Addressing the environmental sustainability of plastics used in agriculture: a multi-actor perspective

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Impact Statement

Plastic products used throughout the agricultural sector provide many benefits, but their usage and disposal come with environmental trade-offs – including large amounts of waste and pollution. A report from the Food and Agriculture Organisation of the United Nations (FAO, 2021) set the stage to initiate the preparation of an international Voluntary Code of Conduct (VCoC) on the sustainable use and management of plastics in agriculture. Use of plastics in agriculture, including in fisheries and aquaculture is also considered during negotiations of the international legally binding instrument on plastic pollution, including in the marine environment.

Despite research advances, knowledge gaps persist concerning the short and long-term implications of plasticulture. Agronomists, farmers and the industry emphasise the benefits of using plastic-based production systems for increased yields, resilience, and efficiency, while environmental scientists and organizations raise concerns about negative environmental implications resulting from certain practices and improper waste management. This dialectic is mirrored in the debate surrounding the policy making in this area where opposing views are sometimes expressed. Understanding and solving, where possible, counterposed concerns is key the effective implementation of future regulation.

This manuscript systematically collects and summarises the current perspectives from different stakeholders and provides an essential background highlighting the existing knowledge gaps that influence such diverse standpoints. As a result, it serves as an important document to initiate and stimulate a constructive dialogue, which will prove instrumental in policymaking within this field.

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Abstract

Plastics used in agriculture, commonly known as agriplastics (AP), offer numerous advantages in terrestrial agriculture, forestry, fisheries, and aquaculture, but the diffusion of AP-intensive practices has led to extensive pollution.

This review aims to synthesize scientific and policy discussions surrounding AP, examining evidence of their benefits and detrimental environmental and agricultural impacts. Following the proposal of a preliminary general taxonomy of AP, the paper presents the findings from a survey conducted among international experts from the plastic industry, farmer organizations, NGOs, and environmental research institutes. This analysis highlights knowledge gaps, demands, and perspectives for the sustainable future use of AP.

Stakeholder positions vary on the options of "rejection" or "reduction" of AP, as well as the role of alternative materials such as (bio-)degradable and compostable plastics. However, there is consensus on critical issues such as redesign, labelling, traceability, environmental safety standards, deployment, and retrieval standards, as well as innovative waste management approaches. All stakeholders express concern for the environment. A “best practice”-based circular model was elaborated capturing these perspectives.

In the context of global food systems increasingly reliant on AP, scientists emphasize the need to simultaneously preserve nature-based and traditional knowledge-based sustainable agricultural practices to enhance food system resilience.

Keywords (up to 5)

Agriplastics, Plastic pollution, Agriculture, Plastic waste, Multi-actor approach

1. Background

1.1 Agricultural plastics at a glance

Plastic is an important commodity for the agricultural sector enabling innovation in production systems oriented to higher efficiency and crop reliability. In terrestrial agriculture, new options for protected cultivation systems made possible by the introduction of plastic films, micro-irrigation systems, and other plastic-based technologies enabled more efficient production to be partly decoupled from climatic and geographic constraints, (FAO, 2021; EIP-Agri, 2024). In fisheries and aquaculture, plastic-based nets, lines, and floaters, among other plastic devices, are critical for cost-effective, high efficiency, industrial-scale operations. The consistent positive trend in the global demand for plastic in agricultural applications – increasing with a compound annual growth rate of 6.2% during the forecast period 2023-2030, reaching 10.6 billion USD in 2022 and expected to surpass 17 billion USD by 2030 (Data Intelligence, 2023) – confirms the success of this sector and the rapid assimilation by farmers, internationally.

The term agriplastics (AP) refer to any products made from plastic that are used in the production, harvesting, storage, and primary distribution (e.g., from farm to wholesale) phases of terrestrial agriculture, forestry, fisheries, and aquaculture (FAO, 2021). According to the Food and Agriculture Organisation of the United Nations (FAO) there were in 2021 12.5 million tonnes of AP used globally, of which 10.2 million tonnes are used for crops and livestock, 2.1 million tonnes for fisheries, and 0.2 million tonnes for forestry (FAO, 2021), with an expanding trend that will possibly result in an increase of 50% in the period between 2018 and 2030.

While some works have initiated the effort of establishing inventories of typologies and tonnages of AP at global and regional level (Briassoulis *et al.*, 2013; Sundt *et al.*, 2018; Cleanfarms, 2021; FAO, 2021), data on AP stocks, usage, geographical distribution, distribution along agricultural value chains, and end-of-life (EoL) processes remain scant and fragmentary. APs are a source of pollution that can pose a risk to soil and aquatic ecosystems (e.g. (de Souza Machado et al., 2019; Schwarz et al., 2019; Huang et al., 2020a; Kruger et al., 2020; Briassoulis, 2023), to vegetable crop and farmed animal health (e.g., (Pizol *et al.*, 2017; Qi *et al.*, 2018; Rillig *et al.*, 2019; Galyon *et al.*, 2023; Zantis *et al.*, 2023), and thus, by extension, for farm productivity (Zhang *et al.*, 2020; UNEP and GRID-Arendal, 2021; Wu *et al.*, 2022). The use of plastics in agriculture generates a large volume of waste (Briassoulis *et al.*, 2013; Morsink-Georgali *et al.*, 2021; Koul, Yakoob and Shah, 2022; Hachem, Vox and Convertino, 2023) distributed across the broader environment which impact terrestrial, freshwater, and marine ecosystems. Damaged, degraded, discarded, or inappropriately used AP contaminate soils, freshwaters, and marine waters, represents a serious threat for the Earth system and economy (including at farm level)(Vox *et al.*, 2016; FAO, 2021; UNEP and GRID-Arendal, 2021; Mihai *et al.*, 2022).

FAO has initiated the development of a Voluntary Code of Conduct (VCoC) on sustainable use and management of plastics in agriculture, which if adopted will guide stakeholders to prevent or reduce the accumulation of agricultural plastic waste (APW) and plastic pollution associated with the food and agriculture sector. It is broadly acknowledged that a multi-actor and cross-sectorial approach is essential to adequately address sustainable solutions for agriculture and food systems and to catalyse innovations in AP product design, production practices, policy instruments, capacity building, and financing. It is of the utmost importance that experiences and perceptions, especially of farmers developed through the everyday use of agricultural plastics and food production are mapped and understood alongside technological opportunities and constraints, coinciding these with scientific research on soil health and plant production. In this way, a broader understanding of the status of knowledge on plastic agricultural uses, benefits, costs, and impacts on environmental and human health will be developed and used as terms of reference to work toward social, environmental, and economic sustainability in food production systems.

Against this background, the aim of this article is twofold – (1) summarising the state-of-the-art of the AP environmental discourse, reviewing scientific knowledge on the sources and effects of plastic pollution from the use of AP (with the latter, especially focusing on the emerging concern of plastic pollution impacts on terrestrial environments); and (2) reinforcing the science-policy interface by mapping knowledge demands and initial suggestions provided by stakeholders to understand and address negative impacts. The review builds on four components: (i) an analysis of the scientific literature available thus far on the sources and ecological and environmental impact of AP-derived debris; (ii) the inputs of 68 international experts (with geographic competence covering both high-income and low-income regions) gathered via an online focused survey – the *International Survey on Agricultural Plastics' Perspectives and Knowledge Gaps* – administered by the International Knowledge Hub Against Plastic Pollution (IKHAPP 2023) from May 19, 2023 to June 9, 2023 and by email; (iii) dialogues conducted within a group of agronomists, engineers, environmental scientists, and toxicologists clustered around two large European research projects: PAPILLONS and MINAGRIS (PAPILLONS 2023; MINAGRIS 2023); and (iv) dialogues with industry and farmer representatives, also conducted as part of the aforementioned projects.

The paper is structured into three sections. Section 1 introduces the background and provides a review of APs, their uses, characteristics and their role as sources of pollution. Section 2 delves into the problem of the generation and management of waste from AP as well as the ecological and potential agricultural problems posed by the accumulation of plastic debris in the environment (with a closer look into the recently emerging evidence of plastic impacts in terrestrial agriculture). Finally, section 3 summarises the perspectives of the stakeholders.

While part 1 and 2 of the paper have a broad scope covering elements pertaining to all types of agriculture (i.e., terrestrial agriculture, forestry, fisheries, and aquaculture), the multi-actor perspective analysis provided in section 3 of the paper deliberately focused on stakeholders specifically within the value chain of terrestrial agriculture. This narrower scope was adopted considering terrestrial agriculture and forestry represent over 80% of the plastic global demand for agriculture and that, unlike for fisheries and aquaculture, limited international debates have been so far conducted among stakeholders in the terrestrial farming and forestry sector.

1.2 Types and benefits of Agriplastics for different agricultural sectors

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In 2021, the world plastic production reached 390.7 Mt, with agricultural application representing around 3% of the total demand (Plastic Europe, 2022). The widespread diffusion of plastic in agricultural production stems from the multiple technical and economic benefits it offers. Plastic can be formulated in a variety of chemical blends or produced as multilayer structures with specific mechanical and physical characteristics and functionalities. While plastic can be used at any stage of agricultural production, specific technologies have emerged whereby plastics have enabled the definition of entirely new production systems in both terrestrial and aquatic agriculture, as well as in fisheries. An initial (and not exhaustive) taxonomy system for AP is proposed in Table 1 (based on (Sundt *et al.*, 2018; FAO, 2021; Briassoulis, 2023).

The deployment of AP in terrestrial agriculture is now expanding beyond common ancillary uses (such as for containers of seeds, crop, agrochemicals) to new materials and components at the base of entirely new and highly efficient production systems. In particular, in the context of protected cultivation systems, the use of plastic covering films, micro-irrigation systems, protection nets, is in expansion in both the developed e.g. (APE Europe, 2024) and developing countries e.g. (NCPAH, 2022). These components can help to achieve a cost-effective control over environmental factors, including soil properties, pest control, water and agrochemical usage and runoff, protection from extreme weather, control over solar radiation, and reduced soil erosion (Kader *et al.*, 2017; Briassoulis, 2023). This has resulted in an expansion of the production of several important crops beyond their traditional geographical or temporal boundaries, also providing farmers with the opportunity to link to new and broader markets (FAO, 2021).

Plastic usage in most fisheries and aquaculture has also brought about several benefits. Plastic has been a core commodity for the manufacturing of gears owing to the low cost, flexible manufacturing, high resistance, and light weight. Plastic is used for the manufacturing of nets and other fishing gear, including cages, buoys, ropes, and floaters, amongst others. Boxes and packaging material made of plastic are used for the transportation, conservation, and distribution of fish products. The use of plastic in these applications reduces logistical and maintenance costs and extends the lifespan of essential tools, ultimately leading to increased yields and economic gains.

International policy documents (e.g. (EEA, 2019)) have listed precision farming, organic farming, and agroecology as the production strategies that will enable sustainable and resilient agriculture with a reduced environmental footprint and the capacity of facing the negative effects of climate change. According to the narrative of some actors operating along the plastic supply chain (APE Europe, 2021), AP is indicated as key to endorse these strategies.

Table 1. Draft nomenclature and classification system for main uses of plastics in agriculture

Agricultural plastics categories	Main types of conventional agricultural plastics
1. Land-based crop production [a, b]	
1.1 Plant protection films and textiles	1.1.1 Greenhouse and high-tunnel films
	1.1.2 Low-tunnel and direct cover films
	1.1.3 Plastic canopy covers for soft fruit protection
	1.1.4 Non-woven textiles for early growth stages protections
1.2 Soil cover films	1.2.1 Mulching films
	1.2.2 Ground covers fabrics

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	1.2.3 Solarisation and fumigation films
1.3 Irrigation and pipes	1.3.1 Irrigation pipes and tapes
	1.3.2 Drippers, and micro-irrigation components
	1.3.3 Drainage pipes
1.4 Agricultural nets	1.4.1 Protection nets
	1.4.2 Shade nets
	1.4.3 Nets for harvest of produce
1.5 Plant growth supporting systems	1.5.1 Twines, support ties, and clips for plants
	1.5.2 Guards and shelters of tree saplings
	1.5.3 Seedling plug trays and nursery pot trays, plant-pots
	1.5.4 Infrastructures for hydroponic cultivation
1.6 Storage, handing and transportation of agricultural products and supplies	1.6.1 Bags and sacks for seeds, agricultural products, or soil
	1.6.2 Wrapping films and trays for produce
	1.6.3 Film silo tubes for grains or hay
	1.6.4 Reusable crates for agricultural products
	1.6.5 Containers of pesticides and fertilisers
1.7 Polymeric encapsulations and formulations for various uses.	1.7.1 Polymer coated seeds
	1.7.2 Polymer coated fertilisers and pesticides
	1.7.3 Polymeric capsule suspension formulations and fertilisers additives
	1.7.4 Polymeric soil conditioners and amendments
1.8 Geotextiles and liners	1.8.1 Geotextile for ground and access road consolidation
	1.8.2 Liners for ground impermeabilization and consolidation
1.9 Consumable tools made of plastics	1.9.1 Brushes, rakes, shovels, and others
2. Livestock farming [a]	
2.1 Fodder applications	2.1.1 Silage films
	2.1.2 Bale wrap films
	2.1.3 Bale net-wraps and press film
	2.1.4 Bale knitted nets and silage nets
	2.1.5 Bale twines
2.2 Storage, handing and transportation of livestock supplies	2.2.1 Bags and sacks for animal feed
	2.2.2 rigid containers and backets for animal feeds
	2.2.3 Containers for hygiene and veterinary products
2.3 Other plastics for livestock farming	2.3.1 Ear tags
	2.3.2 Plastic brushes, yard squeegees, and scrapers
	2.3.3 Polymeric tissues
3. Forestry and landscaping [b]	
3.1 Tree protection	3.1.1 Tree guards
	3.1.2 Tree labels and support ties
	3.1.3 Tapping shades/rain guards
3.2 Forestry Tags	3.2.1 Tree Labels
3.3 Fuel containers for in situ operations	3.3.1 Fuel containers for small machineries (e.g., chainsaw)
4. Fisheries and aquaculture [b, c]	
4.1 Crates and bins	4.1.1 Insulation crates for produce
	4.1.2 Sorting bins

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	4.1.3 Reusable crates for nets, lines, floaters, or any other gear
4.2 Ropes	4.2.1 Polymeric ropes
	4.2.2 Sinking ropes
4.3 Fishing net, net enclosures, and devices to concentrate fish	4.3.1 Fishing nets
	4.3.2 Nets for Fish, Crab, or lobster traps
	4.3.3 Fish farming nets for cages and pens
	4.3.4 Bags for shellfish cultivation
	4.3.4 FADs
4.4 Fishing lines	4.4.1 Hand lines, trotlines, and long lines
4.5 Livestock enclosures and equipment	4.5.1 Tanks for livestock and hatchery tanks
	4.5.2 Liners for ponds and tanks
	4.5.3 Aeration and filtration components (pipes, diffusers, air stones)
	4.5.4 Feeders
4.6 Floats, buoys, and platforms	4.6.1 Floats for lines, nets, and cages
	4.6.2 Buoys
	4.6.3 Rafts and Platforms
4.7 Various containers	4.7.1 Containers and bags for feeds
	4.7.2 Containers for veterinary drugs
	4.7.3 Containers for chemicals for water quality control
4.8 Fishing vessels	4.8.1 GRP fishing boats
	4.8.2 Fishing boats made of other polymeric materials
4.9 Other plastic consumable tools	4.9.1 Tags, plastic strips
	4.9.2 Squeegees
	4.9.3 Scrubbing pads and brushes

[a] (Briassoulis, 2023)
[b] (FAO, 2021)
[c] (Sundt *et al.*, 2018)

1.3 Agriplastics composition and their environmental performance

The most important polymeric compositions of AP are: low density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polypropylene (PP), and to a lower extent ethylene vinyl acetate (EVA), high density polyethylene (HDPE), polycarbonate (PC), polymethyl methacrylate (PMMA), glass reinforced polyester (GRP), and polyvinyl chloride (PVC). Beyond composition, the characteristics and durability of a product depends on its geometrical properties (e.g., the thickness of a plastic film or the section of a fishing line or net line), use of chemical chemical additives in the formulation, climate (mainly related to exposure to solar UV radiation), and management. Resistance to mechanical stress and ageing is key for reducing the chance of pollution. For instance, mechanical stress during deployment or collection of conventional mulching films or other thin or excessively degraded agricultural films, can result in losses typically of up to 30% of the total recoverable volume (EUNOMIA, 2021). Degradation and embrittlement during use, disposal, or as the result of mismanagement are critical for pollution generation, along with practices in which plastic is abandoned or deliberately disposed in the environment. Early signs of degradation include discoloration, surface cracking, and brittleness. These signs typically occur before the material reaches rupture and fragmentation. For example, covering films in protected cultivation systems progressively lose their mechanical and radiometric properties due to their limited thickness, their prolonged exposure to UV solar radiation, interaction with chemical pesticides, wind and hailstorms, and variations in air temperature and relative humidity (Schettini, Vox and L,

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2014). Similar considerations apply also for plastic used in fishery and fish farming, in this case other aspects, such as biofouling, can play a substantial role in determining the durability of the materials. Understanding the useful operational life span of given AP is key for sound management and for avoiding pollution.

Chemical additives in AP formulations are important factors influencing environmental performance. Some substances used as plastic additives have been indicated as harmful for the environment and human health (Wang *et al.*, 2013; Blaesing and Amelung, 2018; Hahladakis *et al.*, 2018; Wiesinger, Wang and Hellweg, 2021) and data on ecological and human toxicity of many of the several thousand chemicals used in different plastic products are not currently available (Hahladakis *et al.*, 2018). Open literature sources reporting information on chemical additives in AP formulations are absent, due to intellectual property protection aspects.

Beyond representing an environmental concern, lack of disclosure on chemical composition has implications for impact life cycle assessments and recyclability (Carney Almroth and Slunge, 2022; Geueke *et al.*, 2023). Because several APs are used in outdoor settings, chemicals that can delay UV-induced photooxidative processes are commonly used. These include UV absorbers (converting high frequency radiation into thermal energy) and UV stabilisers (preventing free radicals' formation or acting as scavengers for free radicals). Beyond photo-stabilisers and filters, chemical additives are typically used as process-aids for the manufacture of products or to achieve other desired optical or mechanical properties.

Growing awareness on the environmental impacts of plastic debris sourced by agricultural practices, as well as the accumulation and the problematic management of large quantity of generated waste, has prompted advances in the use of polymeric materials which can degrade in the environment and/or in composting facilities. While degradable plastic includes a heterogenous family of materials, they have generically been presented by manufacturers as more environmentally friendly options in the context of reducing or even zeroing waste generation while (in the case of materials generated from biomasses), bolstering circularity of organic waste. Biodegradable or compostable plastics represents a minority, yet expanding, share of the AP market, especially in the area of protected cultivation systems in terrestrial agriculture (e.g., mulching films). Biodegradable (in soil and/or composting facilities) polymers used in AP applications include polylactic acid (PLA), sometimes used in blends with fossil-based (recently also bio-based) polybutylene adipate terephthalate (PBAT), and blends or composites of PBAT with natural materials like starch or cellulose. Other biodegradable polymers common in agricultural applications are polyhydroxyalkanoates (PHA) and polycaprolactone (PCL)). Beyond mulching films, biodegradable plastics are used for seed coatings and the formulation of slow-release agrochemicals – which can utilise a broader range of polymers – as well as compostable (e.g., PLA-based) binders and clips (Briassoulis, 2023).

The use of biodegradable plastics has also been indicated as an alternative to conventional polymers for fishing and fish farming gears (or specific parts of these products), to possibly mitigate the impacts of abandoned, lost, or discharged fishing gears. These uses are however still at the development stage (INdIGO, 2024).

Material degradability can be achieved considering non-biological processes. For example, similar to biodegradable mulching films, oxo-degradable materials (especially mulching films) were also introduced to overcome EoL costs. These materials are typically produced from

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conventional polyolefins with the addition of pro-oxidant compounds such as transition metal salts (such as iron, cobalt, or manganese salts). These additives catalyse the oxidation of the polymer chains when the plastic is exposed to radiation and heat, for example during use. This process weakens the polymer structure and makes it more susceptible to fragmentation. At the end of their useful operational time, these materials rapidly disintegrate into small particles which accumulate in soil (Yang *et al.*, 2022).

Whether produced from fossil C or from biomass, the use of degradable plastics in agriculture results in the addition of compounds from chemical syntheses (including both polymers, monomers and chemical additives present in the formulation) to the environment. This has raised concerns among environmental scientists and environmental organisations about possible ecological impacts. In some countries, there has been an effort to establish industrial and regulatory standards aimed at reducing the risks of adverse effects on ecosystem health or compost quality. These standards typically set the requirements for the material degradation rate under laboratory conditions and indicate the limits for the typology and amounts of the chemical additives used in the formulation. Some standards also introduce requirements for basic eco-toxicological testing. For example, the ASTM D6400 standard by the American Society for Testing and Materials specifies the requirements for compostable plastics, and it includes criteria for biodegradation in soil environments. The European standard EN 17033 defines requirements for biodegradable in soil mulch films and includes criteria for biodegradation in soil, basic ecotoxicity, and thresholds or limitations for heavy metals and other toxic or persistent substances. Finally, the EN 13432 focuses on requirements for packaging recoverable through composting and biodegradation to enable circular use of digestates, which may then be used in agriculture as soil amendments.

2. Environmental concerns of Agriplastics

2.1 Sources, drivers, and fate of pollution from agricultural plastics

Plastics used in agriculture represent a driver of pollution across local, regional, and global scales. Fisheries have been directly pointed as important contributors to marine plastic litter: industrial trawls, purse-seine, and pelagic longline fisheries have been estimated to utilise 2.1 Mt of plastic. Accidents leading to the loss of these gears generates between 28 and 99 kt/year of marine debris (Kuczenski *et al.*, 2022). These estimates exclude abandoned and intentionally discarded gear at sea. A metadata analysis from 2019 indicated that 5.7% of all fishing nets, 8.6% of all traps, and 29% of all lines are lost around the world each year, indicating total losses to be in the range of several hundred kt (Richardson, Hardesty and Wilcox, 2019).

Fish farming activities also represent a source of marine debris and microplastics. Global-scale emission inventories from these sectors are not available, nor accurate global figures of the plastic demand by aquaculture. Several studies have, however, provided estimates of plastic pollution emission from fish farming activities at the local or regional level. For example, annual emissions of plastic debris from floating oyster farms in Asia have been estimated in the order of 100g per square meter of the farm area (Tian *et al.*, 2022). Similarly, a study conducted in the Atlantic coast of France evidenced that 70% of the plastics collected from beaches were characteristic of aquaculture materials (Bringer *et al.*, 2021).

The sound management of large volumes of APW is a critical issue for most types of modern farms (Skirtun *et al.*, 2022; Briassoulis, 2023) that have to deal with poorly recyclable waste,

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inadequate infrastructures for waste storage and segregation at farm level, and lack of waste collection and management schemes. APW can be heavily contaminated by foreign materials (e.g., sand, soil, organic matter, biofouling and possibly by veterinary drugs, chemicals, pesticide residues, and fertilisers), which represents an obstacle for recycling. Mismanagement and illegal practices such as the dumping of APW, abandoning or discharging fishing or aquaculture gears at sea, the burial of waste in the farm soil, or open burning are unfortunately common phenomena (Briassoulis *et al.*, 2013; Richardson, Hardesty and Wilcox, 2019).

The negative consequences of the improper disposal of APW in fields and landfills include i) aesthetic pollution and deterioration of the landscape and its social and economic value; ii) threats to domestic and wild animals; iii) blocking of water flow through drainage pipes and channels; and iv) overload of landfills with an immediate environmental and economic impact. Burying APW in fields induces degradation of soil quality and irreversible soil contamination. The uncontrolled burning of APW will release harmful airborne toxic substances and semi-combusted plastic particles and other types of dusts. These emission can be source of hazardous substances (Velis and Cook, 2021).

Some farming practices can also intentionally introduce plastic debris to the farm environment and beyond (Ng *et al.*, 2018). For example, oxo-degradable and very thin mulching films were introduced to overcome the problems and costs associated with post-use handling of plastic-based mulching, as these materials can be intentionally left to physically degrade in the field (Yang *et al.*, 2022). Oxo-degradable mulching films have been banned in some countries (EU, 2019) but they are still an available option for agriculture in many regions. Similarly, thin-film mulching with no post-use recovery, has been a common practice in some countries, leading to cases of extreme soil contamination (Qiu *et al.*, 2022). China, for example, has recently introduced regulation that requires farmers to collect and recycle mulching film (Chang Li *et al.*, 2021).

Biodegradable in soil plastics (used mostly for the production of mulching films, seed and agrochemical coatings and plant clips) also represent an option for overcoming waste management costs. Following complete degradation in soil, mulching films are converted to carbon dioxide and microbial biomass preventing the irreversible accumulation of plastic debris in soils, composts, or other environments (Chia, Lee, Lee, *et al.*, 2023). This occurs at a relatively low rate (e.g., the specification for degradability in soils typically require a period of 2 years for the complete degradation under laboratory conditions), leading to a temporary and reversible accumulation of plastic debris (including microplastics) in soil. If application rates are higher than the rate of degradation (which is a typical situation) relatively high amounts of these debris can be present in soils on a regular base. This situation is accentuated in cold or dry climates, as these conditions can substantially slow down the degradation of plastics (Nizzetto *et al.*, 2024).

Other AP applications resulting in intentionally sourcing microplastics to the environments include polymer-based controlled-release fertilisers, fertiliser additives, plant protection products using capsule suspension, and seed coatings, especially when they are based on conventional plastics. In the context of European agricultural and horticultural sectors, these materials are listed among the activities resulting in the largest intentional releases of microplastics to the environment (ECHA, 2020).

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While other sources can contribute plastic pollution to agricultural soils (Hurley and Nizzetto, 2018), the relative importance of AP-related sources depends on the type of farm, agricultural practices, and possible mismanagement.

2.2 Emerging insights and knowledge gaps on impacts of plastic pollution in terrestrial agricultural ecosystems

While the effects of plastic debris (including those deriving from fisheries and fish farming activities) and microplastic in marine environments are well documented in terms of impacts, the study of the source, exposure and effects of plastic pollution in terrestrial environments is a much more recent undertake. This section therefore is dedicated specifically to review the state of knowledge on risk posed by this pollution in terrestrial agroecosystems.

Recent scientific evidence has substantially increased the awareness on soils as major recipients of plastic pollution and on the impacts on soil properties and biota (Hurley and Nizzetto, 2018; Z. Zhang *et al.*, 2022). Pollution of soils by residues of AP from terrestrial agriculture has already been confirmed in several studies across the globe (Chia *et al.*, 2022; H. Zhang *et al.*, 2022; Z. Zhang *et al.*, 2022). Typically, the highest levels of plastic residues in soils, globally, are reported for farmlands in China, where the majority of studies have focussed thus far, while a substantial paucity of observations exists for other parts of the world. In China, a high level of variability both within and across different locations has been observed (Qiu *et al.*, 2022). Soil plastic pollution derived from AP tends to resemble the original material physically and chemically in several ways. For example, residues of thin films used in protected cultivation systems typically retain morphological characteristics of the film (e.g., the original film thickness). Microplastics left from polymeric encapsulation of controlled release fertilisers will resemble hollow plastic shells (Katsumi *et al.*, 2021) and residues from geotextiles may occur as individual fibres (Gustavsson *et al.*, 2022).

The fate of AP residues once they enter a soil environment remains uncertain (R. Qi *et al.*, 2020a). For instance, two studies found, in one case, that >99% of particles were retained (Schell *et al.*, 2021) and, in another case, that >99% of particles were transported elsewhere (Crossman *et al.*, 2020). Factors such as the particle characteristics (size, density, morphology), the properties of the soil (density, texture, moisture dynamics), and the context of the local environment (aspect and slope of the field, meteorological and climatic conditions, and the activity of soil invertebrates) are all likely to play an important role. Soils and climatic conditions that facilitate export of particles may represent a pathway for contamination of water bodies (e.g., (Katsumi *et al.*, 2021; Jiao *et al.*, 2022)), whilst soils that retain particles may accumulate these from successive inputs and be subject to progressively increasing stress and impacts (Hurley and Nizzetto, 2018; Huang *et al.*, 2020b).

Physicochemical properties of soils may be altered by the occurrence of plastic pollution, such as changes in soil pH (e.g. (Boots, Russell and Green, 2019; Y. Qi *et al.*, 2020; Qiu *et al.*, 2022), soil aggregation processes and aggregate size and stability (e.g. (de Souza Machado *et al.*, 2019; Lozano *et al.*, 2021), soil porosity (e.g., (Jiang *et al.*, 2017), and soil moisture dynamics, including hydraulic conductivity, water holding capacity, and surface desiccation

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(e.g. (Wan *et al.*, 2019; Y. Qi *et al.*, 2020)). Biological processes occurring in soils can also be affected by plastic pollution, including changes in the community structure, and functioning of soil microbial consortia and concomitant changes in soil enzyme activity or biogeochemical cycling (e.g., (Y. Huang *et al.*, 2019; Fei *et al.*, 2020; Rong *et al.*, 2021)). Many of these effects are likely to mediate other changes, such as altered availability of nutrients or altered sorption processes or cation exchange capacity caused by changes in soil pH and microbial functioning (e.g. (Y. Qi *et al.*, 2020; Rong *et al.*, 2021)).

Animals living in the soil also interact with and are affected by AP residues. Ecotoxicological studies have reported changes in the number of individuals, feeding behaviour, reproduction, growth, and mortality (Li, Song and Cai, 2020; Wei *et al.*, 2022). Small plastic particles can affect soil fauna by adhering to them, potentially causing surface damage, or altering their movement, or as a result of ingestion, where particles may cause internal blockages or impart direct toxicity (Chang *et al.*, 2022). In many cases, soil fauna that ingest AP residues may also be effective in excreting these particles, causing minimal to no damage (Büks, Loes van Schaik and Kaupenjohann, 2020). However, toxicological responses described in the literature include histopathological damage, oxidative stress, DNA damage, and metabolic disorders (e.g., (Rodriguez-Seijo *et al.*, 2017; Chen *et al.*, 2020; Cheng *et al.*, 2020)).

Plants may also be affected by the presence of small plastic particles in soils (Zantis *et al.*, 2023). This includes changes in seed germination, the growth of roots and shoots, and the total plant biomass (e.g., (Boots, Russell and Green, 2019; Bintao Li, Huang, *et al.*, 2021; Gong *et al.*, 2021; Lozano *et al.*, 2021)). Measurements of biomolecular stress indicators reveal differences related to exposure to micro or nanoplastics (Zantis *et al.*, 2023). This includes impacts such as oxidative stress (e.g., (Shuxin Li, Wang, *et al.*, 2021; Wu *et al.*, 2021) and changes in antioxidant enzyme activity (e.g., (Jiang *et al.*, 2019)), photosynthetic efficiency (e.g., (Gao, Liu and Song, 2019)), and plant metabolism (e.g., (Shuxin Li, Wang, *et al.*, 2021; Wu *et al.*, 2021). These changes may be caused by the potential uptake of very small plastic particles or physical implications of the presence of larger particles, such as blocking of seed pores, roots, or hindering the uptake of water or nutrients (Zantis *et al.*, 2023). In addition, small plastic particles may alter plant production and quality through indirect effects, such as the different potential alterations to the soil environment discussed above. Whilst several studies report negative effects, some studies that investigate the impact of micro and nanoplastics on plant production or quality identify both positive or negligible changes in a wide array of different endpoints (Zantis *et al.*, 2023).

Despite a growing body of research, it remains difficult to conclude on safety thresholds quantitatively defining the risk posed of plastic pollution on soils. Remarkably, an initial appraisal focused on comparing metadata across studies on both occurrence of plastic pollution in soils and the levels observed to cause negative impacts on soil properties and plants, shows an overlap (Qiu *et al.*, 2022) suggesting several agricultural soils might already be within the risk zone for experiencing the negative effects of plastic pollution.

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3. Knowledge gaps on Agriplastics from a multi-actor perspective

The design, production, use, and EoL management of APs are shaped by, and co-produce a complex socio-political landscape. Policy drivers in this field branch into concerns over climate change, biodiversity loss, food security, human health, and economic development. As such, multiple actors and interests are involved and will be impacted in different ways by future changes in the regulatory landscape. It is therefore important to understand the experiences, concerns, and interests of the implicated stakeholders. Understanding the underlying needs and motivations of AP users and the knowledge and technology gaps identified by policy practitioners, industry, and organisations promoting environmental and/or food security concerns, are essential to guide research and develop effective regulation.

Based on an initial scoping exercise in the EU, conducted through the PAPILLONS research project (PAPILLONS, 2024), four grouped stakeholder perspectives were set forth. These perspectives have been co-developed by the authors and European stakeholder organisations following a series of bilateral meeting and multi-stakeholder fora (PAPILLONS/MINAGRIS, 2024). Furthermore, to address a global scope, we gathered and compiled the inputs of 68 international experts (with geographic competence covering both high-income and low-income countries) via an online qualitative exploratory survey – *the International Survey on Agricultural Plastics' Perspectives and Knowledge Gaps* – using the International Knowledge Hub Against Plastic Pollution (IKHAPP) platform (IKHAPP, 2024) and in some cases by interaction through email. This approach does not pursue statistical representativeness of the results but aimed at collecting comprehensive views from the experts. The survey was co-designed by scientists and experts associated to the PAPILLONS research project and administered by IKHAPP from May 19 to June 9, 2023. The survey responses were analysed by thematic coding of the data. Two matrices were built – i.e., *the knowledge gaps matrix* – from a multi-actor perspective which distinguishes between five gaps categories concerning: science, policy and governance, management, innovation, sustainable products and practices, as well as human health and landscape value (see Table 2), and *the actions matrix* – which differentiates between three actions categories, namely: (1) lay the foundation of sustainable management of agricultural plastics; (2) strengthen demand for sustainable products and practices; and (3) unlock the innovation potential (see Table 3).

As a result, the perspectives provided by stakeholders working in the European agricultural value chain were fine-tuned with the survey results (see Appendix 1- Anonymized Survey results) as well as evidence gathered via desktop research.

3.1 Perspectives from farmers

For farmers, there are a variety of shared motivations and concerns defining the choice of production practices, with the primary being increasing yield and reliability of production in an efficient manner. In addition to this, many farmers are motivated by concerns for cultural heritage and local food products (Daugstad, Rønningen and Skar, 2006; Tekken *et al.*, 2017), cultural landscapes (Akagawa and Sirisrisak, 2008; Murillo-López, Castro and Feijoo-Martínez, 2022), animal welfare and human-animal relations (e.g., (Skarstad and Borgen, 2007; Lien, 2015)), as well as economic profits (e.g. (Cary and Wilkinson, 1997). These drivers are

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obviously also at play concerning whether and how farmers acquire and use AP and adopt various forms of EoL management.

Through the online survey, inputs from farmers, agricultural business representatives, and farmer union representatives were collected. Five of these were based in Europe, two in Latin America, and one in Africa. All highlighted the benefits of plastics for preserving food quality and enhancing productivity, but shared concerns on the increasing amounts of APW and lack of proper waste management infrastructures. This aligns with the broader literature on plastic waste management, where the current infrastructures across the world are unable to effectively handle accumulated plastic waste (UNEP, 2015). While it often appears as a more pressing issue in the Global South and economies with high growth rates, persistent inequalities exists in global waste trade as unprofitable plastic waste with materials with low recyclability have been often exported to countries with less strict waste management regulations (e.g., (C. Wang *et al.*, 2019; Havas, Falk-Andersson and Deshpande, 2022)). This illustrates the global character of plastic waste management in spite of international convention tending to limit the phenomenon.

Farmer representatives in the survey called for publicly available and intelligible research data on the long-term effects of plastic use on soils, the natural environment, and farm productivity. They also advocate for more collaborative dialogue and for incorporating stakeholder knowledge for effective policy development, favouring measures that move at least part of the costs for waste collection and management away from them.

As outlined in section 1.2, the many advantages of AP are appealing for farm efficiency. Initial scoping interviews from Norway raise the concern on soil health and microplastic to the agenda, as farmers are increasingly becoming aware of the impacts of microplastics (or microplastics in combination with toxins/chemical additives) on soil health. While all interviewed Norwegian farmers who used biodegradable mulching film felt it was a necessity for agricultural efficiency and reduction of pesticide use, they expressed concerns over increasing microplastics contents and chemical contaminants in soil. The farmers requested more research into soil and plant health impacts, as well as trustworthy, neutral, and accessible information about farm inputs and products like mulching film.

Beyond efficiency and food safety, many decisions and management practices on a farm are done with consideration for the welfare and sustainability of the environment. Farmers are intricately tied to their natural surrounding and environment, and many develop a grounded and embodied relation with their land, soil, plants, and animals. APs can be used to protect the environment from other harms. As an example, concerns over the environmental impact of waste from commercial fish farming and disease control and fish welfare, has led to innovations in closed containment systems, like the Marine Donut built in HDPE (*Marine Donut - floating closed containment system*, no date).

Based on the authors' interactions with producers and farmer organisations across Europe, a general and increasing awareness about the problems of APW accumulation and the potential for soil pollution by plastics was noted. For farmers and rural producers two main challenges are emerging: optimisation/minimisation of plastic use, and the recycling of used agricultural plastic. A survey conducted between July and October 2020 in Ireland, highlighted that over 85% of farmers fear the consequences regarding the amount of plastic waste generated by farming activities (King *et al.*, 2023).

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The European Union has proposed a series of measures that may minimise plastic usage at the farm level, such as: (i) have farm inputs delivered in bulk to avoid plastic packaging; (ii) adopt agricultural techniques that do not use plastic (e.g., alternative hay storage system in cattle production); and (iii) reuse the plastic on the farm (EIP-Agri, 2024). According to the narratives collected by the authors from European farmer organisations, a one-size-fits-all solution cannot be considered, as there are varying opportunities and constrains to be considered based on environmental conditions, farm size, production type and practice, existing infrastructure and technology, as well as available finances, knowledge and labour. Across the EU, farmers associations are addressing the question of how to improve APW management (EIP-Agri, 2024). A field study in Almeria, Spain, proved a direct relationship between the price of the raw materials needed to produce plastic and the volume of recycled plastics. Overall, recycling post-consumer plastic products is costly and time-consuming for farmers; therefore, to incentivise best practices for waste management, it is necessary to facilitate and harmonise the EoL management of APW (Castillo-Díaz *et al.*, 2021).

3.2 Perspectives from industry and industry associations

The industry perspective summarised here is sourced by 16 respondents from the digital survey. These were representatives from plastic industries, fertiliser and agrochemical manufacturers, waste managers specialised in APW and industry associations, as well as compost and biogas manufacturer associations. Among them, four have global operations, six are based and operate in the EU, two are from North America, two have operations in South America, and two are from Asia and Australia. These data are complemented by a detailed synthesis provided by Agricultural Plastics Environment (APE) Europe on the European agriplastics industry position and perspective.

Respondents have generally highlighted that industries are key stakeholders in the current and future design, promotion, and management of AP and plastic-alternatives, including in the context of addressing solution to prevent pollution and waste accumulation. They underscore that the technical competence, capacity for innovation and access to capital is key for moving towards a more sustainable use and management of AP and APW, including through the design of circular solutions.

For APE Europe, agriplastics only represent part of the climate and environmental impacts of agricultural activities. They highlight how for a small investment in plastic, farmers may reduce the input of pesticides or fertiliser and the use of energy and water, while simultaneously increasing the quality and quantity of the farmed product. Thus, APE Europe call for a holistic understanding of the environmental consequences associated with possible changes in agricultural practices, like reducing the use of AP or using plastic alternatives. This perspective resonates with the responses collected through the survey, where sixteen of the respondents were classified as belonging to the plastic industry and industry associations promoting the use of AP[1]. The respondents identify the unique quality of AP to preserve food quality and safety, provide durable and water-proof packaging for inputs, and push climatic and environmental boundaries for agricultural production.

[1] Out of these sixteen, six operated globally, seven operated primarily in North America and the EU, one operated in Africa, and two operated in Asia.

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The respondents' views show a level of variability regarding whether AP can produce detrimental consequences for the environments, soil health, and human health. Some considered AP to have little or low negative consequences as long as they are handled correctly, whereas some respondents were concerned with potential toxic leakages from plastic products, and with microplastics found in human bodies and the environment. Overall, the respondents called for more research on the quantities and fates of plastic in soil and agricultural environments. In addition to this, bio-based and biodegradable products are mentioned by the survey respondents, with some considering them as a potential sustainable substitution for conventional AP, while others called for more research into their possible contribution to microplastic accumulation in soil and potential increase in CO_2-emissions as the plastic degrades.

Across the survey responses, and aligning with APE Europe's views, proper management of APW remains a key priority. The industry is aware of the problems caused by dumping or burning of AP and do not wish to be associated with these practices. Thus, some explicitly call for improved waste management schemes possibly involving all economics actors of the AP value chain. In particular, based on experiences across different European countries, APE Europe calls for an integrated approach, where producers commit to develop AP designs that eases recycling and minimises pollution, and where the producers take responsibility for regenerating polymer granules from waste and using them in new products. They highlight the important role traders and trade cooperatives have in disseminating good practices to AP users.

Technical and economic efficiency is important for proper EoL management of AP. EoL management is costly, and often APW has a negative value (according to APE). Instead, national collection schemes in Europe are often financed following the Extended Producer Responsibility (EPR) principle, by adding a levy to the selling price to cover EoL management cost. In the survey results, the industry respondents are positive towards increased recycling requirements and encourage governments to develop policy and measures that promote proper EoL management and increase the use of recycled materials in AP products.

Finally, survey respondents in industry sector call for more research collaborations which should include AP users more directly. Collaborations may also be with waste management companies and product developers, to improve recycling technologies and the use of recycled material in AP products. As an example of such collaboration in research and development, APE Europe reports the results achieved from programmes such as RAFU, launched by A.D.I. VALOR and the French Committee for Plastics in Agriculture (CPA), to improve the recyclability of mulching films and develop safe biodegradable products (*A.D.I.VALOR - Agriculteurs, Distributeurs, Industriels pour la VALORisation des déchets agricoles*, no date). Similar programmes may provide grounded insights and cross-stakeholder understanding if launched in other agricultural and geographical regions. Finally, and beyond recycling, industry actors also call for research into plastic fate and impact on environments and human health, including research on biodegradable and bio-based products.

3.3 Perspectives from the environmental NGO sector

A total of six NGOs provided narratives and perspectives. Three of them are based in the EU, one from the US, and two from Africa, covering topics such as broader plastic pollution, waste management, and conservation. Organisations operating both at national and international

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levels were represented. In addition to the respondents to the online survey, the authors have collected information and perspectives directly from representatives of the Plastic Soup foundation and the Environmental Investigation Agency (IEA), an EU-based and a UK-based environmental NGO, respectively, both running strategic work on AP and APW at international and global level. The NGO sector generally considers plastic-intensive agricultural practices as a threat to agriculture, the environment, and human health, and advocates for adoption of, or transition to environmentally friendly and nature-based alternatives in farming. These should be endorsed by policy and instruments that include economic incentives. It was indicated that the costs of transition to environmentally sustainable practices should not be a burden towards specific groups of farmers but the result of a distributed effort, including at the international level.

In countries where AP-intensive production systems are already diffused, farming transitions to a lower plastic footprint will require sustainable production practices alternatives, effective recycling schemes, and the certainty that institutional bodies and governments will support the process through tailor-made funds and programs. There is an awareness that change will be costly and time-consuming, with possible short-term implications for both producers and consumers. These challenges affecting the transition must not be a reason for delayed action considering that the costs of inaction are currently not quantifiable. At the same time, a call for a better understanding of the environmental, agricultural, economic, and human health costs of plastic pollution from the use of AP need to be prioritised by scientific research.

Moving away from AP-based practices may be particularly challenging for farmers in countries and regions where AP-intensive practices are at an initial development stage and in rapid expansion, typically substituting more traditional farming practices. These farmers need access to complete and objective information on the problem and costs concerning APW management and soil pollution in order to make informed decisions on how to orient investments in new production systems. NGOs can play a pivotal role considering their capacity in spreading awareness, mobilising resources, and influencing policy makers to shape decision-making processes. The concerns and focus of environmental NGOs are shifting from the marine environment, where initial attention was placed by researchers on marine debris, to the broader plastic pollution problem including also on the use and misuse of plastics by the industry and consumers and accumulation of plastics in the food chain.

Within the European Union, the level of awareness on the challenges related to microplastics is growing steadily, in the wake of the announcement by the European Commission of the ambitious Farm to Fork strategy and EU Soil Strategy. Some NGOs called for EU institutions to leverage the discussion for the development of the EU “Soil Monitoring Law” to contribute to the overall objective of reducing the amount of microplastic released into the environment by 30% by 2030. Despite the ambitious efforts of many of the EU initiatives, NGOs reacted negatively to the proposal on “Soils Monitoring and Resilience Directive”, calling for improvements and for more ambition to fully address the challenge at the EU level, including integrating in the proposal a list of key pollutants. The NGO sector has also questioned the effectiveness of several proposed substitutes for high-risk agricultural plastic products.

A first draft of the EU Soil Monitoring Law released in 2023, did not consider miroplastic pollution in soil. Following the dialogue and inputs provided by PAPILLONS project researchers with members of the environment committee of the EU parliament, a request of

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amendment to include soil plastic pollution in the law has been brought forward and assimilated in a new draft being currently negotiated.

The urgency for a strong political action towards plastic pollution has been highlighted during the Plastic Health Summit in 2023, where the Plastic Soup Foundation discussed the plastics treaty and re-stated that the short-term gains for farmers from agricultural plastics products do not outweigh the long-term consequences. This NGO has also provided a presentation on biodegradable polymers, which it has, according to them, been unproperly labelled as a one-size-fits-all solution. Biodegradable polymers are designed to be broken down by microorganisms, so they should not contribute to microplastic degradation. However, the NGO claims that the tests do not fully reflect all soil and environmental conditions in which these materials are used, claiming that test requirements from existing standards (e.g. degradation tests in an 'ideal' environment for microorganism activity and therefore biodegradation: at 25 degree Celsius, in a humid and oxygen rich conditions and only on one soil type (Zhang, Huan, et al., 2020)) are insufficient to guarantee full degradation in real operation conditions, resulting in the accumulation of plastic debris in the environment.

The Environmental Investigation Agency (EIA) a UK-based advocacy organization, has been working on AP since 2018, especially in the context of EU and UK supply chains. As part of their work, they documented diffuse cases of APW mismanagement including illegal waste handling practices that highlights farmer challenges in sustainably using AP and the serious environmental impact this can produce. Concerns about EoL management has also been expressed by several respondents to the digital survey that called for a better understanding of the AP life cycle and the waste management process in agriculture, including in both developed and developing countries. The proposals for actions are to improve the formal record keeping of AP use, by environmentally sound management of waste. Overseas and African NGOs have prioritised investments in research and innovation with the aim to improve both technologies for sustainable use and EoL practices and develop new management tools.

Awareness and understanding of plastic pollution impacts on the environment and food security need to be urgently reinforced. Ambiguity on this aspect is reflected by the uncertainty and scepticism surrounding the effectiveness and rapid implementation of policy strategies aiming at zero-plastic pollution to date. The NGO sector advocates for enhanced traceability and transparency for the EoL management of agricultural plastics (e.g. by means of digital tracking technologies, and mandatory reporting of AP volume sales and processed APW), as well as for the development of new waste management models and compact/cost-effective technologies for recycling and reuse, specifically tailored for the agricultural sector which could be deployed locally or even at the farm level. Raising awareness and inducing behavioural changes among farmers are also seen as necessary measures to improve assimilation of plastic pollution reduction measures. Finally, NGOs remark that , internationally, policy makers should define plastic reduction targets for the agricultural sector, and at the same time provide complete and assimilable (by farmers) assessments of the economic viability and cost-effectiveness of sustainable alternatives to AP.

3.4 The environmental scientists' perspective

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The research community has focused on investigating both the sources (Chia, Lee, Cha, *et al.*, 2023) and potential effects of plastic debris including micro- and nanoplastic on aquatic and terrestrial environments (Chia *et al.*, 2021). While historically the research focus has been on marine pollution, in recent years research has provided evidence that plastic pollution in terrestrial environments (and especially agricultural soils) is an environmental concern capable of affecting ecosystem quality, including soil fertility and agricultural performance. This section reports the perspectives of the environmental science community regarding knowledge gaps and priorities for future regulation. This synthesis reflects responses from researchers participating in the IKHAPP survey as well as the positions of a group of environmental scientists from 37 research institutes in Europe and China, including ecologists and toxicologists clustered around two large international research projects (PAPILLONS/MINAGRIS, 2024), as well as the insights from recent scientific literature (Hofmann *et al.*, 2023) and policy briefs (The Scientists Coalition for an Effective Plastic Treaty, 2024).

The ongoing debate has highlighted several knowledge gaps that the research community should urgently address to inform environmental and agricultural policies and ensure sustainable agricultural practices. A first major knowledge gap is represented by the paucity of data on the amounts of plastics that are intentionally or unintentionally introduced into agricultural soils through practices such as the application of compost products or biosolids that may be enriched with microplastics or irrigation from plastic contaminated surface waters, as well as the use and waste handling of AP products. Such an assessment should be quantitative and global in scope, enabling a comparison between different sources, which can help to prioritise pollution reduction measures. A concerted effort to consolidate confidence in assessments of spatial distribution of microplastic plastic pollution in agricultural soil is therefore necessary.

Researchers have also highlighted that insufficient empirical studies exist focusing on the long-term effects of the accumulation of debris from the fragmentation of APs on soil health, soil biodiversity and related soil ecosystem services under different soil conditions (e.g., temperature, moisture) and soil types (Baho, Bundschuh and Futter, 2021). Scientific works have emerged during the last 3 years documenting interactions between soil microbiomes and soil fauna and micro- and nano-plastic pollution (Huerta Lwanga *et al.*, 2016; Selonen *et al.*, 2020; Baho, Bundschuh and Futter, 2021; Ya *et al.*, 2021) (Huerta Lwanga *et al.*, 2017; de Souza Machado *et al.*, 2019; R. Qi *et al.*, 2020b) (de Souza Machado *et al.*, 2018; Liu *et al.*, 2019; Wan *et al.*, 2019; Fei *et al.*, 2020), highlighting adverse effects on the viability of organisms and important ecological functions at environmentally plausible levels of contamination in soils (de Souza Machado *et al.*, 2018; Selonen *et al.*, 2020). Despite this, actual risk assessment approaches lack an accurate framing of exposure scenarios (especially in terms of the typology, characteristics, and representativeness of the particles used as test materials) and tend not to take chronic risks (such as effects on biodiversity and soil fertility) into adequate consideration. This concern is applicable to both conventional and biobased or biodegradable plastics. According to environmental scientists, assessments of the long-term effects resulting from the use of biodegradable polymer as alternatives in AP applications (e.g., biodegradable mulching films) lack sufficient characterisation (Bandopadhyay *et al.*, 2018; Sintim *et al.*, 2019; Bandopadhyay, Sintim and DeBruyn, 2020; Mazzon *et al.*, 2022) (F. Huang *et al.*, 2019; Y. Huang *et al.*, 2019; Serrano-Ruiz, Martin-Closas and Pelacho, 2021) (Serrano-Ruíz, Martín-Closas and Pelacho, 2018; Souza *et al.*, 2020; Ding *et al.*, 2021) (Kapanen *et al.*, 2008; Bettas Ardisson, 2014; Chen *et al.*, 2021; de Souza *et al.*, 2021) (Martin-Closas, Botet and Pelacho, 2014; Iqbal *et al.*, 2020; Schöpfer et al, 2020) (Balestri *et al.*, 2020; Campani et al., 2020; Magni *et al.*, 2020; Zimmermann *et al.*, 2020), while the requirements for biodegradability and environmental safety introduced by current standards are not adequate to fully ensure safe and controlled application in all bioregions and climates. Technical assessments of biodegradation are conducted under standard laboratory conditions – a scenario which is not relevant for many locations.

Furthermore, the transport of macro-, micro-, or nano-plastics by wind, water, and bioturbation may transfer fragments of biodegradable and conventional AP from the fields in which they are applied to other areas, where conditions may be inadequate to achieve rapid biodegradation for biodegradable AP and no degradation for conventional AP – such as aquatic environments (Tsuji and Suzuyoshi, 2002; Lambert and Wagner, 2017; Sashiwa *et al.*, 2018; Nakayama, Yamano and Kawasaki, 2019) (Li *et al.*, 2014; Dilkes-Hoffman *et al.*, 2019; X.-W. Wang *et al.*, 2019; Chamas *et al.*, 2020) (Anunciado *et al.*, 2021). No data on biodegradability in sediments or water (e.g., ground and surface waters) are required for certification in some parts of the world.

The lack of accessible data on the composition and long-term effects of chemical plastic additives used in AP products represents a serious concern for environmental scientists, as chemical additives in plastic may represent a conspicuous fraction of the total mass of the products both for conventional and biobased/degradable materials (Chia, Lee and Cha, 2023). Environmental scientists argue that the current fragmentary knowledge on the use and degradation/ageing of AP can result in an incorrect estimation of the ecological risks posed by these chemicals.

Uptake of micro and nano- plastics by crops and their accumulation in the terrestrial food chain has been proven in recent studies (Sun *et al.*, 2020, 2021; Chengjun Li *et al.*, 2021; Zhou *et al.*, 2021; Lian *et al.*, 2022) (Bosker *et al.*, 2019; Zantis *et al.*, 2023). Still, the risk for human health by such uptake processes has not been studied and remains unknown. The associated risk for consumers should be quantified and considered within future risk assessments before AP-based practices that can cause pollution are incentivised. This should also consider indirect, knock on, and systemic level effects resulting in, for example, reduced soil fertility and agricultural yields and, therefore, risks to global food security, in addition to any direct toxic effects.

Similarly, still limited knowledge about the interaction of APs with other organic pollutants intentionally (e.g., pesticides) or unintentionally (e.g., veterinary drugs) released in agricultural soils (Hüffer *et al.*, 2019; Chengjun Li *et al.*, 2021; Dolar *et al.*, 2021; Sun *et al.*, 2021; Varg *et al.*, 2021) (Zhang *et al.*, 2021; Hanslik *et al.*, 2022; Lajmanovich *et al.*, 2022; Zhou *et al.*, 2022). Pesticides and veterinary drugs are regularly present in agricultural soils and are expected to interact with both conventional and biodegradable plastics. Studies on the transport of plastic residues with adsorbed pesticides and the related risks for environmental and human health are limited.

Acknowledging the available body of evidences and the existing knowledge gaps the environmental research community remarks that soil and sediment pollution by non-degradable micro and nano- plastics is poorly reversible (Chia, Lee and Cha, 2023), while soil is a non-renewable resource. Food production practices that result in continuous releases of plastic debris and their chemical additives, however small, should be critically evaluated and disincentivised. In the context of agricultural practices that cause soil plastic pollution, policy should take into consideration the ecological, agricultural, and potential human health risks posed by an underlying increase in soil and water bodies pollution and the potential transfer of plastic debris or their chemical additives into food over the medium and long-term. Hence, scientists recommend that policy developments incorporate the definition of sustainability criteria that holistically consider long-term impacts of this pollution in natural and agricultural environments.

The use of degradable, biodegradable, or compostable plastics as alternative materials should follow strict criteria related to safety and sustainability by design. The use of any materials that do not achieve complete degradation should be prevented. A revision of the current standards for certifying biodegradability is needed, particularly regarding their suitability to represent the range of environmental conditions in which biodegradable AP are (and will be) used. The sustainability of long-term continuous use of biodegradable AP should be considered. Scientists have highlighted the importance for authorising the use of biodegradable and compostable plastics under a regulatory frame based on risk assessment and management (PAPILLONS, 2022).

The definition of a risk assessment system regulating the use of AP (both conventional and biodegradable) that release plastic debris and associated chemical additives to soil or crops should be considered by regulation. This could for example be framed under the risk assessment frame in a similar way as is done for chemical management regulation (e.g. The European Union Registration, Evaluation, Authorisation, and Restriction of Chemicals, the EU Pesticide regulation, and others). Concerning aspects related to use and management of APs, environmental scientists advocate for regulations that demand the creation and maintenance of inventories of AP use (of both conventional and biodegradable plastics) and management across the entire life cycle as a tool to enable control over the potential sources of pollution and agricultural plastic generation. This includes the need for form of open or targeted disclosure concerning additives used in AP, solid and clear labelling schemes describing composition, usage and waste management practices, and labelling/licensing schemes that can help ensuring best practices and traceability of the materials throughput their life cycle.

Industry and/or retailers should be actively involved in the maintenance of these records at the national or subnational level. Tracking the usage of different AP regulation should impose that conventional plastic products must be removed from fields and disposed properly before excessive ageing and weathering may induce fragmentation and result in pollution. It is possible to predict the useful lifetime of a given material based on factors such as the climate of the area or the cultivation techniques employed, as well as the material properties of the AP product. Farmers must not use the plastic products beyond that time. Technologies to maintain a detailed census of AP in use and track their deployment time are available (e.g., microchips, barcodes, and integrated databases). Besides, instruments to promote mechanisms for a widespread system of collection, storage, management, and recycling of AP waste should be urgently introduced to avoid further additions of plastic pollution to soils. Extended producer responsibility schemes could form part of this initiative. At the same time, regulation should disincentivise international trade of AP waste unless there is a verified guarantee that the

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recipient countries are capable of effectively processing these materials through the formal economy sector with due safeguarding of labour and environmental standards. Closing the loop of the AP life cycle within small geographic units will be necessary to promote circularity, control, and economic sustainability of waste management and, possibly, recycling. While redesigning, recovering, reusing, and recycling are all important steps to improve sustainability of AP-based practices, regulation should take into consideration also the options of reducing and preventing such practices. For example, policy should design instruments whereby plasticulture should be endorsed in a given area only when the social and environmental benefits (and not only the economic benefits) exceed the social and environmental costs, whereby this assessment should take into consideration not only the long-term ecological and agricultural impacts of soil plastic pollution caused by the practices but also the impact on the quality of life and landscape value of the area (PAPILLONS and MINAGRIS 2022).

Aspects linked to the resilience of food systems should be considered when designing policies for AP. Plastic is mostly manufactured from non-renewable raw materials. Agriculture heavily relying on AP is therefore inherently non-sustainable on the long term unless full circularity is achieved in the sector. In addition, the price of fossil fuels is highly volatile, and this can have implications on the cost-effectiveness of AP-based production systems, with possible implications for food security. This aspect counterbalances some of the benefits on improved production efficiency enabled by AP. Accordingly, while the benefits and usefulness of AP is not questioned, policy incentives should somehow also benefit, in each agricultural region, group of farmers that minimise plastic use in their activities or, more in general, that minimise chemical inputs in their production systems while embracing nature-based solution and regenerative farming practices. This would ensure food system resilience and the maintenance of truly sustainable traditional practices and knowledge to be deployed in case of failure of modern plastic-intensive approaches.

4. Policy demands, opportunities and stakeholder contributions for a sustainable use of AP

Policies to address the environmental implications of AP could be articulated along a range of options. The FAO report (FAO, 2021) has advocated for a holistic approach to address negative implications of plasticulture and to guide analysis during the development of the VCoC. This is embodied by the "6R" framework listing Refuse, Redesign, Reduce, Reuse, Recycle, and Recover as elements for consideration in the definition of best practices. Given the interlinkages with food security aspects and farm economy, addressing the problem posed by AP represents a major and difficult endeavour where industries, regulators, farmers, waste management, and scientists will all have an important role. According to the inputs from the stakeholder survey, the specific actions that policymakers and governments should consider, and implement can be clustered around three groups of interventions – i.e. (1) *Lay foundation* of sustainable management of agricultural plastics, (2) *Strengthen demand* for sustainable products and practices, including considering plastic-free practices in production, (3) *Unlock innovation potential.* A synthesis of these actions per group and actor is provided in Table 3.

As for *laying the foundation of sustainable management*, policy could focus on the establishment of mandatory recording of official and spatially resolved data for AP use and waste generation (the disclosure of which is now prevented by market protection aspects) and

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the establishment of mandatory management schemes specifically for APW, which in turn should stimulate circularity. Policy instruments should include financial viability provisions for the development of infrastructure for waste management and recycling.

As for actions that can *further strengthen the demand for sustainable alternatives and practices*, they range from: *support for large scale pilots* (time and area) of alternative plastic materials to vet their effectiveness, with controls, towards implementing alternatives at national scales, and with subsidy schemes for implementation and infrastructure development; *co-funding schemes* for biodegradable mulches with proven effectiveness and safety; *tax reductions* for farms that adopt sustainable plastic management practices; *premium prices* on products sale for the farms that adopt sustainable practices; *development of certification schemes*, awards/recognition schemes – to *setting up framework agreements* between public authorities and the sector, defining objectives, criteria of performance, and implementing a monitoring system adapted to the local situation to ensure sustainable practices goals are achieved. Jointly endorsing innovative designs for the sustainable use of modern AP-based production system and nature-based solutions is essential for resilience of food systems. By maintaining such a diversity in production practices expressed in all regions, policy could simultaneously tackle the elements of *reduction/rejection* and *redesign* (included in the 6R framework (FAO 2021)), by spatially diversifying practices.

Finally, the task of *creating the framework conditions* for unlocking the innovation potential expressed by all economic parties (farmers, distributors, plastics manufacturers, assurance schemes) involved in the implementation of reliable use and EoL of AP, sharing responsibility and governance: *develop robust national and international approaches* on the content, use, and disposal of agricultural plastics paying attention to the specificity of the regions; *entice practitioners* towards the development of alternatives by facilitating new markets creation through customised financial mechanisms depending on existing local practices, crops, and socio-economic conditions; *subsidise businesses* where designed solutions address the full life cycle of agricultural plastics; *adopt regulations and financial incentives* to promote circularity of agricultural plastics; and *finance R&D for new materials* that do not affect soil and plant ecosystems.

The sustainable use and management of plastics in agriculture presents a number of unique challenges and opportunities compared to other sectors caused by a number of factors such as (i) dispersed nature of plastics use and pollution, often in remote locations; (ii) significant gaps or entirely lacking plastic waste management infrastructure forcing farmers to resort to open burning or uncontrolled dumping; (iii) agricultural plastics like mulch films and greenhouse covers are often contaminated with soil, pesticide residues, or plant matter, making recycling more difficult and costly compared to cleaner plastic waste streams; (iv) low residual value of used agricultural plastics provides little economic incentive for farmers to collect and recycle the waste, unlike more valuable plastic waste streams; (v) costs of proper collection, cleaning, and recycling of agricultural plastics can be prohibitive for farmers with limited resources; (vi) lack of clear regulations and extended producer responsibility schemes; and (vii) plastics incl. plastic waste national regulations often do not or not adequately cover the unique challenges of agricultural plastic waste management. For these reasons, the application of a sector-specific approach using voluntary instruments, such as the Voluntary Code of Conduct under development by the FAO, or the inclusion of sector-specific approaches in the international legally binding instrument on plastic pollution, is favoured by many stakeholders.

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The stakeholder perspectives presented here reveal a shared concern among all actors for the potential impacts of AP on environmental health and agriculture, as well as a common view over the usefulness of circularity-oriented solutions. Figure 1 summarizes a circularity model as a possible synthesis of inputs collected from the different stakeholders involved in this analysis. According to this framework, best practices could be implemented at each stage of the value chain thanks to collaborative efforts, whereby, holistic design plays a steering role also for downstream stages. These solutions should involve all main actors along the food production chain whereby the design, labelling, traceability, control over environmental safety standards, and deployment of infrastructures and schemes for waste management are centralised, and whereby the cost of transition are fairly distributed along the food value chain.

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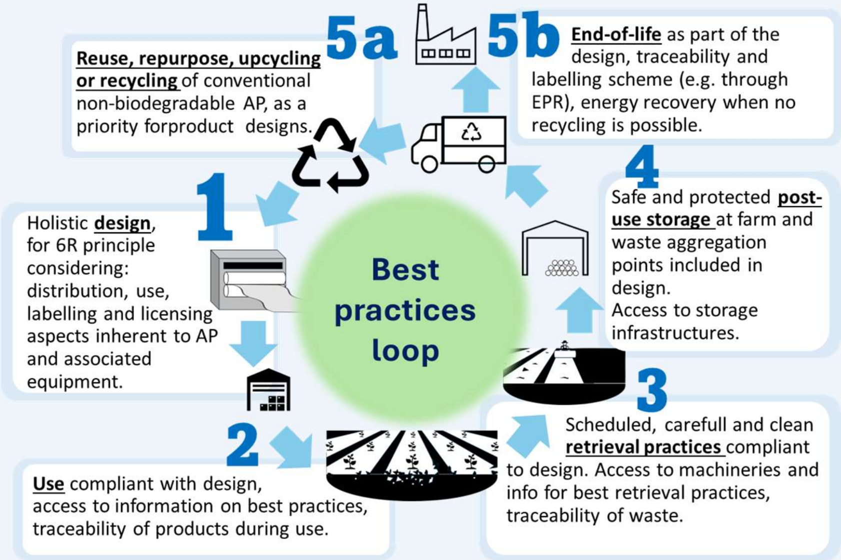

1 **Design** is crucial for providing plastic products and practices with low potential for causing pollution. Beyond crafting "low-emission" products, design shall consider elements of 6R principles, specifically: reduce, reuse, recycle and recover. These elements should be entailed in technological, labelling, traceability, licensing, usage and waste management aspects. Control over products line of custody, volume and place of distribution, use and waste storage, handling, recycling and/or disposal is necessary. Labels shall provide information on best practices for use, retrieval and waste handling. Designs should be co-developed with all associated equipment for application, maintenance, cultivation, retrieval and cleaning of AP from soilage. Rigid and standardized licensing scheme are part of the design and are key to ensure suitability of products and capacity of actors in the product's life cycle.

2 **Use** of AP by farmers should consider also elements of the 6R model, specifically: refuse, reduce, recover. Practices should maintain integrity of products. Practices resulting in intentional releases of non-degradable AP should be refused. Biodegradable AP use should be based on certified and controlled products that degrade rapidly in specific environmental conditions with no release of substances and residues that pose an uncontrolled risk. Access to information on best practices and equipment by farmers is crucial. Whenever possible, consider nature-based alternatives (e.g., plant support twines made of natural fibers). Whenever the conditions for enacting best practices and safe by-design use of AP are not in place, traditional nature-based solutions should be promoted.

3 During use and ageing in field, AP become brittle and can easily break down during retrieval, causing pollution. Thoughtful AP designs, practices for scheduled **retrieval** from fields, access to certified machineries specifically designed/associated to the products allowing safe collection with no damage of AP and in-situ removal of soilage and organic matter, are necessary for sustainable use. Among other AP, mulching films and irrigation pipes are particularly challenging to be recycled in a cost-effective manner as they may accumulate an excess of soilage and agrochemicals residues. Best practices and new designs for careful and clean retrieval operations can improve these products' recyclability. Degradable AP not certified for safety and degradability in-situ under conditions closely reflecting those of operational environments, shall be retrieved, similarly to AP and disposed safely or degraded in controlled composting facilities.

4 Direct observations and farmers' experience show that the conditions and timespan of AP **waste storage at farm level**, before it is handled to further management, are critical for preventing pollution. Quality standards, deployable infrastructures and best practices for contained storage, tracing of waste and segregation of different AP wastes at the farm level are key for sustainable AP use. A truly holistic design of products and associated equipment shall include innovation for these aspects inherent to AP waste storage at farm level.

5a Holistic design should prioritize circularity through **recycling, repurposing or reuse**. Upcycling or recycling of conventional non-biodegradable AP is regarded as a desirable option for a sustainable use of AP if this can be achieved in an environmentally sustainable way. To date only a small fraction of all AP is recycled, including in places where effective waste collection schemes exist. Achieving high recycling rates requires interventions and optimization at all stages of the value chain and should be entailed directly in the design and labelling of products. To safeguard competitiveness and value of innovative "circular products", labelling schemes and new standards should be developed synergistically by regulators and all actors involved in the value circle.

5b **EoL** of most of AP in use today in the world is believed to be based on landfilling or mismanagement in environment. In limited cases energy recovery is employed, but the economic feasibility of this option is bound to collection and transportation costs. Careful consideration of various EoL options should be a central consideration when recycling is not possible. Planning of incentives to plasticulture should take sustainability of these considerations into account. EPR schemes can play a crucial role in facilitating the balanced expansion of waste management infrastructures where plasticulture is in expansion. This is key, for example in developing countries.

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Figure 1. Best practices loop: an AP management model elaborated considering information and insights provided by the stakeholders

Considering these diverse aspects, understanding and solving, counterposed standpoints among stakeholders is key for effective policy making, and for establishing a collaborative dialogue, to stimulate the innovation required to achieve sustainable use of AP. Figure 2 illustrates a model for innovation in the sector which can be used as a frame to enable collaboration among stakeholders towards co-design and testing of new products and solutions. The model addresses four key pillars of innovation: knowledge building, awareness and behaviour change, prototyping and demonstrators. Scientific findings should be assimilated as part of this process and represent the fulcrum for a constructive dialogue, paving the way for co-creation of sustainable solutions, behavioural change, accelerated uptake of innovations in the sector.

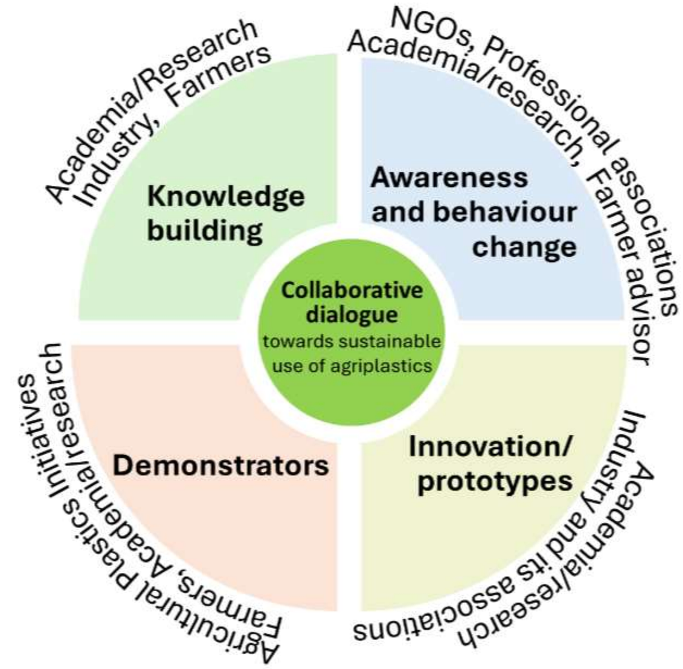

Figure 2 – A co-design and co-development framework proposed to accelerate sustainability-oriented innovation in the area of AP.

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Table 2. Knowledge gaps – Multi-actor perspectives

ACTORS PERSPECTIVE	KNOWLEDGE GAPS: Science	Policy & Governance	Management	Innovation, Sustainable products, and practices	Human health and landscape value
Academia/ Research	exposure and long-term **effects** on soil quality of micro- and nanoplastics; plastics long-term effects on ecosystems; plastics effects on the soil physicochemical parameters and soil microbiota; quantification of plastic pollution and associated chemical contaminants presence in different soil types around the globe; effects biodegradable plastics have on soil physicochemical properties and quality. **impacts** of plastics on terrestrial ecosystems; impact of biodegradable plastic on ecosystem processes; plastics impact on different environmental matrices; environmental impact of plastic in agriculture (soil structure, food security, recyclable and recycled material); **plastics degradation** pathway and their long-term impact; **bioremediation** of both micro & macro plastic; **biodegradability** data of the alternative materials in different climatic and environmental conditions; more evidence that biodegradable plastics is a better solution on long-term; long and short-term harms and benefits of alternatives to plastics in the agricultural setting; **global flows** and **fates** of agricultural plastics	**reliable data** on how much plastic is used on the farms in different parts of the world, in different environmental conditions and socio-economic farming systems, to design and inform policies. **legislation and infrastructures** for APW valorisation mandatory recording of **statistical data** for AP and APW	knowledge on **how to manage deteriorated plastics** – i.e., how to remove them from the soils & how to recycle them for further use; **data on costs** of initial and long-term switches to sustainable forms of agricultural plastics; large scale **evidence on** how efficient the **biodegradable plastics** are in agricultural practices; mechanical devices for a proper material handling and treatment after use.	potential for the **next generation of biodegradable polymers**; new **composting technologies** to biodegrade agricultural mulches; development of biodegradable plastics; **circularity of plastics**; new technologies; **innovative ways** of collecting AP.	harmful **effects** on ecosystems and human health health **impacts** of the plastics use at micro level
Agricultural Plastics Initiatives	**influence** of micro- and nanoplastics in soil microbial activity, root development and uptake of such residues; **internal movement** of micro- and nanoplastics in the crops; long-term **effects** of replacing plastic mulch with biofilms on soil properties, **carbon sequestration** and nutrients concentration; **impact** of agricultural plastic reduction;	**quantification** of plastics in soil, the extent to which it is increasing to inform new policies			
Farmers	short-medium-long term **effects** of plastic use are not highlighted enough		**valid data** on amounts and recycling **overview of costs** triggered by new sustainable agricultural practices	**solutions for substitution** of use of plastics; **development of on-site alternatives** based on crop residues**; innovative production** and **recycling** technologies of plastics	

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Industry Associations	amount of microplastic **emissions** from AP specifically, **fate** of APs after the use phase; **tolerance** of recycled content in agricultural containers; **quantification** of the high consumption of agricultural plastics	**reliable, up to date data** available at country and regional level; general **market studies;** poor **governance models,** lack of learning from effective policies; **key benchmarks** to validate improvement and differentiate effective policy from ineffective policy	**management of flexible plastics,** effective shredders for collection centres, effective transportation, and improved **recycling technologies**; **economic impacts** of AP	**recycling alternatives** for agricultural films; better recycling facilities**;**	long term **impact** on biodiversity, land productivity degradation and human health
Professional Associations	**global flows** and **fates** of APs (quantities, composition, where and how they are used, their environmental fate throughout the supply chain, during use and at EoL);		**reliable data** on AP quantities	**alternative materials** to replace plastic in preservation of fodder; **new technologies** to circulate and collect used plastics;	
NGOs	**environmental fate** and transport of AP; long-term **impacts** of AP and AP residues on soil health and functionality; rate of **degradation of biodegradable mulches** in all potential environmental and climate environments; **data on material flows**, long term impacts of conventional and alternative materials on the likes of yield but also the likes of **eutrophication** for impact out of the farmed area;		**amount** of AP used and **what types** of products are used **where**. **recycling** of AP	**traceability systems** for used AP, development, and evaluation of **biodegradable alternatives** to AP	**uptake of microplastics by crops** and the potential **implications for food safety;** implications of AP use negatively impacting soil health, and subsequently crop yield
Other (Agri-business, Corporate, Consultant, Environmental Protection Agency, Plastic Business)	**final fate** of plastics in the environment and **impact** on human and biodiversity health; quantification of the **biodegradability** of plastics in the open environment (soil, water bodies); becoming of plastic waste in trophic chain;	limited understanding of **farmer needs**; realistic **biodegradation tests** and **criteria** to be applied where APs are effectively used;	**data on the cost** of the retrieval, collection, and recycling of agricultural plastics; what is the optimum cost enabling a robust value chain	**alternatives** for plastic protection against insect pests; alternative methods of cultivation; **chemical recycling** of plastics needs to be further developed; best **solutions** considering differing circumstances in several geographic regions.	harmful **effects** associated with ageing plastics on human health

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Table 3. Actions – Multi-actor perspectives

ACTORS PERSPECTIVE	ACTIONS required to: Lay foundation of sustainable management of agricultural plastics	Strengthen demand for sustainable products & practices	Unlock innovation potential
Academia/ Research	Investigate plasticulture diversity and the amounts of AP consumed to develop region-specific approaches. Mandate reporting of statistics at European level and close monitoring of the APs used to ensure that the related waste is accounted for. Implement on a large-scale European AP waste collection scheme. Develop robust national and international laws on content, use and disposal of APs. Ensure fair sharing of the costs of recycling among the actors of the AP value chain. Information leaflets should be distributed to farmers informing about the emissions produced by the incomplete combustion of plastic if it is burned on the farm.	Introduce co-funding schemes for the biodegradable mulches that proved their effectiveness and safe use. Tighter regulations over what can be used in agriculture - including what additives are in the plastic products. Governments can help to direct stakeholders' attention to where it is needed to support policy making that promote sustainable practices. Set up a framework agreement between public authorities and the sector, defining objectives, criteria of performance and implementing a monitoring adapted to the local situation to ensure sustainable practices goals are achieved. Optimise EoL management technologies with the environment in mind with emphasis placed on material recovery and recirculation.	Fund research into biodegradation techniques for existing plastic contamination. Incentives for development and use of biodegradable alternatives needs to be done carefully and ensure that they are fit for purpose and safe and sustainable. Finance R&D for new materials that do not affect soil and plant ecosystems.
Agricultural Plastics Initiatives	Map the use of APs and their disposal; provide guidelines to reduce the use of plastic, sustainable disposal of APW (e.g., recycling close to the source); generalise good practices (e.g., A.D.I. Valor, France).	Mandate collection targets for APW. Conduct comprehensive life cycle assessments of different AP products and their alternatives.	Entice practitioners towards alternatives development by facilitating new markets creation through customised financial mechanisms depending on existing local practices, crops, socio-economic conditions
Farmers	Develop awareness and capacity building programmes for farmers to learn about new products and practices. Ban non-recyclable plastic use in agriculture;	Plastic composition should be regulated, and sales controlled, to have a traceable, circular economy around AP. Incentives to switch to more sustainable plastic alternatives.	Fund research into biodegrading techniques for existing plastic contamination. Fund research for reuse solutions and innovative substitution of plastic
Industry Associations	Account for and mitigate AP/APW mismanagement risks on local biodiversity. Ban burning and landfilling of AP, provide incentives for farmers to recycle APs. Introduce producer responsibility on AP manufacturers, so not to put the economic burden on farmers. Support the development of national collection schemes, enforce them where they are not yet widely present.	Provide incentives for new recycling technologies. Reduce taxes on farms that adopt sustainable plastic management practices; set a premium price on products sale for the farms that adopt sustainable practices, develop certification schemes, awards/recognition schemes. Introduction of alternative packaging option for fertiliser packaging.	Support research to develop new plastic materials that are biodegradable, compostable, and that can perform at the same level of reliability of current AP items

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	Professional Associations	Create favourable conditions for all economic parties (farmers, distributors, plastics manufacturers, assurance schemes) involved in the implementation of reliable EoL management schemes, sharing responsibility and governance. Educate farmers regarding how to treat, store, and recycle used AP. Provide all economic actors with information and training opportunities from along the supply chain is key as well as individual and collective involvement	Provide incentives for new recycling technologies. Develop awareness and behaviour change among farmers. Assess the economic viability and cost-effectiveness of sustainable alternatives to AP. Stimulate the adoption of agroecological and permaculture approaches	Government and policymakers should engage with industry representatives covering all aspects of the AP sector from production to use to recycling to collectively develop and then implement the right solutions.	
	NGOs	Enhance traceability and transparency for the EoL management of agricultural plastics by increasing the use of digital technologies. Develop new management models for the use of APs and their final disposal. Additional policies are required to enforce regulations, namely the mandatory reporting of AP products sold, used and how they are treated and end of life.	Develop awareness and behaviour change among farmers. Develop compact and cost-effective recycling systems for on-farm use to provide farmers with the means to recycle their own APs. Develop a policy mix, including plastic reduction targets with regards to the AP use, provide sufficient safeguards to close current regulatory loopholes. Assess the economic viability and cost-effectiveness of sustainable alternatives to APs.	Research and development efforts should focus on developing advanced recycling technologies specifically tailored for AP. Subsidise businesses where designed solutions address the full life cycle of AP.	
	Other (Agri-business, Corporate, Consultant, Environmental Protection Agency, Plastic Business)	Invest in the development and improvement of waste management infrastructure for AP. Establish comprehensive regulations and policies that specifically address AP pollution. Implement monitoring systems to assess the extent of AP pollution and its impacts. Provide a fair and workable framework within which key stakeholders can develop a workable approach to the management of AP. Facilitate collaborating across value chains and across businesses, authorities, and other relevant organisations. Raise awareness among all stakeholders, to create an understanding for future regulations to reduce the use of non-recyclable plastics in agriculture. Set up legal frameworks that includes the whole lifecycle and fixes by law the extended responsibility of producers of plastics, or of producers that sell products packed in plastic.	Encourage investment in production facilities, infrastructure, and market development for biodegradable alternatives. Support large scale pilots (time and area) of alternative plastic materials to vet their effectiveness with controls - towards implementing at national scales alternatives, with subsidy schemes for implementation and infrastructure development. Develop awareness and behaviour change among farmers. Implement educational programs and training initiatives targeted at farmers, agricultural workers, and extension services. Develop biodegradable or compostable applications, preferably from organic waste streams.	Adopt regulations and financial incentives to promote circularity of AP. Facilitate knowledge sharing and collaboration among researchers, industry stakeholders, and farmers to accelerate the development and adoption of biodegradable alternatives. Entice practitioners towards alternatives development by facilitating new markets creation through customised financial mechanisms depending on existing local practices, crops, socio-economic conditions	

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Author Contribution statement

Conceptualisation: L.N., R.H., C.B., V.E.T, S.B.R, R.H.T., G.C.; Data curation: V.E.T., C.B., L.N., L.V., A.M., E.S., D.B.; Formal analysis: V.E.T., C.B., L.N., L.V., A.M.; Investigation: V.E.T., C.B., L.N., L.V., A.M.; Writing original draft: V.E.T, L.N., C.B, R.H., E.S., D.B., L.V. A.M., Project administration: L.N., V.E.T; Writing – review & editing: All authors.

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Views and opinions reported are those of the authors and the individuals participating in the survey and stakeholder dialogues and do not necessarily reflect those of the European Union, FAO or any of the granting authorities. Neither the European Union nor the granting authorities can be held responsible for them.

Conflict of Interest statement

Authors affiliated with NIVA, Wageningen University, DISSPA, Agricultural University of Athens, East China Normal University and FAO, declare no competing interests.

Author affiliated to the following organisations declare competing interests:

Farm Europe is a Think Tank participated by European farmer organisations.

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APE is a non-profit organisation representing European Agriplastics industries and waste management

They contributed by providing raw data or syntheses of perspectives collected among actors in the sectors they represent as part of section 3 of the paper "Informing policies on AP from a multi-actor perspective". They did not contribute, or edited data, information and writing presented in sections 1, 2, 3.4, 3.5 and 4.

Ethics statements (if appropriate)

The research meets all ethical guidelines.

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