applications, but their widespread use has led to the accumulation of large quantities in soils. Rational use and reduction, collection, reuse, and innovative recycling are key measures to curb plastic pollution from agriculture. Plastics that cannot be collected after use must be biodegradable in an environmentally benign manner. Harmful plastic additives must be replaced with safer alternatives to reduce toxicity burdens and included in the ongoing negotiations surrounding the United Nations Plastics Treaty. Although full substitution of plastics is currently not possible without increasing the overall environmental footprint and jeopardizing food security, alternatives with smaller environmental impacts should be used and endorsed within a clear socio-economic framework. Better monitoring and reporting, technical innovation, education and training, and social and economic incentives are imperative to promote more sustainable use of plastics in agriculture.

The global population surpassed 8 billion in November 2022 and is expected to increase to about 10 billion by 2050, further increasing the challenge of securing food for humans. Over the past 20 years, innovation in agricultural technologies has increased the Earth's overall capacity to provide food for more people. However, agriculture exerts one of the greatest pressures on the environment, and current practices frequently conflict with the United Nations

[1] University of Vienna, Environmental Geosciences (EDGE), Research Platform Plastics in the Environment (PLENTY), Environment and Climate Research Hub (ECH), Josef-Holaubek-Platz 2, 1090 Vienna, Austria. [2] McGill University, Department of Civil Engineering, Trottier Institute for Sustainability in Engineering and Design, 817 Sherbrooke Street West, Montreal, QC H3A 0C3, Canada. [3] McGill University, Department of Chemical Engineering, 3610 University Street, Montreal, QC H3A 0C5, Canada. [4] McGill University, Department of Bioresource Engineering, 21 111 Lakeshore Drive, Ste Anne de Bellevue, QC, Canada. [5] McGill University, Department of Food Science and Agricultural Chemistry, 21111 Lakeshore, Ste Anne de Bellevue, QC, Canada. [6] East China Normal University, State Key Laboratory of Estuarine and Coastal Research, 500 Dongchuan Road, Shanghai 200241, China. [7] Rutgers University, Nanoscience and Advanced Materials Center, Environmental Occupational Health Sciences Institute (EOHSI), School of Public Health, 170 Frelinghuysen Road, Piscataway, NJ, USA. [8] Department of Crop and Soil Sciences, Washington State University, Puyallup, WA 98371, Pullman, WA 99164, USA. [9] University of Vienna, Environmental Geosciences (EDGE) Josef-Holaubek-Platz 2, 1090 Vienna, Austria. [10] Institute of Water Chemistry, Chair of Analytical Chemistry and Water Chemistry, School of Natural Science, Technical University of Munich, Lichtenbergstr. 4, 85748 Garching, Germany. [11] State Key Laboratory of Pollution Control and Resource Reuse, Nanjing University, Xianlin Avenue 163, 210023 Nanjing, China. [12] Department of Environmental Systems Science, ETH Zurich, Universitätstrasse 16, 8092 Zurich, Switzerland. [13] ETH Zürich, Dep. of Environmental Systems Science, Universitätstrasse 16, 8092 Zürich, Switzerland. [14] Environmental Psychology Group, Department of Cognition, Emotion and Methods, Faculty of Psychology, Research Platform Plastics in the Environment (PLENTY), Environment and Climate Reserach Hub (ECH), University of Vienna, Wächtergasse 1, 1010 Vienna, Austria. [15] Freie Universität Berlin, Institute of Biology, Altensteinstr. 6, 14195 Berlin, Germany. [16] School for Resource and Environmental Studies, Dalhousie University, Halifax, NS B3H 4R2, Canada. [17] The Connecticut Agricultural Experiment Station, 123 Huntington Street, New Haven, CT 06511, USA. [18] Université de Montréal, Department of Chemistry, 1375 Ave. Thérèse Lavoie Roux, Montreal, QC H2V 0B3, Canada. ✉email: thilo.hofmann@univie.ac.at; subhasis.ghoshal@mcgill.ca; nathalie.tufenkji@mcgill.ca

Sustainable Development Goals (SDGs)[1]. While food production needs to increase further, agriculture is already responsible for 29% of greenhouse gas (GHG) emissions, 30% of energy consumption, 33% of land use, 70% of groundwater extraction, and 75% of deforestation[2]. Global warming, associated with many of these factors, negatively impacts crop yield. Linking agricultural intensification with ecosystem protection and spurring technological innovation is key to raising productivity[3]. In recent decades, plastics have played an ever-increasing role in achieving these goals to the point that they have become an integral component of modern plant agriculture. However, it is important that the short-term benefits of plastic use do not compromise long-term sustainability.

The aim of this review is to present a comprehensive and balanced assessment of the advantages and drawbacks associated with the utilization of plastics in agriculture, with a specific focus on plant agriculture. In addition to inspecting current applications, benefits, adverse effects, and risks, we specifically address the requirements for technological advancements, incentives and regulations, and social processes that could contribute to mitigating plastic pollution and identify pathways toward more sustainable use of plastics in agricultural practices.

Plastic is a generic term for a material based on one or more organic polymers and containing additional substances (additives) for the desired material properties, for example, flame retardants, antistatics, coloring and spinning agents, stabilizers, reinforcing materials and fillers, UV-adsorbents, and plasticizers. Conventional polymers, such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are environmentally persistent due to the high chemical stability of their polymer backbones. Agricultural plastics composed of these conventional polymers can physically fragment into micro- and nanoplastics (MNP), which can accumulate in soils over time, be taken up by biota, or be transported into adjacent receiving environments. In contrast, biodegradable polymers are designed to undergo microbial metabolic utilization, a process in which the polymer carbon is converted to CO_2 and microbial biomass under oxic conditions. The biodegradability of a polymer depends not only on its physicochemical properties but also on the environmental conditions in which the polymer degrades. Although biodegradable polymers are designed to be ultimately completely mineralized to CO_2, the process may also entail the transient formation of ever-smaller MNP fragments. Biodegradable (and conventional) polymers can be from non-renewable petrochemical or renewable bio-based sources[4]. For example, polybutylene adipate-co-terephthalate is produced from petrochemical sources, while starch, cellulose, chitosan, and poly(lactic acid) are derived from renewable sources. While this review focuses mainly on structural polymers, non-structural polymers (polymers in liquid formulation, water-soluble polymers) are also widely used in agriculture, e.g., for encapsulation or dispersion of pesticides, herbicides and nutrients, seed coatings, and soil conditioners. In general, structural polymers can potentially be collected after the intended use, reused, or recycled, while non-structural polymers cannot, as they dissipate into the environment. However, the key concepts presented here also apply to non-structural polymers.

There are multiple applications of plastics in agriculture and their use has increased over the last 70 years to an estimated 12.5 million tons annually[5], which has led to the accumulation of large quantities of macro-, micro-, and nanoplastics in soils and other receiving environments. The pervasive use of plastics in agriculture poses a growing risk to soil functions, and the wider natural environment, highlighting the urgency for a more sustainable use of plastics in agricultural food production. In March 2022, 175 countries agreed to negotiate a global and legally binding Plastics Treaty (UNEA-5.2) to end plastic pollution by 2024[6–8]. This international policy instrument aims to address the ecological and human health risks posed by the entire plastic lifecycle, including those linked to agriculture. It is anticipated that regular reporting will be required by governments and non-government stakeholders on the implementation and performance of their goals to reduce plastic pollution[9].

Current applications and benefits

Plastics in plant agriculture have many environmental and societal benefits[5,10] (Fig. 1). Plastic mulch films, which alone account for ~50% of the mass of all agricultural plastics, are widely used in crop production[11]. They provide multiple agronomic benefits, including weed and pest control, soil moisture conservation, a means to control soil and air temperatures, and enhanced nutrient uptake. All these benefits translate to an increase in yield, improved water and nutrient use efficiency, and reduced pesticide use. In China, for example, without the use of mulch film, an additional 3.9 million hectares of arable land would be required to produce the same amount of food[12]. The increased soil temperature below plastic mulch films allows farmers to plant and harvest crops earlier and thus provides a market benefit. Plastic mulch films are also used in organic agriculture because they help suppress weed and insect infestation without the need to apply synthetic pesticides.

Conventional plastic mulch films are typically composed of low-density PE, but can also be made of other polymers such as PVC or ethylene-vinyl acetate copolymers. At 40–50 kg/ha, the use of plastic mulch films is highest in Europe and Asia, while it is slightly lower in North and South America at 10–20 kg/ha[5]. Incomplete collection after use leads to the accumulation of persistent plastic residues in soils. Furthermore, chemical additives can leach out from the mulch films. Thus, over repeated mulch applications, the accumulation of plastic residues and released additives can lead to detrimental effects on soil productivity and soil health. Certified soil-biodegradable mulch films are marketed as alternatives to thin (<20–25 μm) conventional mulch films. These biodegradable films can be ploughed into the soils after harvest, where under oxic conditions they are intended to completely biodegrade into CO_2 and microbial biomass[13].

Plastic sheets are standard covering materials in greenhouses[14] and high and low tunnels, providing thermal insulation, radiant energy capture, and protection against weather and pests. They are produced from a range of polymers and contain additives that provide diverse optical and energetic properties. Plastics are also used as shade and protective nets[15] (e.g., sunshades, anti-hail, anti-bird covers) or as seedling plugs.

Food security depends on nitrogen fertilizers, but their production and use account for 5% of global GHG emissions[16]. Increasing nitrogen-use efficiency is the most beneficial strategy to reduce emissions, and polymer coatings are an efficient means to control the release of nutrients in fertilizer formulations so that they better coincide with the plant life cycle[17]. For example, it is estimated by the Japanese Association of Agriculture and Forestry Statistics that between 1976 and 2018, 2.3 million tons of polyurethane- and PE-coated fertilizers were used in Japan, and these helped to control nutrient release, increase nutrient use efficiency, and reduce nutrient loss[18]. The European Chemicals Agency (ECHA) has proposed to ban non-biodegradable polymer coatings for controlled-release fertilizers, and the draft regulation with a transition period of 5 years was discussed by the European Commission in September 2022. Recent developments have focused on biodegradable, non-toxic biopolymers to further optimize efficiency and ensure targeted release. For example, using this strategy, 25% of the recommended nutrient loading has been shown to yield an equivalent photosynthetic performance in

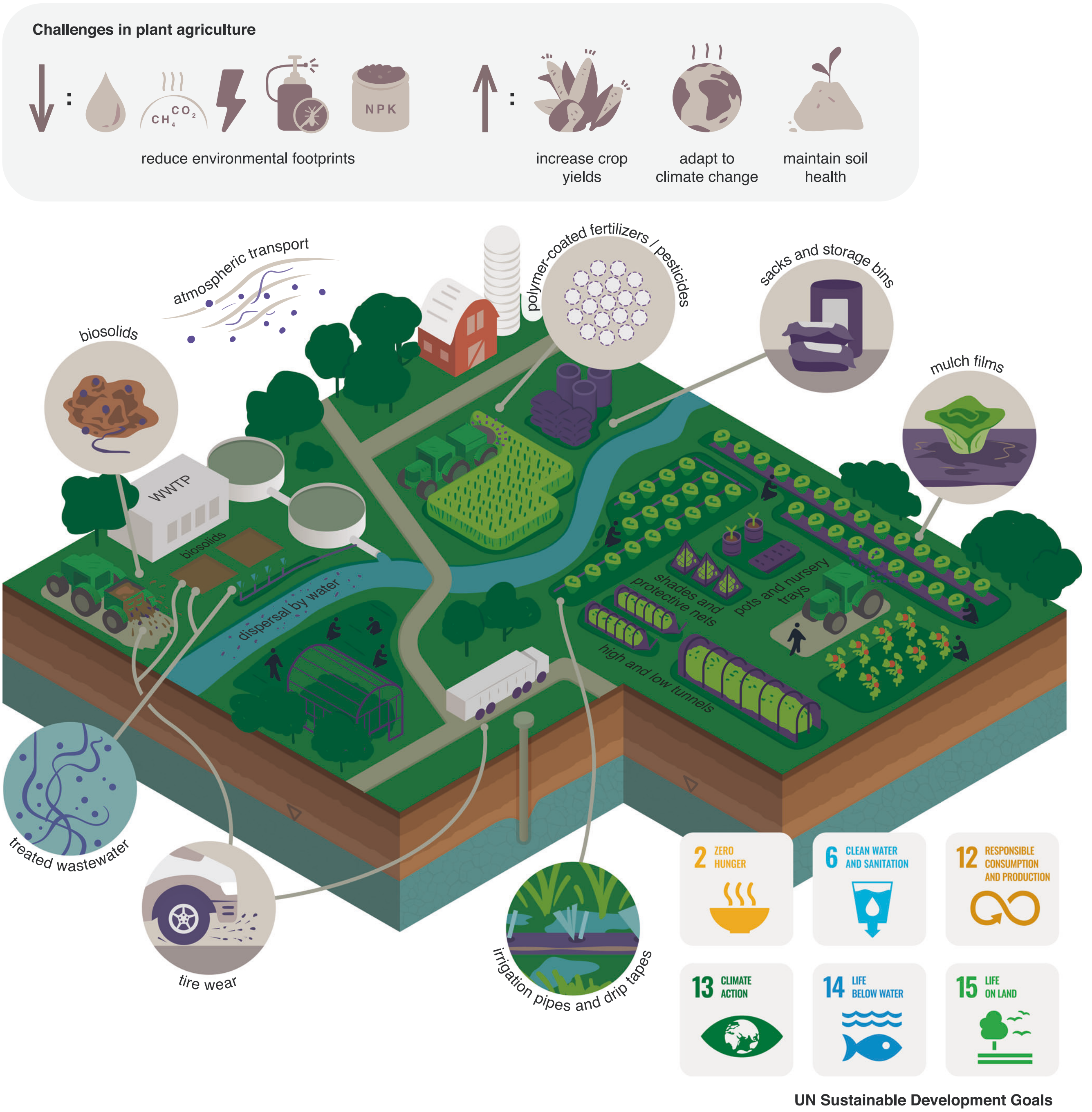

Fig. 1 Applications of plastics in plant agriculture. There are multiple applications of plastics in plant agriculture. Plastics help to reduce irrigation water, pesticide, and fertilizer demand, leading to reduced greenhouse gas emissions and increased crop yield, which impacts several UN Sustainable Development Goals. There are also diverse sources of incidental plastic pollution on croplands; for example, during the dispersal of wastewater biosolids or treated wastewater from wastewater treatment plants (WWTP), including tire wear particles contained therein.

soybean and wheat as did a 100% application rate of the conventional formulation[19].

Water scarcity is a major factor limiting crop growth and yield[20]. In addition to mulch films, irrigation pipes and drip tapes help to direct precise amounts of water to plant roots, and, hence, to improve water use efficiency. Irrigation equipment is usually made of conventional polymers like high-density PE or PVC. Seedling plugs and nursery pot trays are widely used in crop production. Seedling plug trays allow for efficient germination and optimize plant growth. In addition, some crops require support during cultivation (climbing species, vines). Finally, nursery pot trays are used for transport, and plastics are used to produce agricultural packaging materials such as fertilizer and storage bags, flexible bulk containers, crates, and containers for pesticides. While the focus of this review is on field applications, a variety of plastics are also used in hydroponic systems and indoor vertical farming for tubing, clamps, grow trays, grids, packaging, and net pots.

Adverse effects and risks

Plastics are an additional stressor that potentially harm essential soil functions. The widespread use of plastics in crop production

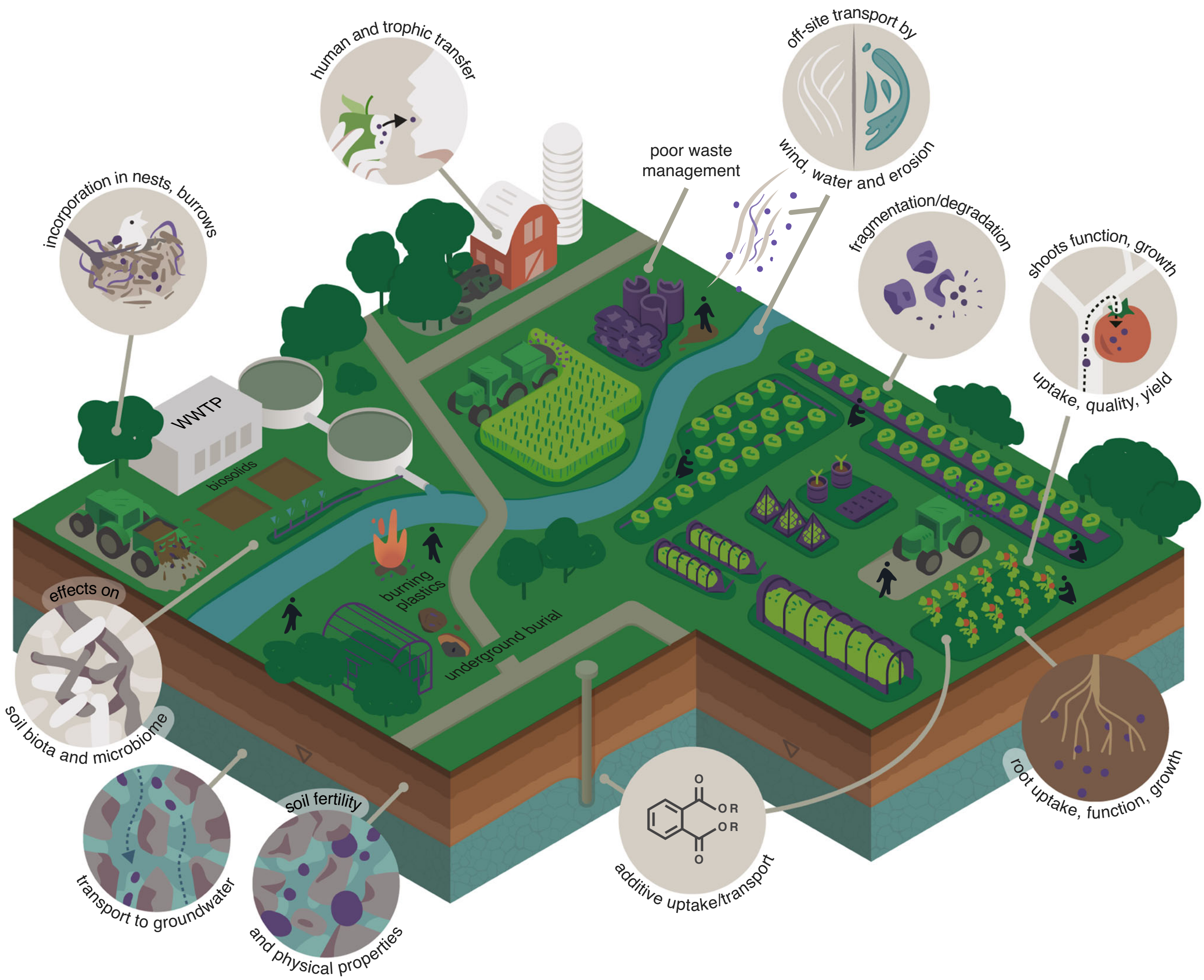

Fig. 2 Adverse effects of plastics in agriculture. The widespread use of conventional plastics in agriculture has led to their accumulation in soils with diverse and long-term effects on crop production, for example, reduced crop quality, and adversely impacted soil health and ecosystem functioning, with unclear uptake potential through the human food chain and impact on human health.

has been reported to affect the physical, chemical, and biological properties of soil (Fig. 2). Due to the persistence of conventional plastics in the environment, plastic fragments will inevitably accumulate in soils over time, disintegrate into MNP and release additives, which may also negatively impact soil health. The effects of plastics on soil properties and fertility are strongly influenced by the properties of the material (i.e., size, morphology, and chemical composition)[21]. The residues of conventional mulch films in the soil can hinder water infiltration, decrease water holding capacity, impact microbial communities and macrofauna, and decrease soil fertility[22,23]. As a result, plant growth and yields may be negatively impacted. Negative impacts have been observed at high plastic concentrations (>240 kg/ha)[24], where conventional, non-biodegradable plastic mulch films are repeatedly incompletely removed or tilled into the soils.

Plastics are not the only stressors acting on agricultural ecosystems. Many global change stressors are acting concurrently on agricultural ecosystems[25], including physical (e.g., warming), chemical (e.g., pesticides), and biological (e.g., invasive plant species or weeds) stressors. Recent work suggests that the combined pressures and the high number of factors acting on agricultural soils can lead to unpredictable effects in the soil ecosystem[26,27]. The comprehensive effects on soil systems are driven by multiple natural and anthropogenic factors and dissecting the important interactions with plastics should be a major research effort[28].

Soil particle transport and the co-transport of contaminants have been intensively studied and the governing processes are generally transferable to the transport of plastics in soils and to aquifers[29]. The properties of the plastics themselves (e.g., size, morphology, surface properties), the properties of the soils (physicochemical and hydraulic conditions, biogenic activity), and the soil-plastic-particle interactions determine their transport in soils and groundwater[30]. However, recent studies show that, in general, plastics are not a dominant vector for contaminant co-transport to deeper soil layers and groundwater[31]. Soil erosion is anticipated to be an important diffuse pathway for plastics to water bodies[32] and plastic fragment size is a sensitive parameter in determining erosion[32]. Atmospheric plastic transport involves (re)suspension–deposition cycles[33] and due to the lower density of plastics compared to soil particles, plastic concentrations in wind-eroded soil materials might be higher than in the original agricultural soils[34].

Plastics are taken up by biota and can disrupt microbiome functions. Plastic particles of sufficiently small size can be taken up into plants, while larger plastic fragments can attach to root surfaces and be consumed by humans in the case of root crops. Crossing plant barriers and translocation through plant cells is limited to nanoplastics (<1 µm), with the apoplastic pathway being the main transport pathway, although the symplastic route cannot be excluded based on available data[35]. Nevertheless, most plant uptake studies so far have been performed under hydroponic conditions and not in soil systems[36]. While the trophic transfer of plastics in terrestrial food chains has been demonstrated, there is no clear information on the magnitude of the direct transfer of plastics from crops to humans through food.

A better understanding of the potential of plastics and leached plastic additives to accumulate in plants and enter the food chain is critical for food safety. The effects of plastics in food on human health are unclear and further research is needed on their translocation across biological barriers and uptake into organs, as well as the adverse health effects that may result[37,38].

Plastics have been shown to negatively affect the growth of crops and animals (e.g., ciliates, flagellates), and cause soil bacterial community structure dysbiosis. Physiological and biochemical impacts on seeds, shoots, and roots of crop plants (e.g., cucumber, wheat, rice, beans) following exposure and uptake have been demonstrated in hydroponic systems at higher concentrations[39,40]. The effects of plastics on soil microfauna (e.g., *Caenorhabditis elegans*), mesofauna (e.g., *Folsomia candida*), and macrofauna (e.g., snails, earthworms) include adverse behavioral (mobility, avoidance), physiological (growth, reproduction, mortality) and biochemical impacts (oxidative stress, energy metabolism)[29]. Plastic particles induce microbiome compositional and functional disruption[41]. The uptake and effects of MNP also vary strongly, and distinguishing individual and mixture effects is challenging[42]. Nonetheless, one caveat with respect to available research results is that experiments often use hydroponic systems and high concentrations of 0.1-10% w/w, which are not representative for soils or field conditions[43].

Leaching of additives from plastics increases the chemical burden on soils. Aging and fragmentation of macroplastics into MNPs is expected to not only contribute to the dispersion of plastics in the environment but also enhance the release of additives and their degradation products. Leached additives can be transferred to biota and plants[44], or sorb to soil. Time scales over which chemicals are released vary widely. For example, the release of hydrophobic phthalates such as di(2-diethylhexyl) phthalate (DEHP) can extend over centuries due to slow diffusional aqueous boundary mass transfer, while more polar phthalates such as di-butyl phthalate are released within days[45,46]. The consequences of a long-term release of chemicals due to the degradation of plastics in soils are unknown[47] and the plastic toxicity debt needs to be reduced. Additives such as phthalates and bisphenols are known to have direct toxic effects from endocrine-disrupting properties[48], while others such as the transformation products of the tire antioxidant 6PPD have shown toxicity across multiple environmental compartments[49]. Following their release, phthalate esters and additives from tires may accumulate and be metabolized in edible plants, serving as a point of entry to the human food web. The application of agrochemical formulations stored in fluorinated polyethylene containers used in agriculture and fragments from discarded plastic containers in agricultural soils may be a source of contamination of per- and polyfluoroalkyl substances for agricultural soils[50].

Sustainable use of plastics in plant agriculture

The sustainable use of plastics in plant agriculture will require alignment with the "3 R" waste hierarchy concept of reducing, reusing, and recycling plastics as preferred options over disposal after use. Greater scrutiny is required for plastic applications that only have non-circular end-of-life treatment options. Adding to these principles, two additional criteria can provide guidance in determining sustainable use strategies and identify after-use treatment options for plastics in agriculture: (i) collectability of plastics after use and (ii) duration of plastic use. For applications that allow complete collection after use, reuse, and recycling are the preferred treatment options, irrespective of the usage duration (Fig. 3). For these applications, advances toward sustainability must be made by using plastics that do not chemically weather and fragment, and by implementing technologies that ensure complete collection after use, especially for plastics used below ground level, such as irrigation pipes.

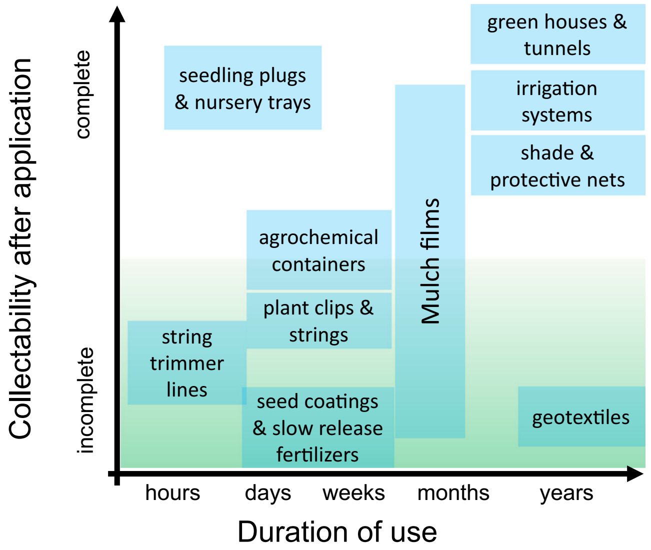

Fig. 3 Collectability and duration of use of plastics in agriculture. Collectability after use and duration of use. For plastics that can be collected in their entirety (i.e., complete collectability after use), priority should be given to reuse and recycling. Innovation in the material design must be geared towards complete collectability, recyclability, and reuse. Plastics that cannot be collected in their entirety after use should be fully biodegradable, e.g., seed coatings, slow-release fertilizers, and thin (<20–25 µm) mulch films. Material design must be geared towards ensuring sufficient stability of the plastics during use, while allowing for biodegradability after use.

For applications where plastics cannot be completely collected after use, or where the collected plastic is too degraded or soiled to be reused or recycled, less toxic and biodegradable polymers should replace conventional persistent polymers, especially in cases with a short duration of use such as mulch films or non-biodegradable polymer coatings for controlled-release fertilizers. The biodegradable plastics must be able to function throughout the entire period of application and, at the same time, be completely converted to CO_2 and microbial biomass in the soil within a specified time period, at the end of their life. These applications include, but are not limited to seed coatings, slow-release fertilizers, thin mulch films, as well as geotextiles (Fig. 3).

Collection after use, reuse, and recycling should be prioritized. The rates of reuse and recycling for agricultural plastic waste are currently very low (<10%) and need to be substantially increased[51]. In cases where the reuse of agricultural plastics is challenging, it is imperative to prioritize the elimination of problematic types. For instance, we strongly advocate for the prohibition of oxo-degradable mulches, the restriction of harmful

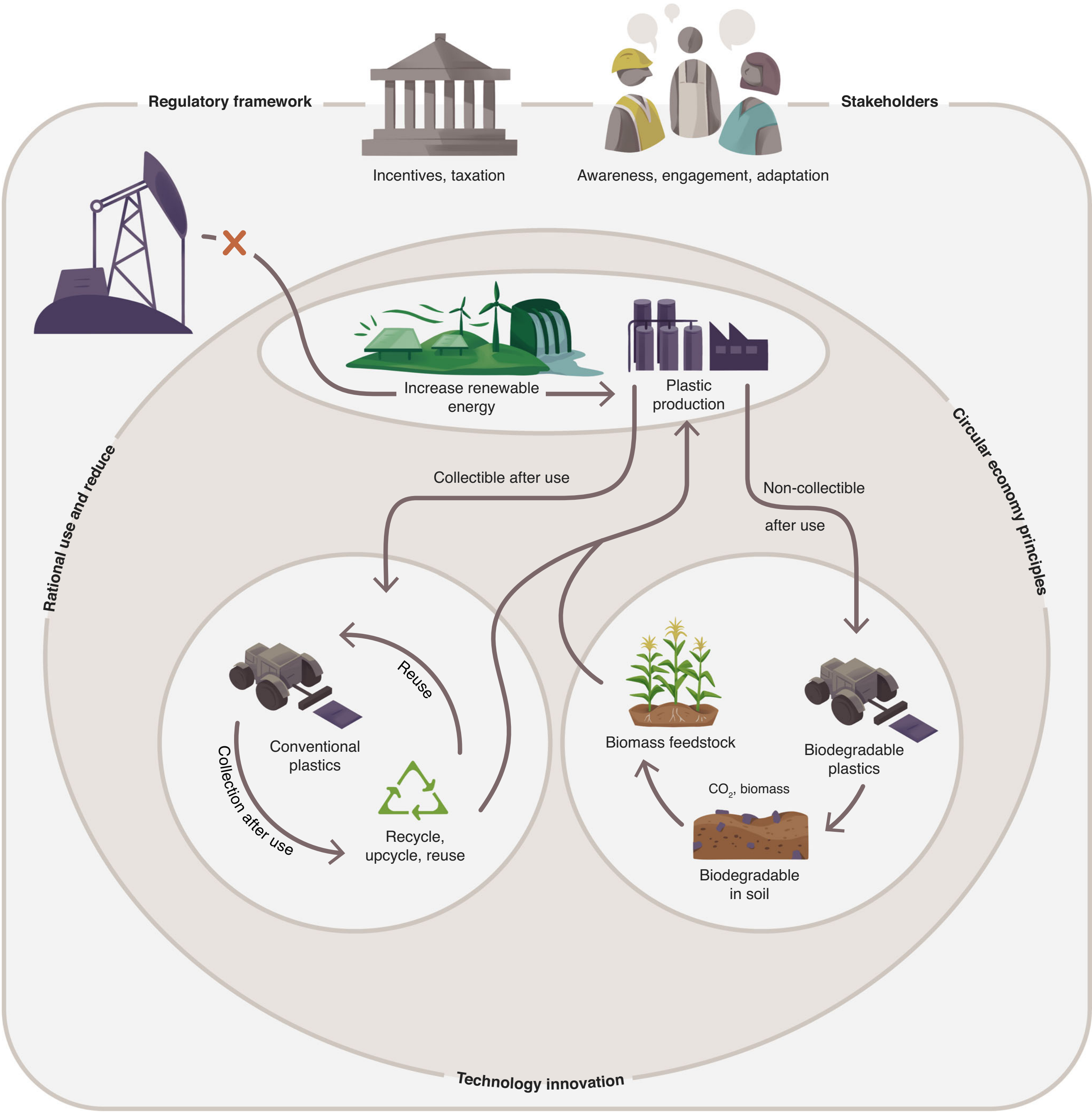

Fig. 4 How to use plastics more sustainably in plant agriculture. The regulatory framework and targets for the use of plastics in plant agriculture should be strict and legally binding for all UNEA member states. Awareness, engagement, and adaptation are needed to reduce the use of plastics, involving all stakeholders. A shift to renewable energy sources is needed in plastics production to reduce greenhouse gas emissions. Plastics that can be collected in their entirety after use must be recycled, upcycled, or reused. Rates of reuse and recycling need to be substantially increased. Non-collectable plastics must be fully biodegradable in the soil. To ensure sustainable use, technological innovation, circular economy principles, rational use, and reduced use of plastics are required in all areas of agricultural food production.

polyvinyl chloride usage, and the phasing out of intentionally added microplastic applications (see Fig. 4). Therefore, plastics that are not substantially damaged during routine use should be prioritized for reuse on farms, or through collection, facilitated by programs such as extended user responsibility and reverse logistics[52,53].

After collection, non-reusable agricultural plastics should undergo a rigorous cleaning process to eliminate soil contamination and other debris before being sent to materials resource facilities (MRF) for recycling. Some agricultural plastics, such as agrichemical containers, can be effectively decontaminated and reused[54]. Economic feasibility and environmental benefits can be realized by collecting bale wrap films, which are typically less soiled compared to ground-collected mulch films[55]. Additionally, plastic mulch films can be recycled through pyrolysis to produce fuels or polymers, as the presence of soil or other contaminants does not affect this thermal treatment process[56]. To facilitate agricultural plastic recycling, it is essential to establish dedicated programs either through legislation or voluntary initiatives, encompassing well-coordinated and widely accessible collection facilities. If agricultural plastic waste is excessively contaminated or physically degraded, it should be appropriately disposed of in a landfill, but this option is the least desirable.

MRF sort and processe plastics using mechanical means such as shredding followed by melting and re-extrusion to generate downcycled plastic resins or asphalt. Chemical processing techniques such as pyrolysis, dissolution, re-extrusion, chemical or enzymatic methanolysis, or gasification can produce a range of up-cyclable products. These include feedstock chemicals such as aromatic chemicals and olefins, high-quality plastic resins and original plastic monomers, methanol, syngas, and transportation fuels[57]. There is substantial research on different upcycling technologies for waste plastics such as hydrogenolysis of plastics to yield lubricants and oils, and enzymatic treatment or chemical and enzyme-assisted mechanochemical processing of PET to yield the primary monomers[58,59]. Newly developed zirconium-catalyzed C-H and C-C alumination processes might make it easier to recycle and upcycle plastics, or make them biodegradable[60]. Technologies are mostly in operation commercially, with some at industrial demonstration stages, but they should be able to address recycling of the various types of plastics used in agriculture. Although processing techniques are specific to plastics and their mixtures, plastics used in agriculture are in general recyclable. In fact, plastic film waste from greenhouses has been directly used for laboratory demonstration of catalytic cracking to enable feedstock recycling[61]. Furthermore, a closed-loop supply chain analysis for bale wrap collection, sorting, and recovery in Finland showed substantial economic savings and reduced global warming potential[55]. A closed-loop recycling philosophy could also be employed for self-immolative polymers. Although the feasibility of a larger-scale application of breaking down and then re-constituting the polymers for many cycles has not yet been fully explored, recent reviews have highlighted the interest and importance of such materials[62,63].

The types of chemical additives present in plastic products can substantially affect recyclability. For mechanical recycling, the presence of certain additives and their transformation products affects the safety and marketability of the secondary plastics. For instance, when plastics with different pigments are mixed, this may result in the coloration of the secondary product, restricting its further utilization[64]. Toxic by-products may also be produced if recycling is performed at unsuitable temperatures, which may lead to an accumulation of these substances and a reduction of the suitability of the plastics in a circular economy[65]. Therefore, it will be essential to integrate management of chemical additives into the global Plastics Treaty in order to reduce their complexity in plastic mixtures[66]. Technologies such as dissolution-based recycling can be designed to selectively remove problematic additives and components, but these techniques are likely to be more expensive and energy intensive[57].

Although plastic wastes in agriculture have the advantage of providing a relatively homogeneous stream of compositionally viable materials for recycling, within concentrated geographic locations, there are nonetheless technical obstacles. Thin films that are too brittle or weathered cannot be collected in their entirety after use. Exposure to heat, solar UV radiation, soil, and agricultural chemicals can degrade some of the plastics and make recovery difficult or only allow down-cycling by mechanical processing[67,68]. Furthermore, the seasonal variability linked to the generation of agricultural plastic wastes makes it challenging for recycling facilities to create stable secondary markets.

For plastic mulch films, the major obstacle to recycling is the contamination with soil adhering to the plastics when they are recovered from the field after harvest. Soil and plant residue contamination can account for up to 80% of the total weight of plastic materials, while existing recycling facilities require contamination levels below 5%[56]. Therefore, it is crucial to develop effective techniques for removing soil and plant residues from plastic films. These techniques may involve mechanical or manual cleaning processes and minimizing soil adhesion. Ideally, they should be implemented directly on-site at the farm to reduce transportation costs, using mechanical rotary brooms or manual methods on dry days, which facilitate collection and recyclability[56]. Consequently, there is a pressing need for improved techniques and standardized methods for post-use collection, decontamination, and handling to enhance recycling[67,69,70].

Plastics that cannot be collected in their entirety after use should be biodegradable. Biodegradation is considered a viable end-of-life option for agricultural plastic applications in which the plastics cannot be collected from the field in their entirety after use, as well as for cases where the collected plastics fractions are too weathered or soiled to allow for reuse and recycling (Fig. 4). Applications where collecting plastics after use is challenging, if not impossible, include for example thin agricultural mulch films, abraded plastic from string trimmers and plant clips, and geotextiles[71,72]. In these cases, complete biodegradation of the plastics to CO_2 and biomass ensures that no residues will accumulate in soils. The use of polymers with cleavable bonds such as esters or amides[73] can allow biodegradation to be tuned to occur at the end of life. Modifications of the backbone chemistry of existing polymers to render them biodegradable is an emerging field of research. For example, a novel bio-based polyester-2,18 exhibits high-density PE-like properties, but is readily hydrolyzable by naturally occurring enzymes[74]. Conversely, using prooxidant (i.e., "oxo") additives that trigger polyolefin breakdown upon thermal or photochemical activation is an inadequate technology that has failed to ensure plastic biodegradability[75].

It will be necessary to carefully scrutinize elevated inputs of biodegradable plastics in order to ensure that they indeed biodegrade in situ over a reasonable, defined timeframe. Presently, the biodegradability of plastics in soil is assessed in laboratory soil incubation studies under oxic conditions that couple respirometric analyses of polymer conversion to CO_2 under constant humidity and elevated, constant temperatures (typically at 20–25 °C). These conditions are expected to favor biodegradation compared to the field, and research is needed to determine the extent to which biodegradation data obtained in the laboratory are transferable to more realistic field conditions. Furthermore, greater efforts need to be directed toward monitoring the concentrations of biodegradable plastics in situ over long periods (~years) and following repeated applications, in order to determine steady-state concentrations in soils and to identify the key factors affecting biodegradation rates. Analytical techniques for accurately quantifying low concentrations of polymers in soils are sorely required[76]. Stringent biodegradability standards that define testing conditions and stipulate the required mineralization timeframe for the incubation are key to ensuring biodegradability. Such a standard exists for biodegradable mulch films (EN 17033:2019), which stipulates 90% of polymer mineralization in soils over a two-year laboratory soil incubation at 20–25 °C, as assessed by established methods (ASTM-D5988). Scientific advice will be critical to future regulatory efforts for both the plastics and their additives. Indeed, additives are expected to be readily released during biodegradation, resulting in potentially higher concentrations in soil porewaters compared to additives leached from conventional plastics, highlighting the need for using environmentally benign additives only.

Presently, biodegradable plastics are 20–80% more expensive to produce. Although high costs could considerably reduce their acceptability[77], the costs of collection, recycling, or disposal needed for conventional plastics are generally not included in such calculations. Furthermore, negative impacts on soil productivity, resulting from the long-term accumulation of conventional non-biodegradable plastics in agricultural soils have not been valorized.

Mandatory use of environmentally benign additives is necessary to reduce toxicity burdens. Plastic (bio)degradation and the concomitant leaching of additives into soils are of concern. Plasticizers have been intensely scrutinized due to their high loading in many plastic materials (e.g., typically about 30-35 wt% for PVC). One of the most common plasticizers used, DEHP and its monoester metabolite, were shown to act as endocrine disruptors[78], leading to its ban in children's toys[79]. Understanding degradation pathways for phthalates has led to the development of alternative plasticizers, such as the non-phthalate di(2-ethylhexyl) terephthalate and others such as di(isononyl) cyclohexane-1,2-dicarboxylate (DINCH). These alternative plasticizers have been grouped under the umbrella of "green plasticizers", and, along with their metabolites, are viewed as being non-toxic. However, it has recently been discussed that DINCH might have a metabolic toxicity to aquatic organisms[80], and the challenges of assessing whether a plasticizer is truly "green" has been highlighted in several reviews[81–83]. While some plasticizers may use renewable feedstocks, their syntheses often involve hazardous chemicals, underscoring the importance of performing life cycle analysis to avoid regrettable substitutions[84].

More than 10,000 chemicals are used in the production of plastics, many of which are substances of concern based on persistence, bioaccumulation, and toxicity criteria[85]. A transition towards sustainable plastic applications will require transparency and accessibility of information regarding the chemicals used in the production of plastics. For some chemicals such as phthalates, there is extensive literature on their release from plastics and their uptake by soil organisms. However, for most plastic products used in plant agriculture this information has not been thoroughly documented and fate studies are needed[44,86]. To address plastic pollution concerns holistically, including the diversity and complexity of chemicals added to plastics, chemicals should be included in UNEA-5.2, which will foster innovation in the design of agricultural plastics[66].

Sustainability innovation should be linked to social processes. Public concern about plastic waste in general, and microplastics specifically, is high[87,88] and shifting from marine environments to soils, air, and human health[21,87], even though evidence for the adverse effects of MNP on human health is currently lacking[89]. Food safety is a particularly sensitive topic. Microplastics in food were among the top ten food safety concerns in Europe in 2022[90]. Such public concern can affect consumer demand and the reputation of producers.

There is a gap in research on risk and benefit perceptions of plastic in the context of food from the perspectives of stakeholders in the entire supply chain, including producers, processors, packaging industry, and end users, and a gap in research on relevant education and training programs to change current practices. Relevant factors may include convenience, cost, industry communications, and regulatory frameworks, but also awareness of the systemic and long-term risks of plastics to ecosystems and future livelihoods, all of which could predict stakeholder willingness to make changes.

For farmers specifically, recent work showed that 80% of Irish farmers reported an increase in plastics use and 88% reported concern about negative environmental impacts[70]. Disposal practices varied widely, depending on materials in use, reported knowledge, perceptions of costs and facilities, and education level, but links between general education level and behavior are inconsistent[91].

Moreover, while some attempts are being made to provide specific training, for example, "Plastics in Agriculture Lessons—Preventing Plastic Pollution"[92], to the best of our knowledge, there are currently no comprehensive programs regarding the life cycle implications of plastics and practical know-how on new skills and practices. Such new training programs should be addressed to diverse stakeholders and cover all life cycle phases of plastics. Crucially, such programs should not just teach factual knowledge, but integrate best practice in line with psychological approaches that emphasize the importance of factors beyond mere knowledge, such as motivations, norms, and values in predicting behavior change[93].

Thus, the reduction of plastic pollution is a question of perceptions and behavior, as well as of the materials available, production practices on farms, and contextual constraints. It would be useful to quantify the variance attributable to different behavioral practices to determine the importance of this particular lever in agriculture and along the food supply chain. Future work to reduce plastic pollution should build on existing approaches from soil conservation behaviors and environmental stewardship, and must better capture the interplay between environmental and social processes[94,95].

Renewable energy production and sources. The use of plastics involves larger-scale aspects related to the sustainability of the production process. For example, while the production and use of plastics account for 4.5% of global greenhouse gas emissions, 96% of these emissions are attributable to their production using non-renewable resources. These emissions can be allocated to fossil fuel extraction (10%), electricity generation (32%), polymer production and manufacturing (41%), and other sectors (17%), underscoring the importance of reducing the production of primary plastics[96]. In cases where the use of plastics in agriculture is essential, effective measures to reduce the carbon footprint of the plastics include transitioning to renewable energy, increasing energy efficiency in the fabrication process, and promoting the use of bio-based plastics. The use of agricultural plastics from non-renewable sources should be disincentivized (e.g., with environmental taxes), and innovations that promote bio-based materials should be prioritized (e.g., with tax subsidies). Although the raw materials for bio-based polymers can in some cases be produced from waste materials such as crab shells, shellfish waste, or insect exoskeletons for chitosan[97], a substantial increase in demand for the biological raw materials may result in undesired competition with food production[98,99]. Increased demand could also substantially intensify pressure on marine and terrestrial ecosystems. Therefore, the substitution of fossil-based materials with bio-based materials must be carefully evaluated, by considering the entire life cycle, to avoid unwanted concomitant risks.

Regulatory frameworks and incentives. There is consensus among scientists, members of government, non-governmental organizations, and stakeholders that sources of plastic pollution must be addressed across many areas of society, including plant agriculture. Achieving a more sustainable use of plastics in plant agriculture will require science-based decisions built on circular economy principles, including innovations in material design, collectability after use, reuse, and recycling, and changes in usage practices (Fig. 4).

Currently, plastic products in agriculture cannot be easily eliminated or replaced with non-plastic materials without incurring serious environmental and societal costs[10], and alternatives to plastics with a smaller environmental footprint are not currently widely available. However, commitment to increasingly 'plastic-free' agriculture could stimulate technological innovation[100]. Agricultural actors can be rewarded with tax breaks or certifications if they adopt more sustainable plastic use practices, including the collection of used plastics for reuse and recycling and the use of fully biodegradable plastics, where appropriate. Such incentives could encourage rapid and widespread adoption. Socio-economic frameworks that disincentivize the use of non-collectible conventional plastics would facilitate such a transition in the agricultural sector. However, as it is imperative to minimize negative economic impacts on farmers, clear policy guidelines are required to ensure a just transition. Global production patterns are diverse, and thus, any approach needs to consider regional and cultural differences in food production. Such a holistic approach must include rational use, optimization of the collection after intended use, reuse, and recycling, innovative design for environmentally benign materials, modification of agricultural practices, and improved management strategies to reduce environmental pollution originating from plastics and associated chemicals. Circular economy principles can provide a framework for specific measures to minimize the environmental footprint and contribute to the sustainable use of plastics in plant agriculture[101].

Current negotiations to develop and implement a legally binding global plastics treaty within the United Nations Environment Assembly (UNEA-5.2) aim to curb plastic pollution, including pollution from agricultural plastics[6,9,102]. Achieving this aim requires an international regulatory framework that considers the full life cycle of agricultural plastics. Targets should be strict and legally binding for all UNEA member states[103] and regularly adapted to the current state of research. Governments and non-government stakeholders must regularly monitor and report on the use of plastic in agriculture in order to assess the implementation of UNEA-5.2 goals[104] and the performance of actions taken. In addition, an inventory of all plastics used, collected, reused, and recycled would need to be created. Data would be collected by the sector and reported at the national level to establish standardized plastic pollution monitoring databases and track compliance with reduction targets. Monitoring and reporting of plastics used in agriculture with detailed post-use treatment analysis will help ensure that reduction strategies are effective.

Plastics are essential in modern agriculture, aiding in weed and pest control, water conservation, and improving crop quality and yield. While providing agronomic benefits, their production, improper disposal, loss during operations, or abandonment in fields and farmland can pose substantial environmental risks. To mitigate these negative impacts, responsible and sustainable utilization of plastics is imperative. Achieving sustainability in agricultural plastic usage necessitates a comprehensive approach, encompassing rational use, technological advancements in reuse and recycling, adoption of less toxic and biodegradable materials, education and behaviour change, social and economic incentives, and legislative enforcement.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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References

1. McGreevy, S. R. et al. Sustainable agrifood systems for a post-growth world. *Nat. Sustain.* **5**, 1011–1017 (2022).
2. Hofmann, T. et al. Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture. *Nat. Food* **1**, 416–425 (2020).
3. Willett, W. et al. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).
4. Rosenboom, J.-G., Langer, R. & Traverso, G. Bioplastics for a circular economy. *Nat. Rev. Mater.* **7**, 117–137 (2022).
5. FAO. Assessment of agricultural plastics and their sustainability. A call for action. https://www.fao.org/3/cb7856en/cb7856en.pdf (Rome, 2021).
6. Bergmann, M. et al. A global plastic treaty must cap production. *Science* **376**, 469–470 (2022).
7. Thompson, R. C., Pahl, S. & Sembiring, E. Plastics treaty — research must inform action. *Nature* **608**, 472 (2022).
8. United Nations Environment Assembly. 5/14. End plastic pollution: towards an international legally binding instrument - resolution adopted by the united nations environment assembly on 2 March 2022 [UNEP/EA.5/Res.14]. (2022).
9. Walker, T. R. Calling for a decision to launch negotiations on a new global agreement on plastic pollution at UNEA5.2. *Mar. Pollut. Bull.* **176**, 113447 (2022).
10. Andrady, A. L. & Neal, M. A. Applications and societal benefits of plastics. *Philos. Trans. R. Soc. B Biol. Sci.* **364**, 1977–1984 (2009).
11. Kasirajan, S. & Ngouajio, M. Polyethylene and biodegradable mulches for agricultural applications: a review. *Agron. Sustain. Dev.* **32**, 501–529 (2012).
12. Sun, D. et al. An overview of the use of plastic-film mulching in China to increase crop yield and water-use efficiency. *Natl. Sci. Rev* **7**, 1523–1526 (2020).
13. Hayes, D. G. et al. Biodegradable plastic mulch films for sustainable specialty crop production. *In:* Polymers for Agri-Food Applications 183–213 (Springer International Publishing, 2019).
14. Maraveas, C. Environmental sustainability of greenhouse covering materials. *Sustainability* **11**, 6129 (2019).
15. Maraveas, C. Environmental sustainability of plastic in agriculture. *Agriculture* **10**, 310 (2020).
16. Gao, Y. & Cabrera Serrenho, A. Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. *Nat. Food* **4**, 170–173 (2023).
17. Jariwala, H., Santos, R. M., Lauzon, J. D., Dutta, A. & Wai Chiang, Y. Controlled release fertilizers (CRFs) for climate-smart agriculture practices: a comprehensive review on release mechanism, materials, methods of preparation, and effect on environmental parameters. *Environ. Sci. Pollut. Res.* **29**, 53967–53995 (2022).
18. Katsumi, N., Kusube, T., Nagao, S. & Okochi, H. The input–output balance of microplastics derived from coated fertilizer in paddy fields and the timing of their discharge during the irrigation season. *Chemosphere* **279**, 130574 (2021).
19. Xu, T. et al. Enhancing agrichemical delivery and plant development with biopolymer-based stimuli responsive core–shell nanostructures. *ACS Nano* **16**, 6034–6048 (2022).
20. Zhang, G. et al. Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China. *Field Crops Res.* **211**, 137–146 (2017).
21. Rillig, M. C. & Lehmann, A. Microplastic in terrestrial ecosystems. *Science* **368**, 1430–1431 (2020).
22. Qian, H. et al. Effects of soil residual plastic film on soil microbial community structure and fertility. *Water. Air. Soil Pollut.* **229**, 261 (2018).
23. Qi, Y. et al. Impact of plastic mulch film debris on soil physicochemical and hydrological properties. *Environ. Pollut.* **266**, 115097 (2020).
24. Gao, H. et al. Macro-and/or microplastics as an emerging threat effect crop growth and soil health. *Resour. Conserv. Recycl.* **186**, 106549 (2022).
25. Rillig, M. C., Ryo, M. & Lehmann, A. Classifying human influences on terrestrial ecosystems. *Glob. Change Biol.* **27**, 2273–2278 (2021).
26. Rillig, M. C. et al. The role of multiple global change factors in driving soil functions and microbial biodiversity. *Science* **366**, 886–890 (2019).
27. Yang, G. et al. Multiple anthropogenic pressures eliminate the effects of soil microbial diversity on ecosystem functions in experimental microcosms. *Nat. Commun.* **13**, 4260 (2022).
28. Bank, M. S., Mitrano, D. M., Rillig, M. C., Sze Ki Lin, C. & Ok, Y. S. Embrace complexity to understand microplastic pollution. *Nat. Rev. Earth Environ.* **3**, 736–737 (2022).
29. Xu, B. et al. Microplastics in the soil environment: occurrence, risks, interactions and fate – a review. *Crit. Rev. Environ. Sci. Technol.* **50**, 2175–2222 (2020).
30. Lwanga, E. H. et al. Review of microplastic sources, transport pathways and correlations with other soil stressors: a journey from agricultural sites into the environment. *Chem. Biol. Technol. Agric.* **9**, 20 (2022).
31. Castan, S., Henkel, C., Hüffer, T. & Hofmann, T. Microplastics and nanoplastics barely enhance contaminant mobility in agricultural soils. *Commun. Earth Environ.* **2**, 193 (2021).

32. Rehm, R., Zeyer, T., Schmidt, A. & Fiener, P. Soil erosion as transport pathway of microplastic from agriculture soils to aquatic ecosystems. *Sci. Total Environ.* **795**, 148774 (2021).
33. Aeschlimann, M., Li, G., Kanji, Z. A. & Mitrano, D. M. Potential impacts of atmospheric microplastics and nanoplastics on cloud formation processes. *Nat. Geosci.* **15**, 967–975 (2022).
34. Rezaei, M., Riksen, M. J. P. M., Sirjani, E., Sameni, A. & Geissen, V. Wind erosion as a driver for transport of light density microplastics. *Sci. Total Environ.* **669**, 273–281 (2019).
35. Li, L. et al. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. *Nat. Sustain.* **3**, 929–937 (2020).
36. Rillig, M. C. Plastic and plants. *Nat. Sustain.* **3**, 887–888 (2020).
37. DeLoid, G. M. et al. Toxicity, uptake, and nuclear translocation of ingested micro-nanoplastics in an in vitro model of the small intestinal epithelium. *Food Chem. Toxicol.* **158**, 112609 (2021).
38. DeLoid, G. M. et al. Incineration-generated polyethylene micro-nanoplastics increase triglyceride lipolysis and absorption in an in vitro small intestinal epithelium model. *Environ. Sci. Technol.* **56**, 12288–12297 (2022).
39. Li, Z., Li, Q., Li, R., Zhou, J. & Wang, G. The distribution and impact of polystyrene nanoplastics on cucumber plants. *Environ. Sci. Pollut. Res.* **28**, 16042–16053 (2021).
40. Wu, X. et al. Metabolomics revealing the response of rice (Oryza sativa L.) exposed to polystyrene microplastics. *Environ. Pollut.* **266**, 115159 (2020).
41. Santos, A. L., Rodrigues, C. C., Oliveira, M. & Rocha, T. L. Microbiome: a forgotten target of environmental micro(nano)plastics? *Sci. Total Environ.* **822**, 153628 (2022).
42. Cao, G. et al. New evidence of rubber-derived quinones in water, air, and soil. *Environ. Sci. Technol.* **56**, 4142–4150 (2022).
43. Meng, F., Yang, X., Riksen, M., Xu, M. & Geissen, V. Response of common bean (Phaseolus vulgaris L.) growth to soil contaminated with microplastics. *Sci. Total Environ.* **755**, 142516 (2021).
44. Castan, S. et al. Uptake, metabolism, and accumulation of tire wear particle-derived compounds in lettuce. *Environ. Sci. Technol.* **57**, 168–178 (2022).
45. Henkel, C., Hüffer, T. & Hofmann, T. Polyvinyl chloride microplastics leach phthalates into the aquatic environment over decades. *Environ. Sci. Technol.* **56**, 14507–14516 (2022).
46. Wang, Y. et al. Risk assessment of agricultural plastic films based on release kinetics of phthalate acid esters. *Environ. Sci. Technol.* **55**, 3676–3685 (2021).
47. Rillig, M. C., Kim, S. W., Kim, T.-Y. & Waldman, W. R. The global plastic toxicity debt. *Environ. Sci. Technol.* **55**, 2717–2719 (2021).
48. Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E. & Purnell, P. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazard. Mater.* **344**, 179–199 (2018).
49. Tian, Z. et al. A ubiquitous tire rubber–derived chemical induces acute mortality in coho salmon. *Science* **371**, 185–189 (2021).
50. Rand, A. A. & Mabury, S. A. Perfluorinated carboxylic acids in directly fluorinated high-density polyethylene material. *Environ. Sci. Technol.* **45**, 8053–8059 (2011).
51. Cassou, E. Plastics. Agricultural Pollution. (World Bank, Washington, DC, 2018).
52. De Lucia, C. & Pazienza, P. Market-based tools for a plastic waste reduction policy in agriculture: a case study in the south of Italy. *J. Environ. Manage.* **250**, 109468 (2019).
53. Braga Marsola, K., Leda Ramos de Oliveira, A., Filassi, M. & Elias, A. A. & Andrade Rodrigues, F. Reverse logistics of empty pesticide containers: solution or a problem? *Int. J. Sustain. Eng.* **14**, 1451–1462 (2021).
54. Picuno, C. et al. Decontamination and recycling of agrochemical plastic packaging waste. *J. Hazard. Mater.* **381**, 120965 (2020).
55. Mayanti, B. & Helo, P. Closed-loop supply chain potential of agricultural plastic waste: economic and environmental assessment of bale wrap waste recycling in Finland. *Int. J. Prod. Econ.* **244**, 108347 (2022).
56. Madrid, B. et al. End-of-life management options for agricultural mulch films in the United States—a review. *Front. Sustain. Food Syst.* **6**, (2022).
57. Li, H. et al. Expanding plastics recycling technologies: chemical aspects, technology status and challenges. *Green Chem.* **24**, 8899–9002 (2022).
58. Tricker, A. W. et al. Stages and kinetics of mechanochemical depolymerization of poly(ethylene terephthalate) with sodium hydroxide. *ACS Sustain. Chem. Eng.* **10**, 11338–11347 (2022).
59. Kaabel, S. et al. Enzymatic depolymerization of highly crystalline polyethylene terephthalate enabled in moist-solid reaction mixtures. *Proc. Natl. Acad. Sci.* **118**, e2026452118 (2021).
60. Kanbur, U. et al. Zirconium-catalyzed C–H alumination of polyolefins, paraffins, and methane. *J. Am. Chem. Soc.* **145**, 2901–2910 (2023).
61. Serrano, D. Feedstock recycling of agriculture plastic film wastes by catalytic cracking. *Appl. Catal. B Environ.* **49**, 257–265 (2004).
62. Yardley, R. E., Kenaree, A. R. & Gillies, E. R. Triggering depolymerization: progress and opportunities for self-immolative polymers. *Macromolecules* **52**, 6342–6360 (2019).
63. Wong, A. D., DeWit, M. A. & Gillies, E. R. Amplified release through the stimulus triggered degradation of self-immolative oligomers, dendrimers, and linear polymers. *Adv. Drug Deliv. Rev.* **64**, 1031–1045 (2012).
64. Schiller, M. PVC Additives: performance, chemistry, developments, and sustainability. (Carl Hanser Verlag GmbH & Co. KG, 2015).
65. Budin, C. et al. Detection of high PBDD/Fs levels and dioxin-like activity in toys using a combination of GC-HRMS, rat-based and human-based DR CALUX® reporter gene assays. *Chemosphere* **251**, 126579 (2020).
66. Dey, T. et al. Global plastic treaty should address chemicals. *Science* **378**, 841–842 (2022).
67. Briassoulis, D., Hiskakis, M. & Babou, E. Technical specifications for mechanical recycling of agricultural plastic waste. *Waste Manag.* **33**, 1516–1530 (2013).
68. Dong, H. et al. Recycling, disposal, or biodegradable-alternative of polyethylene plastic film for agricultural mulching? A life cycle analysis of their environmental impacts. *J. Clean. Prod.* **380**, 134950 (2022).
69. Muise, I., Adams, M., Côté, R. & Price, G. W. Attitudes to the recovery and recycling of agricultural plastics waste: a case study of Nova Scotia, Canada. *Resour. Conserv. Recycl.* **109**, 137–145 (2016).
70. King, C. D., Stephens, C. G., Lynch, J. P. & Jordan, S. N. Farmers' attitudes towards agricultural plastics – management and disposal, awareness and perceptions of the environmental impacts. *Sci. Total Environ.* **864**, 160955 (2023).
71. European Commission & Directorate-General for Research and Innovation. Biodegradability of plastics in the open environment. (Publications Office of the European Union, 2020).
72. Bauchmüller, V. et al. *BioSinn: products for which biodegradation makes sense*. (Report from nova-Institute and IKT-Stuttgart 25, 2021).
73. von Vacano, B. et al. Sustainable design of structural and functional polymers for a circular economy. *Angew. Chem. Int. Ed.* **62**, e202210823 (2022).
74. Eck, M. et al. Biodegradable high-density polyethylene-like material. *Angew. Chem. Int. Ed.* **62**, e202213438 (2023).
75. European Commission. The impact of the use of 'oxo-degradable' plastic on the environment: final report. (Publications Office, 2016).
76. Nelson, T. F., Remke, S. C., Kohler, H.-P. E., McNeill, K. & Sander, M. Quantification of synthetic polyesters from biodegradable mulch films in soils. *Environ. Sci. Technol.* **54**, 266–275 (2020).
77. Biodegradable Plastics Market Size & Share, Report 2026. MarketsandMarkets.
78. Svechnikov, K., Svechnikova, I. & Söder, O. Inhibitory effects of mono-ethylhexyl phthalate on steroidogenesis in immature and adult rat Leydig cells in vitro. *Reprod. Toxicol.* **25**, 485–490 (2008).
79. Fromme, H. et al. Non-phthalate plasticizers in German daycare centers and human biomonitoring of DINCH metabolites in children attending the centers (LUPE 3). *Int. J. Hyg. Environ. Health* **219**, 33–39 (2016).
80. Qadeer, A., Kirsten, K. L., Ajmal, Z. & Xingru, Z. Rebuttal to comment on "alternative plasticizers as emerging global environmental and health threat: another regrettable substitution?" focus on DINCH as an example. *Environ. Sci. Technol.* **56**, 5294–5297 (2022).
81. Jamarani, R., Erythropel, H., Nicell, J., Leask, R. & Marić, M. How green is your plasticizer? *Polymers* **10**, 834 (2018).
82. Jia, P., Xia, H., Tang, K. & Zhou, Y. Plasticizers derived from biomass resources: a short review. *Polymers* **10**, 1303 (2018).
83. Bocqué, M., Voirin, C., Lapinte, V., Caillol, S. & Robin, J.-J. Petro-based and bio-based plasticizers: chemical structures to plasticizing properties. *J. Polym. Sci. Part Polym. Chem.* **54**, 11–33 (2016).
84. Qadeer, A., Kirsten, K. L., Ajmal, Z., Jiang, X. & Zhao, X. Alternative plasticizers as emerging global environmental and health threat: another regrettable substitution? *Environ. Sci. Technol.* **56**, 1482–1488 (2022).
85. Wiesinger, H., Wang, Z. & Hellweg, S. Deep dive into plastic monomers, additives, and processing aids. *Environ. Sci. Technol.* **55**, 9339–9351 (2021).
86. Sun, J., Wu, X. & Gan, J. Uptake and metabolism of phthalate esters by edible plants. *Environ. Sci. Technol.* **49**, 8471–8478 (2015).
87. Ekane, N., Barquet, K. & Rosemarin, A. Resources and risks: perceptions on the application of sewage sludge on agricultural land in sweden, a case study. *Front. Sustain. Food Syst.* **5**, 647780 (2021).
88. Kramm, J., Steinhoff, S., Werschmöller, S., Völker, B. & Völker, C. Explaining risk perception of microplastics: results from a representative survey in Germany. *Glob. Environ. Change* **73**, 102485 (2022).
89. Dietary and inhalation exposure to nano- and microplastic particles and potential implications for human health. *World Health Organ*. (2022).
90. European Food Safety Authority (EFSA). *Food safety in the EU: report*. (Publications Office, 2022).
91. Galati, A., Sabatino, L., Prinzivalli, C. S., D'Anna, F. & Scalenghe, R. Strawberry fields forever: that is, how many grams of plastics are used to grow a strawberry? *J. Environ. Manage.* **276**, 111313 (2020).
92. Plastics in Agriculture Lessons. Preventing Plastic Pollution https://preventingplasticpollution.com/resources/plastics-in-agriculture-lessons/.
93. Pahl, S., Wyles, K. J. & Thompson, R. C. Channelling passion for the ocean towards plastic pollution. *Nat. Hum. Behav.* **1**, 697–699 (2017).

94. Greiner, R., Patterson, L. & Miller, O. Motivations, risk perceptions and adoption of conservation practices by farmers. *Agric. Syst.* **99**, 86–104 (2009).
95. Bennett, N. J. et al. Environmental stewardship: a conceptual review and analytical framework. *Environ. Manage.* **61**, 597–614 (2018).
96. Cabernard, L., Pfister, S., Oberschelp, C. & Hellweg, S. Growing environmental footprint of plastics driven by coal combustion. *Nat. Sustain.* **5**, 139–148 (2022).
97. Sutherland, W. J. et al. A global biological conservation horizon scan of issues for 2023. *Trends Ecol. Evol.* **38**, 96–107 (2023).
98. Wellenreuther, C., Wolf, A. & Zander, N. Cost competitiveness of sustainable bioplastic feedstocks – a Monte Carlo analysis for polylactic acid. *Clean. Eng. Technol.* **6**, 100411 (2022).
99. Brizga, J., Hubacek, K. & Feng, K. The unintended side effects of bioplastics: carbon, land, and water footprints. *One Earth* **3**, 45–53 (2020).
100. Mitrano, D. M. & Wagner, M. A sustainable future for plastics considering material safety and preserved value. *Nat. Rev. Mater.* **7**, 71–73 (2022).
101. MacArthur, E. Beyond plastic waste. *Science* **358**, 843 (2017).
102. Simon, N. et al. A binding global agreement to address the life cycle of plastics. *Science* **373**, 43–47 (2021).
103. Ammendolia, J. & Walker, T. R. Global plastics treaty must be strict and binding. *Nature* **611**, 236 (2022).
104. Zhu, X. & Rochman, C. Emissions inventories of plastic pollution: a critical foundation of an international agreement to inform targets and quantify progress. *Environ. Sci. Technol.* **56**, 3309–3312 (2022).

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Author contributions

T.H., S.G., and N.T. planned and organized the workshop. T.H. led the manuscript writing and editing. The sections of this manuscript are based on the written input from T.H., S.G., N.T., J.F.A., S.B., Q.C., P.D., M.F., Th.H., N.I., R.J., R.L., M.M., D.M., M.S., S.P., M.R., T.W., J.W., and K.W., which was the basis of the final manuscript. T.H., S.G., N.T., J.F.A., S.B., Q.C., P.D., M.F., Th.H., N.I., R.J., R.L., M.M., D.M., M.S., S.P., M.R., T.W., J.W., and K.W. carefully revised the manuscript and approved the submission.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Thilo Hofmann, Subhasis Ghoshal or Nathalie Tufenkji.

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