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Review

Employing a systems approach to unravelling the complexities of the agricultural plastics value chain

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ABSTRACT

Agriplastics encompass all plastic materials, components and products used in agriculture. Valued for their versatility and cost-effectiveness, and functionalities related to productivity and weather protection, their widespread use has resulted in considerable plastic waste and pollution, exacerbated by poor handling and mismanagement. Applying systematized evidence mapping and a systems-based approach this study assesses the agriplastics value chain, particularly in crop cultivation, aiming to develop a cutting-edge understanding of both the known and unknown aspects of their sustainability and identify potential interventions. Findings reveal that while agriplastics play a critical role in enhancing agricultural productivity and efficiency, they pose complex sustainability challenges related to their production, use, and end-of-life management. Key issues, such as the accumulation of microplastics and the leaching of harmful chemicals like phthalates into the soil, along with fragmented data on sustainability impacts, inadequate infrastructure, and weak policy frameworks, demand urgent attention. Additionally, the potential for biopolymers to replace petrochemical-based agriplastics remains underexplored from a holistic, multidimensional perspective. Addressing these challenges requires coordinated efforts across the entire agriplastics value chain to promote sustainable agricultural practices and mitigate environmental, economic, and social consequences. While mitigation measures and alternatives are being developed, their uptake has been slow due to low stakeholder engagement and the challenges of moving away from established practices. These gaps delay necessary actions to manage the growing agriplastic waste stream. Further research is urgently needed to better understand the long-term effects of agriplastics use, disposal, and management, and to facilitate the agricultural sector's transition toward more sustainable practices. A central dilemma that emerged from this study is whether agriplastics can be significantly reduced or phased out, given their low cost and crucial role in ensuring food security—a topic that, while not the focus of this study, warrants deeper exploration in future research.

1. Introduction

Modern intensive agriculture practices increasingly rely on the production and use of various plastic materials, components and products, referred to as agriplastics (Pazienza and De Lucia, 2020). Agriplastics are often petrochemical-based polymers (Maraveas, 2020) with high versatility, affordability and other benefits that make them widely used for increased productivity yields and optimised utilisation of resources such as water and fertilizers, protection of yield and the soil from weather events (FAO, 2021). In 2021, 4% of global plastics production and use, was for utilisation in the agriculture, farming and gardening sectors accounting for 390.7 million tonnes (Mt) (PlasticsEurope, 2022), while the latest report from the Food and Agriculture Organization of the United Nations (FAO) noted that the global demand for plastic films used in greenhouses, mulching, and silage is projected to increase by approximately 50% by 2030 (FAO, 2023).

Agriplastics offer substantial benefits in the agricultural sector, with a study highlighting that without their use, 60% of the production of crops and animals would be jeopardised (Le Moine and Ferry, 2018). However, a considerable amount of agriplastics is mismanaged, leading to detrimental effects on the environment, such as soil erosion, reduced water infiltration, and diminished microbial activity (FAO, 2023). Notwithstanding, the wide variety of agriplastics used in the agricultural sector, their management poses a significant threat to environmental and human health (Pazienza and De Lucia, 2020; Rentizelas et al., 2018). According to FAO, agriplastics are capable of causing "*harm … to*

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terrestrial and freshwater ecosystems [that] currently falls far behind that of the marine environment" (FAO, 2021). Efforts to promote circularity in the plastics value chain have led to post-consumer recycled content in new agriplastics produced for utilisation in the agriculture, farming and gardening sectors in the EU market (EU, 2017). In 2021, an estimated 25.4% of agriplastics were made with recycled content (PlasticsEurope, 2022), however, there is a gap in the regulatory framework at the EU level concerning the requirements for an efficient policy practice to tackle agriplastic waste within the circular economy model (PlasticsEurope, 2022).

To date, several research studies have highlighted the detrimental impacts of agriplastics use in the agriculture sector and overall sustainability, making it a significant global concern that is gaining increasing attention from both scientists and society (Lakhiar et al., 2024). Much of the research so far has focused on specific aspects of sustainability, with a major emphasis on environmental dimensions (Briassoulis, 2023; Maraveas, 2020). In addition, some studies examine particular categories of agriplastics, such as mulching or greenhouse covering (Razza et al., 2020; Steinmetz et al., 2016), while others explore their impacts on distinct stages of the value chain, particularly at the end-of-life phase (Batista et al., 2022; Blanco et al., 2018; Castillo-Díaz et al., 2021). However, a holistic view of the sustainability impacts of agriplastics is currently lacking. Given their extensive global use, there is an urgent need to assess agriplastics sustainability from a holistic perspective. This approach will help develop a cutting-edge understanding of what is known and unknown about the sustainability potential of these specialised plastic materials, components and products (collectively referred to as MCPs).

A systems-based approach is critical in addressing plastic pollution in agriculture, an aspect also emphasized by the Global Plastics Treaty. This approach (systems-based) promotes the adoption of integrated waste management practices to prevent and mitigate the multidimensional impacts - spanning environmental, economic, social and technical domains - of agriplastics (Iacovidou et al., 2020). In contrast, piecemeal and unilateral strategies often hinder progress, leading to negative trade-offs and unintended consequences within the system (Iacovidou et al., 2021). Assesing the environmental, economic, social, and technical impacts of agriplastics, collectively referred to as complex value from a systems-based perspective is, thus, essential for unpacking the complexities of plastic pollution, as there is no one-size-fits-all solution to this challenge (Iacovidou et al., 2020, 2021; Richter et al., 2020). Complex value is shaped by various factors, such as climate, geography, culture, and political regimes (Iacovidou et al., 2017; Gregson and Crewe, 2003), which indicates the importance of accountability in (agri) plastics production, use and management, and calls for the adoption of sustainable practices to mitigate environmental and human health harm (FAO, 2023).

Recognizing the tremendous importance of filling this knowledge gap, this study aims to unpack the complexity of the agriplastics value chain, focusing on agriculture crop cultivation, to highlight points of intervention that can enhance the sustainability of the agricultural sector. To achieve this, the study will: i) conceptually assess the sustainability performance of the agriplastics value chain including both petrochemical-based and biodegradable plastics through the lens of environmental, economic, social and technical aspects; ii) identify mitigation strategies to guide the agriculture sector towards a more sustainable and circular economy. To navigate readers of this paper, **Section 2**, presents the methodological approach used for the systematized evidence mapping; **Section 3** presents the Results and Discussion covering the peer-reviewed evidence on the sustainability of agriplastics value chain (**Section 3.1**), the sustainability performance of petrochemical-based and bio-based-biodegradable agriplastics (**Section 3.2**), and mitigation strategies including measures and alternatives (**Section 3.3**). Finally, **Section 4**, sums up the major findings of this evidence mapping and highlights the main concluding remarks.

2. Methodology

This study follows a systematized approach to retrieving evidence, distinguishing itself from a stricter systematic evidence-mapping methodology. It delves into the global scientific literature to provide a structured and comprehensive overview of the existing knowledge on the sustainability of agriplastics. Initially, the research question was articulated using the **PO** (**P**opulations-**O**utcomes) statement, where the *population* refers to agriplastics including both petrochemical-based (i.e., petrochemical-based and non-biodegradable) and biobased, biodegradable plastics, and *outcome* refers to their multidimensional performance including environmental, economic, technical and social aspects, across the entire value chain.

Eligibility criteria were formulated to obtain an accurate framework that addresses the research question, as follows: i) inclusion of studies that examine the performance of agriplastics, either from a holistic perspective or focused on specific sustainability dimensions, specifically within the context of crop cultivation in the agricultural sector; ii) inclusion of studies that tested the performance of agriplastics in any geographical region and scale; iii) inclusion of studies that focused on alternative materials and practices to mitigate the impacts of the agriplastics value chain. The following exclusion criteria were used to screen out studies, that are out of scope for the present analysis: iv) exclusion of studies that assessed the performance of secondary agriplastics, i.e., produced by bio-based agricultural waste without providing their application area (i.e., non-agricultural application); v) exclusion of studies that assessed the performance of agriplastics in agricultural sectors other than crop cultivation, such as livestock farming, fishing and fish farming; and vi) exclusion of studies that assessed the circularity of agriplastics broadly, without focusing on a specific application area.

The second and third steps of our methodological approach involved the development and implementation of the search strategy. The second step was conducted by creating four lists of keywords that included synonyms and related terms to agriplastics (77 keywords), sustainability (25 keywords), and function in agriculture (41 keywords). The selected keywords were chosen based on an analysis of terms frequently used by researchers in related fields, as identified through a preliminary literature search. This initial phase involved reviewing existing studies and publications to identify commonly used keywords, phrases, and terminology relevant to our focus area. Individual keywords of each list were combined with the OR Boolean operator resulting in three long search strings (one for each list), and then connected with the AND Boolean operator. These were applied in bibliographic databases, including Web of Science Advanced Search (WoS) and Scopus. We used the citation reference manager EndNote to create the bibliography list.

The third step included the screening process by reading the titles and abstracts of identified studies followed by full-text reading of studies that were included in the previous stage of screening according to the eligibility criteria. Fig. 1 presents the flow diagram of the number of studies that were identified, screened, and included or excluded at each stage of the review process. In total, 125 studies out of 614 were taken to the full-text reading stage, where 67 studies were found to be eligible and were included in the analysis, leaving out 58 studies. Even though no specific timeline criteria were established, evidence was collected from the years 2000–2023.

Following the eligible studies selection process, data collection was conducted by creating a template (see Supplementary Material, Table S1) that categorized eligible studies according to their aim and objectives, as follows:

- **Type of agriplastic**: e.g., petrochemical-based, biobased-biodegradable, or both.
- **Agriplastic application**: e.g., mulching films, packaging, nets, drainage plastics or generally agriplastics.
- **Stage of the agriplastics value chain**: e.g., design and production (P), use stage, often known as consumption stage (C), and waste

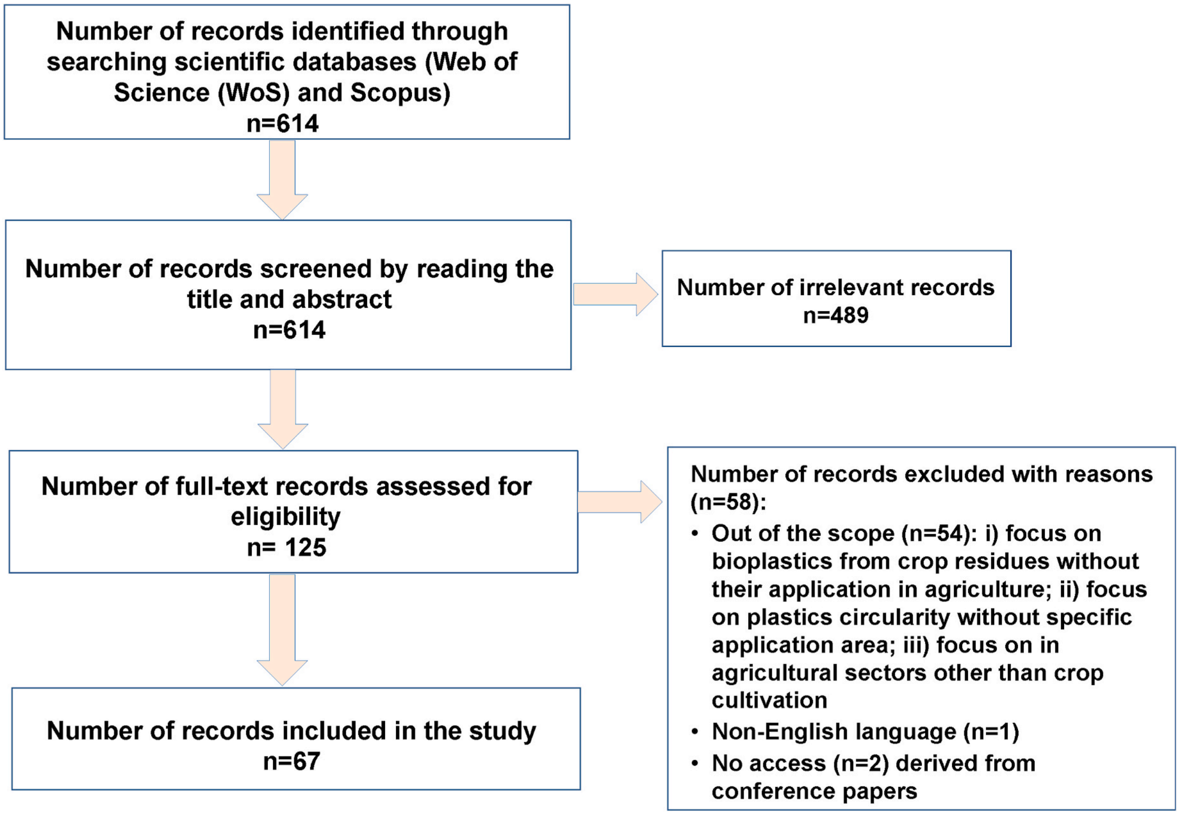

Fig. 1. Flow diagram detailing the results of literature searching on the sustainability performance of agriplastics.

management stage (M), which includes waste generation and waste management, often known as end-of-life (EoL) stage (studies that investigated the entire value chain were signified as P-C-M).

- **Sustainability domain:** e.g., environmental, economic, technical and social.
- **Geographical origin** of the assessment.
- **Methodological approach**: e.g., laboratory and field testing, conceptual analysis, survey, life cycle assessment (LCA) and material flow analysis.
- **Scope**: i) studies that focused on the sustainability performance (SP) of petrochemical-based and/or bio-based biodegradable agriplastics; and ii) studies that focused on mitigation strategies. The studies with the latter scope area are further distinguished into a) studies that looked at mitigation measures (MM) aimed at improving the sustainability performance of agriplastics, i.e., the introduction of new policy measures, innovations from technological or design perspective, or waste valorisation processes; and b) studies that focused on mitigation alternatives (MA) aimed at exploring new materials and practices that can replace the use of both petrochemical-based and bio-based-biodegradable agriplastics, entirely (e.g., replacement of plastic mulching films with organic mulching).

To analyse the studies that focused on the sustainability performance (SP) of petrochemical-based and/or bio-based biodegradable agriplastics we employed the complex value optimization for resource recovery (CVORR) systems-based approach (Iacovidou et al., 2020). CVORR is a step-wise framework designed to synthesise relevant information and conceptualize the complex value across a system (Iacovidou et al., 2020). It has been applied to assess the circularity of plastic packaging systems, in various contexts (Gerassimidou et al., 2022a), and to assess the sustainability performance of resource recovery systems, including compost oversize, food waste, and construction materials (Gerassimidou et al., 2021, 2022b). CVORR's structure offers users the flexibility to either analyse a 'snapshot' of the current status quo through life cycle sustainability evaluations or conduct a deeper evaluation and assessment of current and potential future conditions and interventions (Gerassimidou et al., 2022b). Herein, CVORR was used to develop a cutting-edge understanding of the status quo of agriplastics from a sustainability perspective across all stages of the value chain, from production (P), use (C), and EoL management (M) and depict the pertaining challenges. This systemic perspective provides insights into the whole life cycle of agriplastics, identifies inefficiencies within the system, and highlights intervention points that could promote sustainable circularity in the agricultural sector.

3. Results and Discussion

Globally, the most commonly used polymers in the manufacture of agriplastics are polyolefins, i.e., polyethylene (PE) and polypropylene (PP), and ethylene-vinyl acetate copolymer (EVA) with a lesser use of, polyvinyl chloride (PVC), polycarbonate (PC) and poly-methyl-methacrylate (PMMA) (PlasticsEurope, 2023). In Europe, the most prevalent polymers in the agriculture, farming and gardening sectors are PE (LDPE and LLDPE) and PP, followed by PVC (PlasticsEurope, 2022; Briassoulis et al., 2013). The main categories of agriplastics according to their application area in crop cultivation, are as follows (Pazienza and De Lucia, 2020; De Lucia and Pazienza, 2019):

- **Protected cultivation plastic films,** including mulching, greenhouse, nursery films, direct covering, covering for vineyards/orchards, tunnel, and solarization films.
- **Irrigation and drainage system components,** including water reservoirs, irrigation tapes and pipes, drainage pipes, drippers, and channel linings.

- **Plastic netting,** including wind-break nets, shade nets, nets for harvesting, anti-insect, anti-bird and anti-hail nets, soil stabilization nets, ground cover nets, and tree support nets.
- **Packaging plastic components,** including containers and sacks for pesticides and fertilizers, tanks for liquid storage, hanging baskets, pots, and crates.
- **Plastics for silage storage**, including silage films, fumigation films, bale wraps, nursery pots, twines, strings and ropes.

The vast majority of agriplastic waste consists of films (Briassoulis et al., 2013).

3.1. Approaches and tools used for assessing the sustainability performance

The definitions of circular economy and sustainability in agriplastic studies are extremely limited. For instance, in the study of Perez-Ortega et al. (2021), it is reported that a circular economy is one where *"the change of productive system … [is] framed within the concept "Cradle to Cradle" (C2C) - where the design can and must have a strong role to seek eco-effectiveness by achieving a balance between economy, equity and ecology"* (Perez-Ortega et al., 2021) . Razza et al. (2020) exacerbates the need for *"A new regenerative economic view, based on a balance between economy, environment and society, a total resource efficiency and a Zero Emission Strategy that aims to maximize products value with zero, or minimal, environmental impact* (*Ghisellini* et al., *2016*; Razza et al., 2020). Whilst useful, these definitions are too theoretical, pointing to a lack of concrete, and pragmatic definitions in the sector. This could be construed as an important shortcoming as it prevents joint efforts to promote sustainability in a shared and agreed manner. A detailed overview of the approaches and tools used in the studies included in the analysis for investigating the sustainability of different types and applications of agriplastics across the value chain is given in the Supplementary Material (Table S1).

Out of the 67 eligible studies, 28 focused on laboratory testing of the agriplastics to characterize their technical performance concerning their properties, their impact on productivity, or assessing the efficiency of processes downstream in the value chain. A considerable number of studies (13) carried out field testing, to assess mainly technical aspects with a focus on the contribution of agriplastics to increased crop yields (i.e., productivity) as well as environmental aspects with a focus on microplastic accumulation in soil. It should be noted that among the

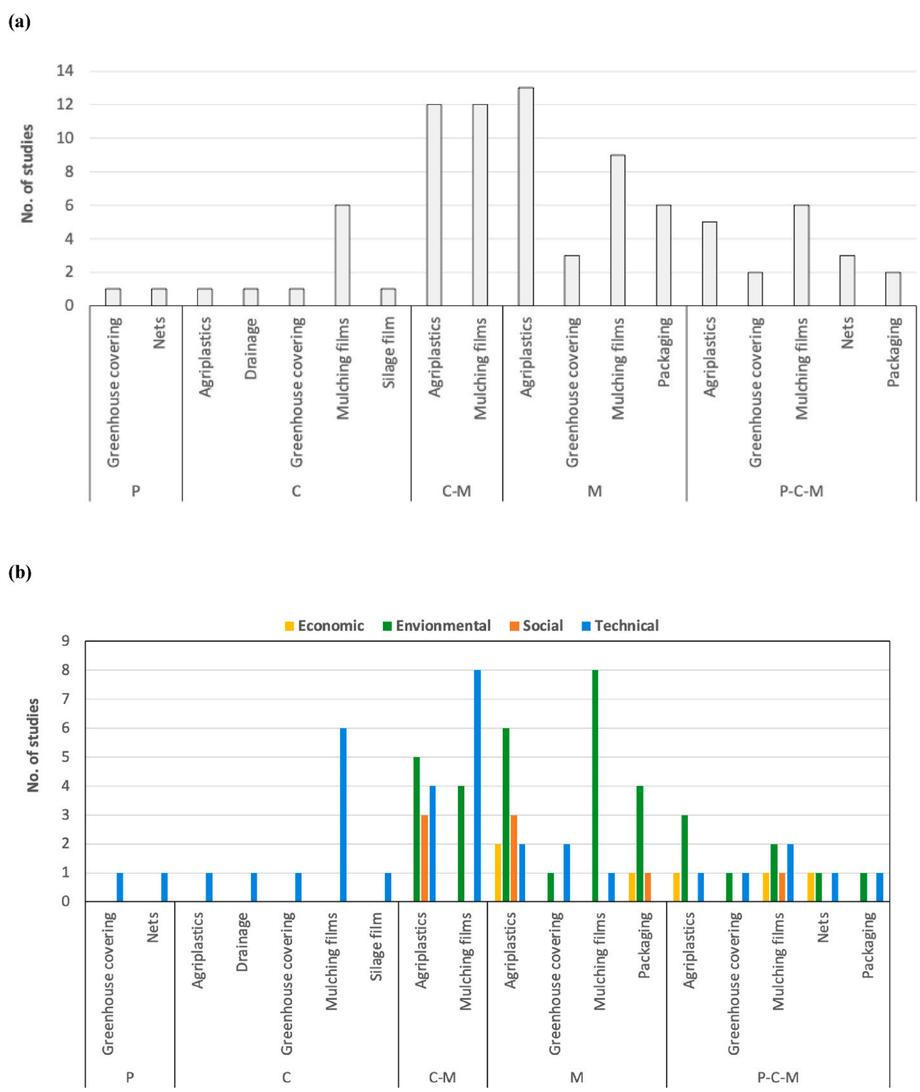

Fig. 2. The number of eligible studies that focused on sustainability across the value chain of agriplastics grouped by the type of agriplastic, stage of value chain, and sustainability aspect including environmental, economic, social and technical. Notes: 1) The stages of the value chain include the stage of production (P), consumption/use (C), and waste management (M), which includes waste collection, sorting and waste processing; 2) *Agriplastics* refer to the generic category of plastic MCPs used in agriculture.

studies there appear to be two distinct areas of focus on the technical domain. Specifically, there is a focus on 1) evidence on the properties of agriplastics and 2) evidence on the effect of agriplastics on crop productivity. The latter dimension is because crop productivity refers mostly to the agronomic performance of agriplastics indicating how well they function in enhancing crop growth and yield. This could be considered relevant to the environmental and social domains since it has a direct and indirect influence on food security. There were limited LCA studies, three in total, while a few review studies used LCA results to describe the environmental impacts of agriplastics either from cradle-to-gate analysis of biopolymers without considering their destined application (Mukherjee et al., 2019) or cradle-to-grave analysis of biopolymers used in the packaging sector (Maraveas, 2020). In addition, qualitative approaches and tools were used in 14 studies, where farmers' attitudes (social), mitigation measures and circularity of agricultural bioplastics were explored. Finally, 13 review studies conducted conceptual assessments focusing on assessing the sustainability of agriplastics either multidimensionally or not across their value chain highlighting challenges, implications and future opportunities.

Fig. 2 (a) depicts the types of agriplastics that have gained increased research attention, and the stage of the value chain these were mostly looked at, whereas Fig. 2 (b), provides granularity on the distribution of studies according to the focus on sustainability domains.

Fig. 2 shows that research attention was mostly placed on mulching films (20 studies in total) followed by the broad category of agriplastics (21 studies in total). The attention to mulching films is attributed to their intensive use in open fields, and thereafter mismanagement or neglect that raised concerns over microplastic accumulation in the soil (due to direct contact of mulching films with the soil). This can be seen by the considerable number of environmental studies (14 in total) mid- (at the stage of consumption/use), and downstream (at the management/EoL stage) in the value chain (i.e., M in Fig. 2). However, the highest number of studies that investigated mulching films focused on the technical domain (17 studies in total), due to the current focus on the technological performance of biodegradable films as alternatives to petrochemical-based ones. Similarly, agriplastics as a generic category were explored mainly from an environmental (14 studies) and technical (8 studies) perspective, while the social and economic aspects have gained less attention.

Additionally, Fig. 2 shows that most studies focused on a specific stage of the value chain with the most prevalent being the stage of consumption/use (C) and Management/EoL (M). Only a few studies investigated the performance of agriplastics across their entire value chain, either from one specific domain or a multidimensional perspective. This highlights that the pervasiveness of holistic assessments, i.e., multidimensional, across the entire agriplastics value chain, remains alarmingly low.

3.2. System analysis of agriplastics: evidence distribution in the value chain

This section provides a reality check on the sustainability performance of the agriplastics value chain including petrochemical-based plastics (**Section 3.2.1**) and bio-based-biodegradable plastics (**Section 3.2.2**), by amassing evidence that unpacks the complexity of the system and identifies gaps and where changes in the system may occur to move towards a more sustainable plastics agriculture sector.

Fig. 3 summarizes key evidence collected from the evidence map, which shows progress on identifying MM (20 studies) to improve the sustainability of the agriplastics value chain and MA (5 studies) to both petrochemical- and biobased-biodegradable plastics considering the sustainability aspect. For example, MA was explored mainly for substituting conventional agriplastics from a technical standpoint, followed by their environmental performance. However, evidence on MA is scarce indicating that it is currently more realistic to improve practices and design characteristics of petrochemical-based agriplastics across the value chain rather than to replace agriplastics with alternative materials and practices that will lead to the prevention of agriplastics use. MM was mostly examined concerning the use of petrochemical-based agriplastics, particularly through the lens of environmental impacts. This is due to addressing challenges related to the EoL stage, indicating that the inefficient management of agriplastic waste is acknowledged as a key barrier towards circularity. Still, most studies (43) focused on investigating the sustainability performance of agriplastics with relatively balanced attention placed between petrochemical-based and bio-based agriplastics. This can be attributed to the current belief that bio-based biodegradable agriplastics can replace petrochemical-based ones, providing a more sustainable future in agriculture, and therefore their performance has been compared particularly from a technical perspective.

3.2.1. Value chain of petrochemical-based plastics in agriculture: challenges and opportunities

Table 1 summarizes evidence on the multidimensional impacts - both

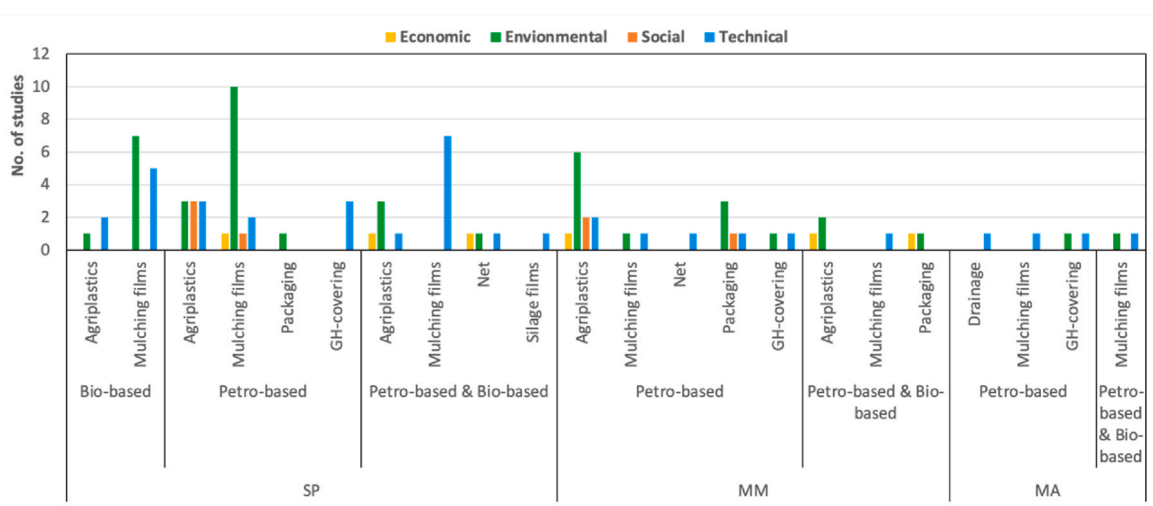

Fig. 3. Number of eligible studies according to their focus area based on current sustainability performance (referred to as *petro-based* or *bio-based*) and mitigation strategies including mitigation measures (MM) or mitigation alternatives (MA) grouped by the type of agriplastic and sustainability aspects including environmental, economic, social and technical. Note: 1. GH-covering refers to greenhouse covering; 2) *Agriplastics* refer to the generic category of plastic MCPs used in agriculture.

Table 1
Multidimensional impact (positive/negative) accrued using petrochemical-based agriplastics across the entire value chain.

Impact	Application	Description of impact	Value chain stage[a]	Sustainability domain	Reference
(+)	Mulching films	Effective soil conservation promoting selective existence and abundance of favorable bacterial and fungi communities for long term planting land	C	Technical, economic and social	Yang et al. (2021)
(+)		Prevention of soil dehydration, erosion and use of pesticides	C	Environmental and technical	(Maraveas, 2020; Mansoor et al., 2022)
(+)		Controlled agriculture conditions (i.e., temperature, soil moisture content, weed growth, nutrient load)	C	Technical and economic	(Maraveas, 2020; Ruíz-Machuca et al., 2015; Steinmetz et al., 2016; Mansoor et al., 2022; Cuello et al., 2015)
(+)		Higher production yield	C	Technical and economic	(Ruíz-Machuca et al., 2015; Steinmetz et al., 2016; Cuello et al., 2015)
(+)		Salinity mitigation	C	Technical	Mansoor et al. (2022)
(−)		Microplastics accumulation in soil through *in situ* degradation due to biogeochemical processes at use stage (C) and/or improper waste disposal practices (burning, burying, or littering) (M).	C-M	Environmental	(Jung et al., 2022; Yuan et al., 2022; Maraveas, 2020; Qi et al., 2020; Briassoulis, 2023; Huang et al., 2020; Li et al., 2022; van Loon et al., 2024; Hurley et al., 2024)
(−)		Leaching of phthalates into soil affecting crop and soil quality.	C-M	Environmental and social	(Qi et al., 2020; Steinmetz et al., 2016; Wang et al., 2016)
(−)		Soil organic matter decomposition leading to increased carbon emissions	C-M	Environmental	Cuello et al. (2015)
(−)		Soil degradation and soil water repellence in the long-term due to pesticide and water runoff enhancement	C-M	Environmental and technical	Wang et al. (2016)
(+)	Nets	Pest management (known as exclusion netting) preventing the use of pesticides for relatively small field sizes.	C	Technical, economic and social	(Mukherjee et al., 2019; Maraveas, 2020)
(+)		Controlled exposure to ultraviolet radiation and extreme weather conditions	C	Technical, economic and social	(Mukherjee et al., 2019; Maraveas, 2020)
(+)		Higher production yield	C	Technical, economic and social	(Mukherjee et al., 2019; Maraveas, 2020)
(−)		Reduced microbial biodiversity	C	Environmental and technical	Maraveas (2020)
(−)	Packaging	Chemical contamination	M	Environmental	(Eras et al., 2017; Picuno et al., 2019, 2020)
(+)	Greenhouse covers/films	Creation of local micro-climate to protect crops from external environmental conditions.	C	Economic and technical	Maraveas (2020)
(−)		Reduced microbial biodiversity	C	Environmental and technical	Maraveas (2020)
(+)	Agriplastics	• Early harvest •Crop yield increase •More effective and efficient land irrigation	C	Technical, economic and social	(De Lucia and Pazienza, 2019; Lakhiar et al., 2024)
(+)		Conservation of agricultural resources such as water and agrochemicals	C	Environmental	(De Lucia and Pazienza, 2019; Lakhiar et al., 2024)
		Food security of international territories	C	Social	Castillo-Díaz et al. (2022)
(−)		Seasonal accumulation of agriplastic waste generation (e.g., greenhouse films used to be collected between August and September)	M	Environmental	(De Lucia and Pazienza, 2019; Pazienza and De Lucia, 2020)
(−)		Difficult to be recycled due to agriplastics formulation (i.e., flexible agriplastics or with low thickness) and high level of cross-contamination	M	Environmental	(Van Tuyll et al., 2022; Steinmetz et al., 2016; Briassoulis, 2023)
(−)		Potential leaching of organic chemicals (e.g., volatile and phthalates) in soil and groundwater contamination during the slow degradation of agriplastics	C-M	Environmental	(Batista et al., 2022; Steinmetz et al., 2016)
(−)		Impede the recovery of minerals/nutrients from non-edible biomass due to the mixture of agriplastics with residual biomass (e.g., crop residues)	M	Environmental and economic	(Van Tuyll et al., 2022; Lakhiar et al., 2024)

[a] The stages of value chain include the stage of production (P), consumption/use (C), waste management (M) including the steps of waste collection, sorting and waste processing.

positive and negative - of petrochemical-based agriplastics throughout their entire value chain. The consensus based on the evidence presented in Table 1, is that the use of petrochemical-based agriplastics is advantageous in increasing crop yield, maintaining controlled agricultural conditions and minimizing the use of agrochemicals, all of which denote important environmental, and economic savings and technical value recovery. Notwithstanding, the implications occurring downstream in the value chain at the handling and EoL management of agriplastics and agriplastic wastes may negate the value accrued by their use up- and mid-stream in the value chain, especially as farmers may not adhere to the prescribed management practices and measures.

As shown in Table 1, one of the major implications of using mulching films is microplastic accumulation in the soil. For instance, as Yuan et al. (2022) suggest, mulching film degradation can release microplastics into the soil, which, in turn, can be absorbed by organisms, posing reproductive toxicity on animals and/or entering the food chain (Yuan et al., 2022). While the association of mulching films – typically composed of various polymers, including polystyrene (PS), PE, PP, polybutylene (PB), and PVC (Yuan et al., 2022) – with microplastic accumulation is widely acknowledged due to the challenges in retrieving these materials after harvesting (FAO, 2023), a significant knowledge gap remains regarding the quantitative relationship between different types of mulching films and microplastic accumulation. Some researchers tested the production of microplastic from PE mulching films and starch-based bio-degradable mulching films (Hurley et al., 2024; van Loon et al., 2024), but still comparative evidence regarding how different types of mulching films and various handling methods influence microplastic accumulation in soil is currently lacking. In addition, literature evidence has shown that the presence of microplastics in the soil is positively related to the use of greenhouse films and irrigation pipes (Gündoğdu et al., 2022).

Microplastic generation mechanisms and their accumulation in the soil, which can affect soil properties (e.g. permeability and water retention (Verma et al., 2024)), soil microbial activity, and therefore soil fauna, having direct implications in the harvest quality and yield (Batista et al., 2022; Yuan et al., 2022; Chand and Suthar, 2024; Verma et al., 2024), is a topic that remains underexplored (Batista et al., 2022; Huang et al., 2020). Nonetheless, the impact of microplastics on soil properties and microbial activity is influenced by various factors, including the type, size, shape, and concentration of microplastics, as well as the characteristics of the soil and surrounding environmental conditions (de Souza Machado et al., 2019). For instance, microplastics can disrupt soil structure by filling pore spaces, which reduces the soil's capacity to retain air and water (de Souza Machado et al., 2019). Additionally, they may affect the decomposition of soil organic matter and alter microbial metabolism, potentially slowing down enzymatic processes and disrupting nutrient cycling (de Souza Machado et al., 2019). Microplastics can change the composition of soil microbial communities by promoting the growth of certain species while inhibiting others (de Souza Machado et al., 2019). Furthermore, microplastics might carry several contaminants and a range of biological communities, when they migrate vertically, which could be exposed to new habitats and present new ecological challenges (Verma et al., 2024). Further research on microplastic properties and how they affect biological activity in food crops (Verma et al., 2024), is urgently needed to fully understand the breadth of these effects.

Amongst other key negative impacts of using mulching films, is the release of phthalates during the degradation of films in the field. Phthalates are endocrine-disrupting chemicals, used as plasticizers in plastics, which have the propensity to be released into soil affecting crop and soil quality and posing a significant risk to human health (Qi et al., 2020; Steinmetz et al., 2016; Wang et al., 2016). Phthalates, due to their loose incorporation in polymers, can easily leach out and be absorbed by plants, potentially contaminating crops for human consumption. They can also accumulate in the soil, reaching concentrations that exceed natural background levels, which pose risks to soil organisms by inhibiting enzyme activities and disrupting essential ecological processes (Steinmetz et al., 2016; Qi et al., 2020). The absorption of phthalates by edible crops poses a potential human health risk through the food chain, as endocrine-disrupting chemicals are toxic substances that may be carcinogenic, mutagenic, or toxic to reproduction (Qi et al., 2020; Wang et al., 2016).

The long-term use of mulching films can also lead to the depletion of soil organic matter stocks due to the induced acceleration of C/N metabolism (Wang et al., 2016). The altered microclimate created by mulching films—characterized by elevated temperatures and increased moisture—enhances the decomposition process leading to microorganisms breaking down organic matter more rapidly, resulting in an expedited cycling of carbon and nitrogen in the soil, referred to as C/N metabolism (Cuello et al., 2015). As organic matter decomposes at a quicker rate, it causes a reduction in soil organic matter stocks since the carbon contained in organic matter is released into the atmosphere as carbon dioxide faster than it can be replenished by new organic matter inputs (Cuello et al., 2015).

Nets and greenhouse covers and films are particularly beneficial in pest management and the creation of suitable micro-climate for production, respectively. Both, are considered effective in protecting crops from exposure to weather conditions and offer controlled conditions for crop yield (Mukherjee et al., 2019; Maraveas, 2020). Nets are widely used in the agriculture sector due to their effectiveness in solarization technique, which entails soil wrapping with plastic films – typically polyethylene – during the hot season and is applied to prevent crops from insects and dehydration. This technique may offer environmental benefits regarding the prevention of pesticide use, still, the significant amounts of waste generated at their EoL stage is a considerable trade-off (Maraveas, 2020). While these are important attributes, both nets and greenhouse cover/films contribute to reduced microbial biodiversity, which is an important trade-off that must be considered when these agriplastics are used for long periods.

A holistic depiction of the challenges and barriers that need to be considered and overcome to improve the sustainability potential of agriplastics across all stages of the value chain is presented in Fig. 4.

Hereafter, is a detailed description of the challenges at each stage of the value chain:

3.2.1.1. Design and production stage (P).

> Challenge 1: The large amount of intentionally added substances used at the production stage, can induce negative impacts across the entire value chain of agriplastics.

A considerable number of phthalates are used in the production of mulching films such as plasticizers to increase their flexibility, durability, and ease of processing. Phthalates pose a significant risk to humans and the environment when they leach at the stage of use and EoL, and therefore their use at the production stage needs to be controlled (Qi et al., 2020; Wang et al., 2016; Steinmetz et al., 2016). Tests on the leaching potential of phthalates from mulching film residues have shown that the higher the presence of residues from mulching films in soil, which might be impacted also by the film colour (e.g., more residues by white films than by black ones), the higher the concentration of phthalates in soil. This correlation was found to be statistically related to lower amounts of nutrients in the soil and reduced microbial activity and diversity (Wang et al., 2016).

> Challenge 2: The way chemical, mechanical and other properties can be modified to support the improved performance of agriplastics is poorly understood.

The durability of agriplastics is specified by material composition (polymer mix) and structure (e.g., multilayer), as well as the presence of intentionally added substances and physical characteristics (e.g., thickness) (Briassoulis, 2023). For example, PA and EVOH used as barrier layers in multilayer greenhouse agricultural films can accelerate their ageing, and hence reduce their lifespan, due to the low ductility of these barrier layers that accelerate the rapid photo-degradation of the barrier layers (Briassoulis et al., 2018). Characteristically, agricultural films often present limited working life, even if considerable amounts of additives are used at the stage of production to prolong their lifetime. This is due to external environmental factors (Picuno, 2014; Maraveas, 2020), that can downgrade agriplastics mechanical strength (e.g., reduced elasticity and elongation at break) and their physio-chemical characteristics (e.g., reduced solar transmissivity and thermal conductivity) (Picuno, 2014). Likewise, the optical properties of shade nets are determined by their colour, which in turn affects a plant's infrared (IR) absorbance and transmittance and heat transfer, e.g., dark-coloured films absorb more solar radiation converting it into heat energy, while light-coloured films reflect more solar radiation. The net's colour suitability depends on the plant type and local weather conditions and therefore there is no standard net colour or shading intensity that is appropriate for plant production (Maraveas, 2020). Moreover, the

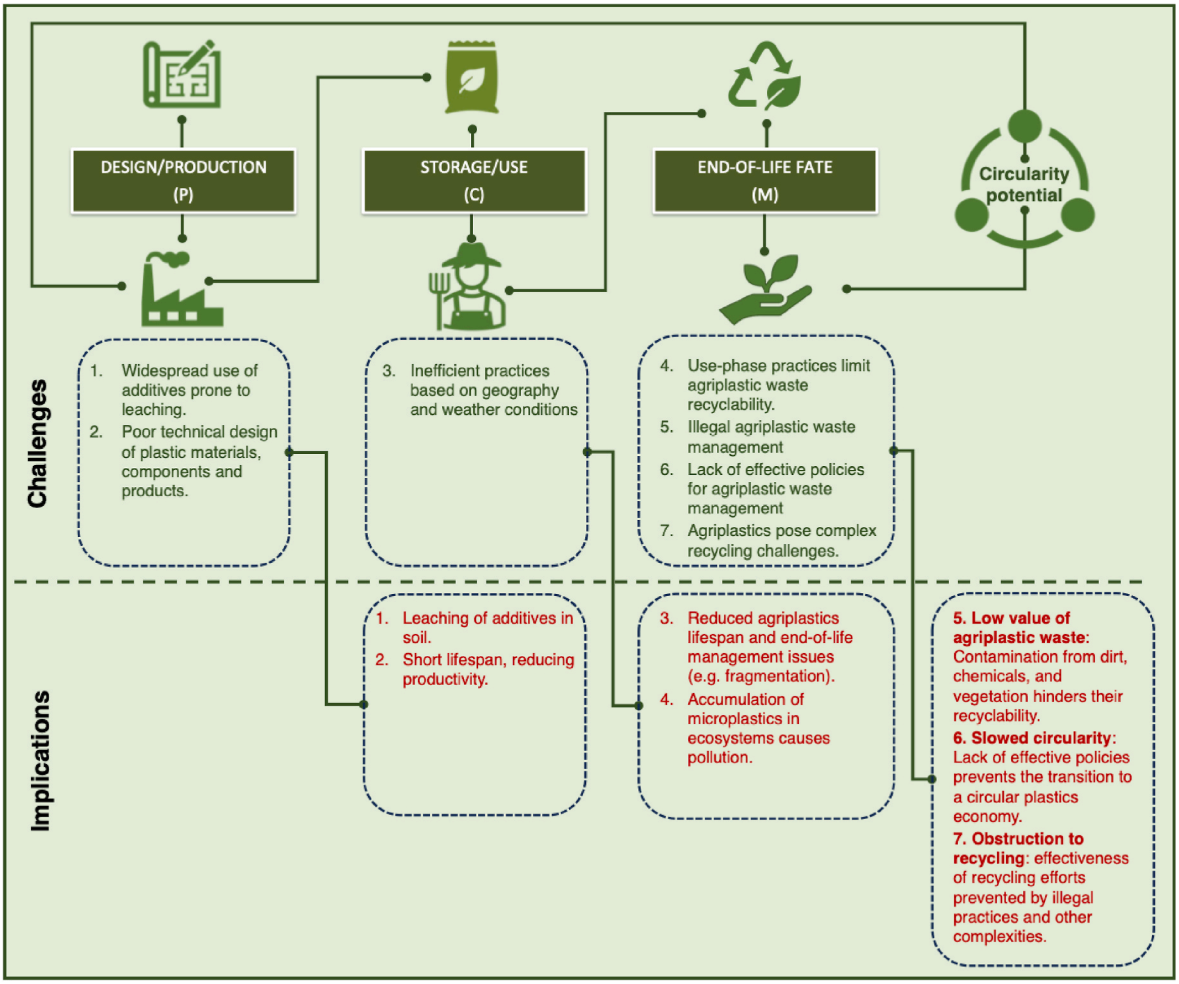

Fig. 4. Overview of the main challenges/barriers across the value chain of petrochemical-based agriplastics as obtained from the eligible studies.

contribution of mulching films to microplastic accumulation in soil could be mitigated by an improved design of mulching films, e.g., by increasing the thickness of the films to become less fragile during handling, respectively (Li et al., 2022).

The above examples point to a challenge that requires industry professionals (e.g., engineers and product designers) in the agriplastic manufacturing sector, to integrate the environmental aspects into the agriplastics design process (Perez-Ortega et al., 2021).

3.2.1.2. Consumption/use stage (C).

Challenge 3: Agricultural practices by geographical area and weather conditions.

At the use stage, the major challenge with agriplastics is the fact that these are necessarily single-use (in the order of several weeks or months) due to high levels of contamination, damage, and degradation (Briassoulis, 2023). In this regard, agricultural practices can either keep agriplastics in use for as long as technically feasible, based on their properties, or they could shorten agriplastics lifetime and EoL behaviour as a result of ineffective practices or insufficient knowledge of the suitability of agriplastics under different weather conditions (Franco et al., 2022). For instance, films left in the field can be degraded over time, leading to microplastic generation and accumulation in the soil (Jung et al., 2022). Moreover, the use and handling of mulching films under different weather conditions can influence their durability. Studies have shown that mulching film durability performance is influenced by temperature (with laboratory tests confirming that agricultural film lifetime is up to two times higher at 40 than at 50 °C (Dehbi et al., 2010)), or when soaked in water (Briassoulis and Giannoulis, 2018); though, it must be noted that the correlation between ageing and exposure time to external conditions is not linear (Dehbi et al., 2010; Picuno, 2014). Additionally, the durability of films can also be negatively affected by their exposure to agrochemicals, especially those containing sulphur and/or chlorine. Barrier layers in films absorb chemicals that can accelerate the effect of the ultraviolet radiation on barrier layers; hence can lead to degradation (Briassoulis et al., 2018).

Further research is needed to assess the rate of agriplastic fragmentation at different environmental conditions (e.g., agricultural practices and soil properties (Kim et al., 2021)) and geographical locations. The chemical, radiometric and mechanical properties of agriplastics should be evaluated when considering their suitability for specific geographical areas (Franco et al., 2022).

3.2.1.3. Management and EoL fate (M).

Challenge 4: The use and exposure of agriplastics to weather conditions, affect their properties in such a way that can lower their mechanical recycling potential.

The marking of end-of-use for agriplastics can often be dictated by their condition (fragmentation, loss of colour) leading to their disposal as agriplastic waste. As noted earlier, the use and exposure to weather conditions (including time of exposure) and geographical area can affect significantly their properties which in turn, can affect their recyclability potential (Picuno, 2014; Tzankova Dintcheva et al., 2001). Moreover, agriplastics that are in contact with the soil during their use, such as mulching films, are highly contaminated resulting in a higher weight of agriplastic waste, ca. 3–4 times compared to the original weight of the agriplastic MCP (Briassoulis, 2023). The high level of contamination by dirt, chemicals, and vegetation makes agriplastic waste less recyclable (Batista et al., 2022; Pazienza and De Lucia, 2020; Picuno et al., 2019; Briassoulis, 2023). Mulching films are considered the most contaminated agriplastic waste type, while greenhouse covering and tunnels are considered less contaminated and could potentially be more recyclable if collected systematically and managed properly (Briassoulis, 2023). At present, incineration with energy recovery and landfilling are the prevalent EoL management options (Batista et al., 2022).

Challenge 5: Illegal agriplastic waste management practices

As the lack of technical knowledge on the way agriplastics properties are influenced by geography and weather isn't by itself limiting efforts to promote circularity in the sector, a considerable amount of agriplastic waste is mismanaged either through burning, burying or littering (Picuno et al., 2019; Briassoulis, 2023). These illegal practices are also related to logistic challenges, such as the limited provision of waste collection services especially in developing countries, where the agriculture sector is the main driver of the economy. Meanwhile, it is difficult to detect geo-locations of waste generation (De Lucia and Pazienza, 2019; Marnasidis et al., 2018). These logistical challenges have emerged from the absence of an efficient regulatory framework.

Challenge 6: Lack of efficient policy instruments and tools for the management of agriplastic waste

Guidelines for the post-use handling and waste management of agriplastics implemented in the field are important to improving the value of agriplastic waste. Although these guidelines do not currently exist at a pan-European level, countries like France and Spain have a post-use scheme for the management of agriplastic packaging waste following the recommendations of the European Crop Protection Association (ECPA) (Picuno et al., 2019). According to the ECPA policy, common practices that can be implemented manually by farmers for the decontamination of containers from agrochemicals (coming from pesticides and fertilisers) are triple-rinsing, pressure rinsing or a combination of them (Picuno et al., 2019), still their decontamination efficiency remains unclear.

Results showed that triple-rinsing is not adequate for the entire removal of chemicals since considerable amounts may persist within the polymeric matrix (Eras et al., 2017; Picuno et al., 2019). The efficiency of triple-rinsing can even be worsened if farmers do not follow the appropriate protocol (e.g., shaking time at least 30s, all inner surface was rinsed, rating or rolling large containers, and addition of clean water at 20–30% of container's capacity) immediately after emptying the containers or if farmers store half-used containers for a long-time (Picuno et al., 2019). In addition, it remains unclear if triple-rinsing enables the treatment of packaging waste as non-hazardous waste. For example, Eras et al. (2017) reported that the remaining amounts of pesticides in packaging waste after triple-rinsing typically did not exceed the legal limits for hazardous substances, as specified by Regulation EC 1272/2008 (<0,1% w/w), while the analytical testing conducted by Picuno et al. (2020) showed that triple-rinsed containers classified as acute toxic within "Category Acute 2″ (Picuno et al., 2020). Still, amounts of pesticides that remain in the polymer may be released during recycling or reuse depending on the pesticide and polymer combinations, e.g., extraction experiments showed that PA or EVOH coating in the inner surface of the agriplastic container can inhibit the diffusion of pesticide into the polymeric matrix, while PET containers could be more appropriate for pendimethalin pesticide compared to HDPE (Eras et al., 2017).

Continuing on the regulatory front, De Lucia and Pazienza (2019), pointed out that only eight EU countries have adopted national regulations on the extended producer responsibility (EPR) schemes for agriplastics, while Scandinavian countries are testing mixed policy tools for their management. Yet, these policy tools have been ineffective towards the reduction of agriplastic waste in the EU, indicating the need to obtain a better understanding of the relationship between policy and practice (at the farm level, including farmers' behaviour) (De Lucia and Pazienza, 2019; Pazienza and De Lucia, 2020). Surveys collecting evidence from more than 1700 farmers in South Italy found that farmers' acceptability of using policy tools varies with the type of agriplastic waste generated (De Lucia and Pazienza, 2019) and farm size (Pazienza and De Lucia, 2020).

However, initiatives aimed at promoting sustainable practices in the agricultural sector, such as the use of a traceability system for identifying improper practices for waste generation may create an additional cost burden for farmers, even with the provision of subsidies by the government (Castillo-Díaz et al., 2022). This is due to high upstream costs (development, installation system, etc.) that are often passed on to the users mid-stream in the value chain (Castillo-Díaz et al., 2022). For example, a case study in Spain showed that under the existing agricultural packaging management system, the use of biodegradable agriplastics, or establishing a traceability system may lead to an increase of greenhouse crop expenses by up to 9.80%, while the current system of subsidies can soften the burden of the cost to 4.03% (Castillo-Díaz et al., 2022).

Regulatory proposals and action plans on the management of agriplastic waste need to consider important variables such as the agricultural system in place, the cultivated area and the irrigation regime to be adjusted to specific needs and consequently favour the circularity of agriplastics in the agriculture sector (Castillo-Díaz et al., 2022). In addition, proposed policy tools, such as subsidies, tax credits and pay-back mechanisms under EPR, need to be properly implemented to ensure the proper management of agriplastic waste across EU member states. This complexity has slowed down the progress of EU strategy implementation for a circular agriplastics economy (De Lucia and Pazienza, 2019; Pazienza and De Lucia, 2020).

To develop new policy tools and adopt sustainable agricultural strategies, it is essential to foster collaborative efforts and interdisciplinary research involving all stakeholders in the value chain, including industry and policymakers. The focus should be on mitigating soil contamination by agriplastics, and promoting user engagement in more circular and sustainable practices (King et al., 2023). Obtaining insights into the economic and perceptual (i.e., consider short-term benefits omitting the long-term implications) incentives (Steinmetz et al., 2016) and the short-term versus the long-term impacts of agriplastics on ecosystem services is crucial (Steinmetz et al., 2016; Li et al., 2022). According to the European Innovation Partnership 'Agricultural Productivity and Sustainability' (EIP-AGRI), reducing the environmental footprint of agriplastics involves several strategies, such as developing policies that encourage innovative alternatives to traditional (agri) plastics, establishing comprehensive good agricultural practices focused on the reduction, reuse, and recycling of plastics, organizing large-scale plastic waste collection, improving recycling practices to handle contamination from soil and organic materials, and fostering collaborative research to address knowledge gaps. These measures will ultimately lead to improved economic and environmental outcomes in agricultural production (EC, 2021).

Challenge 7: Agriplastics are difficult to recycle from a multidimensional perspective

An LCA study showed that the production of recycled LDPE granules from greenhouse covering films exhibits better environmental performance compared to the production of virgin counterparts destined to e.

g., construction and agricultural applications such as pipes in terms of carbon emissions, energy and water consumption (Cascone et al., 2020). However, this is expected with recycled plastics, yet one must account for technical, economic and social aspects to have a holistic view of the sustainability performance.

In this regard, the number of extrusion steps in mechanical recycling may negatively affect the technical performance of secondary agriplastics (Picuno, 2014) since testing results showed that the elongation at break decreased with the extrusion step (Tzankova Dintcheva et al., 2001), while their transmissibility (i.e., optical property – the ability to transmit light) was lower compared to virgin agriplastics due to the use of dyed by-products (Castillo-Díaz et al., 2021). Plastic pellets from reprocessed agriplastics do not meet the quality criteria required by the manufacturing industry of different agriplastics, such as greenhouse films (Castillo-Díaz et al., 2021). Since the properties of secondary agriplastics are worse than those of virgin agriplastics, higher amounts of chemicals are required which can considerably affect the production cost and their environmental performance (Castillo-Díaz et al., 2021).

From the social perspective, factors, including attitudes, norms, behaviours and socio-demographic characteristics, can affect the participation of farmers in more circular waste management practices such as reuse and recycling (Galati et al., 2020; Meng et al., 2015). For example, a survey of strawberry producers operating in an Italian area showed that younger producers who manage smaller farms and have a higher level of education are more willing to participate in agriplastic recycling programs (Galati et al., 2020). Another survey in the USA showed that the higher the number of employees and the level of education in an environmental horticulture firm, the higher the willingness to participate in agriplastics recycling (Meng et al., 2015); both studies indicated that informed and educated farmers constitute a critical factor for moving towards a more circular model (Galati et al., 2020). Nevertheless, realities around the lack of waste collection service, inequitable enforcement of regulations, costs of waste collection, and labour and space limitations act as barriers towards a more circular EoL fate of agriplastics, even when farmers are well-informed (Chen, 2022; Marnasidis et al., 2018; King et al., 2023).

A survey of 430 farmers in Ireland found that farmers are relatively aware of the high amounts of agriplastics waste generation and the negative environmental impacts induced by the illegal management methods, yet, the logistical and monetary burdens currently impede the recycling rate of agriplastics (King et al., 2023). This points to economic lock-ins driven not only by the high logistical and processing costs but also by the high volatility in the price of oil, the low market demand for additives to be developed that can improve the quality of recycled products and the fixed rate of bonuses for using secondary agriplastics that does not suffice to compete the market price of virgin materials (Castillo-Díaz et al., 2022).

3.2.2. Value chain of biobased-biodegradable plastics in agriculture: challenges and opportunities

This section discusses the application of bio-based biodegradable agriplastics from the standpoint of displacing petrochemical-based agriplastics, following the approach taken by the evidence collected from the literature. Of considerable interest, has been the bio-based biodegradable agriplastics that are considered an efficient alternative to petrochemical-based agriplastics, such as bio-HDPE, PLA and PHA, particularly, in agricultural netting in terms of production cost and mechanical properties (Mukherjee et al., 2019). Evidence shows that bio-based biodegradable agriplastics may offer similar benefits to petrochemical-based agriplastics in terms of controlling agricultural conditions (Rai et al., 2021; Serrano-Ruiz et al., 2021), e.g., regulating soil moisture and temperature, enabling drip irrigation and fertigation, limiting weed and insect infestation (Maraveas, 2020) and effective soil solarization (Di Mola et al., 2021).

The sustainability performance of bio-based biodegradable agriplastics against petrochemical-based agriplastics is still under-researched. The value proposition of bio-based biodegradable agriplastics is related to the renewable nature of their feedstock (i.e., biomass). However, requirements, such as land occupation (referring to 1st generation of bio-based plastics), their actual carbon neutrality over their carbon emissions from several activities across their value chain such as transportation, additional materials and production process, and consideration of other environmental impact categories apart from carbon emissions, muddle their environmental performance (Mukherjee et al., 2019; Qi et al., 2020). Whilst some studies suggest that the biobased-biodegradable agriplastics offer a similar technical performance to petrochemical-based ones (Caetano et al., 2023; Merino et al., 2021; Stroe et al., 2021; Di Mola et al., 2021; Kapanen et al., 2008; Setti et al., 2020), others claim that bio-based-biodegradable agriplastics have a relatively low resistance to UV photooxidation especially in tropical and/or arid regions where solar radiation is intense (Maraveas, 2020). Yet, the effect of biodegradability on tensile strength, and optical and radiometric properties has not been adequately tested (Maraveas, 2020).

Here, are insights collected from the systematic evidence mapping:

3.2.2.1. Design and production stage (P) and consumption/use stage (C). Several studies examined bio-based biodegradable agriplastics production and application as a substitute for petrochemical-based agriplastics (21 studies in total). Table 2 provides a summary of the studies that tested the technical performance of bio-based biodegradable agriplastics, and their results indicated their potential successful implementation. Table 2 shows that there is a variable performance of bio-based biodegradable films in terms of durability and biodegradability in different testing scenarios. This is due to differences in both environmental conditions, such as weathering, microbial diversity, moisture and pH in soil, and polymer characteristics, such as content of additives, crystallinity, functional groups and molar mass (Mansoor et al., 2022; Maraveas, 2020). For example, agricultural weathering can affect differently the physiochemical properties of biodegradable mulching films depending on their polymeric composition, e.g., a mulch film composed of PLA/PHA is more susceptible to degradation than PBAT mulch films in warmer locations, due to lower crystalline morphological regions and lower molecular weight of polymer molecules of the former mulch film (Anunciado et al., 2021).

As Table 2 shows all studies focused on agricultural films, particularly in mulching films, indicating a perceived imperative need to replace petrochemical-based mulching films with bio-based and biodegradable. Still, their variability regarding technological performance constitutes a limiting factor for the wider adoption of bio-based biodegradable agriplastics. Moreover, the production and use of biocomposites (Pagliarini et al., 2023; Merino et al., 2021) or biopolymer mixtures (Caetano et al., 2023; Mansoor et al., 2022) in the agriculture sector is included as a substitute for petrochemical-based agriplastics, yet it presents many challenges when it comes to the leachability potential of additives at the use stage and their biodegradability potential at the EoL stage, with the former receiving no attention up to date. This underlines the need for biobased-biodegradable and biocomposite solutions to be tested according to the field requirements (Mukherjee et al., 2019; Maraveas, 2020).

3.2.2.2. Management and EoL fate (M). Regarding the EoL fate of bio-based biodegradable agriplastics, several studies in Table 2 show that biodegradable mulching films may provide fast biodegradation in soil, still these findings are based on laboratory testing. The biodegradation of these materials needs to be tested under real testing conditions in the open environment providing a realistic evaluation of their sustainability performance from technical (e.g., durability and plant growth conditions), environmental (e.g., complete biodegradation or not) and economic aspects (e.g., period of its operational use) (Stroe et al., 2021; Serrano-Ruiz et al., 2021). Evidence supports that biodegradable films

Table 2
Production and use of bio-based biodegradable agriplastics as substitutes to petrochemical-based agriplastics (incl. comparative analyses).

Design and Production (P)	Consumption/Use (C)	Innovation/achievement	Reference
Proteins extracted from black soldier fly (BSF) are used as bio converters, to produce BSF-mulching film and BSF-mulching film mixed with LDPE film (50–50 wt%)	Single BSF films LDPE-BSF films	Technical performance: (−) Single BSF films: need to reduce its biodegradability in water and thickness (−) LDPE-BSF films: better performance than single BSF films; need to reduce its thickness and increase tensile strength Environmental performance: (+) Bio-based content (50–100%) through the valorisation of organic residues (+) Biodegradability potential of single BSF films (−) Controversial biodegradability of LDPE-BSF film	(Barbi et al., 2021; Setti et al., 2020)
Commercially available biodegradable corn-starch-based film	Replacement of: - Petrochemical-based silage films, with - Corn starch-based films	(−) Corn-starch films provided similar oxygen barrier characteristics to petrochemical-based film for the first three months, after that it started to biodegrade indicating it is not suitable for long-term silage conservation.	Tabacco et al. (2020)
Nan-compartmentalized films synthesized by the single emulsion–solvent evaporation technique that combines nanoparticles blends from PBAT and PLA containing an active compound (Neem oil)	Nano-compartmentalized biodegradable films in agriculture	(+) Environmental performance: natural biodegradability of films (+) Economic performance: low-cost production process (+) Technical performance: sufficient mechanical, barrier and optical properties of films	Caetano et al. (2023)
Mulching films produced by particulate composites containing PBSA and up to 30 wt% of coffee silver skin through melt compounding at high temperature applied in lettuce crop	Mulching films composed of biocomposites from PBSA and coffee silver skin	(+) Technical performance: coffee silver skin acted as plant growth promoter due to release of endogenous bacteria in soil. (+) Economic performance: reduced cost of production due to addition of coffee silver skin (+) Environmental performance: Decrease of polymeric materials in mulching products; Valorisation of coffee waste; and natural biodegradability	Pagliarini et al. (2023)
Mulching films produced by biocomposites from orange peels and spinach through hydrolysis in a weak acid medium	Mulching films composed of biocomposites from plant-derived natural polymers	Technical performance: (+) good mechanical and optical properties promoting soil fertilisation (−) very fast biodegradation in soil (21 days)	Merino et al. (2021)
Mulching film manufactured from 100% PLA fibres with different lengths and bonded together through a thermic treatment, was tested on soil burial biodegradation behaviour	Mulching films composed of non-woven PLA fibres	(+) Technical performance: relatively sufficient properties - it can be used for at least two cultivation cycles (from March to November) (+) Environmental performance: complete degradation in the soil	Stroe et al. (2021)

may increase microbial activity during their biodegradation in soil due to the release of nutrients and reaction products that can feed the soil microbial population (Sartore et al., 2018; Setti et al., 2020; Castillo-Díaz et al., 2021; Pagliarini et al., 2023; Merino et al., 2021; Stroe et al., 2021; Álvarez-Castillo et al., 2021) providing an opportunity for farmers to self-mage their agriplastic waste by incorporating them into the soil directly (Castillo-Díaz et al., 2021; Marín-Guirao et al., 2022; Stroe et al., 2021; Bandopadhyay et al., 2018). However, it is recognized that more research is needed to assess the long-term impacts of biodegradable film incorporation into soil on plant nutritional quality (Sartore et al., 2018; Serrano-Ruiz et al., 2021; Kapanen et al., 2008) and soil properties (Sartore et al., 2018; Yang et al., 2021; Setti et al., 2020; Bandopadhyay et al., 2018; Serrano-Ruiz et al., 2021). So far, the accumulation of micro and nanoplastics from biodegradable films in agricultural soils as well as the presence of additives in these films considering the safety aspect have passed unnoticed (Serrano-Ruiz et al., 2021).

3.3. Mitigation strategies: measures and alternatives

The need for promoting sustainability in the agriculture sector is gaining precedence (Pazienza and De Lucia, 2020). To achieve this, numerous mitigation strategies have been proposed through cooperation by governments, policy-makers and other stakeholders (King et al., 2023; EIP-AGRI, 2021), who need to acknowledge the complex value of agriplastics in the system as a whole (Marín-Guirao et al., 2022). These strategies are discussed from a two-fold view: mitigation measures (MM), aiming to improve the sustainability potential of the agriplastics value chain (**Section 3.3.1**); and mitigation alternatives (MA), aiming to break free from the excessive agriplastic usage (**Section 3.3.2**).

3.3.1. MM: mitigation measures

Table 3 presents some key MM that could enable a sustainable agriplastics value chain if combined properly considering regional specificities (Batista et al., 2022). The core mitigation measures presented in Table 3 refer to 1) *policy* including the formulation of effective policy measures able to prevent improper waste disposal/management methods and reduce waste generation (Qi et al., 2020), 2) *innovation* able to identify the flows across the system and introduce more sustainable agriplastics (referred to *technological* innovation), as well as the adoption of eco-design strategies and practices in modern agriculture (referred to *design* innovation) (Galati et al., 2020; Qi et al., 2020), and 3) *valorisation* including the introduction of technologically advanced waste management options. Specifically, chemical recycling processes through more advanced techniques assisted by catalysts could be more suitable for the recycling of heterogeneous and contaminated agriplastic waste streams indicating the need for further research (Huang et al., 2022). Table 3 indicates that the EoL fate of agriplastics requires more attention, while individual and collective initiatives are needed (Le Moine and Ferry, 2018).

3.3.2. MA: mitigation alternatives

Table 4 presents alternative materials practices that could potentially be able to replace both petrochemical-based agriplastics. Current findings are not very encouraging, i.e., there is a limited number of alternatives with relatively inefficient performance, indicating that agriplastics have wider and substantially effective application potential in most cases. For example, the use of ridge-furrow with plastic mulching proved to promote better microbial diversity to facilitate maize growth compared to straw mulching or bare soil indicating that the use of plastic mulching is a superior soil conservation approach compared to no-plastic alternatives in terms of crop productivity (Yang

Table 3
Mitigation measures across the value chain of agriplastics as obtained from the eligible studies.

MM category	Description	Sustainability benefits	Ref.
Valorisation	Transformation of contaminated agriplastic waste (i.e., dirty sheeting PS plastics to cover crops) into activated carbons (ACs) by activation with $K2CO_3$	**Environmental benefits:** efficient use of ACs for the removal of four pesticides; potential to be reused; application in effluent treatments on a large scale; added-value product, waste diversion from landfills – extending to **economic** and **social** benefits	Batista et al. (2022)
Innovation (technological)	Traceability through mapping agricultural lands (e.g., satellite images and GIS) for monitoring quantities and typologies of agriplastic waste generation	**Environmental benefits:** localisation of areas with intensive waste generation; better decision-making for collection and transportation systems of agriplastic waste; better implementation of action plans for waste management facilities	Blanco et al. (2018)
Policy	Traceability of agriplastic waste generation through documentation (e.g., contracts, identification documents, and/or record-keeping documents, compulsory operating logbook)	**Socio-economic benefits:** Identification of waste producers who carry out improper (or illegal) practices	Castillo-Díaz et al. (2021)
Policy	Establishment of ad hoc policy mechanisms for waste management (e.g., subsidies, tax-credits, and pay-back mechanism under EPR) based on farms' features (e.g., size and type of activities)	**Social benefits:** increased behaviour change; transformation of policy tools into effective practices **Environmental benefits:** efficient waste management improving the circularity potential of agriplastics;	(De Lucia and Pazienza, 2019; Pazienza and De Lucia, 2020)
Innovation (technological)	Use of information technology through a mobile app that allows the identification of farmers who dispose waste aiming to develop a financial incentive system	encouragement of agriplastics recycling – extending to **economic** and **social** benefits **Technical benefits:** increased traceability of disposal requirements and associated activities - fostering **economic** and **environmental** improvements	Castillo-Díaz et al. (2021)
Policy	Regulatory reformulations: increased subsidies for use of biodegradable agriplastics and bonuses for recycled agriplastics under a fixed rate system	**Environmental benefits:** increased recycling rates; increased use of recycled and biodegradable agriplastics in agriculture sector	Castillo-Díaz et al. (2022)
Innovation (design)	Combining the use of plastic covering films on raised beds with improved agronomic practices, i.e., a combination of crop residue mulch and plastic film cover with no tillage for rice production	**Technical benefits:** increased productivity yields; soil organic matter and available nitrogen in soil **Environmental benefits:** reduced use and waste generation of petrochemical-based agriplastics; valorisation of crop residues	Lv et al. (2019)
Innovation (technological and design)	Design of nets with enhanced functionalities for pest exclusion applications through two technological developments: i) manufacturing of finer fibres and mesh configuration that improves the ventilation rates; ii) using radiation absorbing additives at specific wavelengths that interfere with the orientation of the insect's light receptors	**Technical benefits of (i):** improved ventilation rates of nets, but lower mechanical durability. **Technical benefits of (ii):** effective but nets should be applied with caution to avoid excessive shading.	Giannoulis et al. (2021)
Innovation (design)	Eco-design strategies in the agriplastic packaging sector: combination of CAD/CAE tools with LCA for the redesign and development of containers for fruit and vegetable distribution in Spain	**Environmental benefits:** better performance for specific LCA impact categories (i.e., carbon emissions, atmospheric acidification and water eutrophication); reduced mass of raw materials and minimisation of superfluous components by 70% without compromising mechanical/structural resistance (optimum relationship between continent and content); 17.6% lighter improving the weight of load in transport and distribution; higher number of reuse times; 100% recycling vs a combination of recycling, incineration and landfilling – extending to **economic benefits**. **Technical benefits:** in line with other manufacturers (modularity); rounded geometries and simpler shapes (ergonomics); higher strength/weight ratio; higher shelf life; 17.6% lighter - extending to **social benefits**, with emphasis on occupational health.	Perez-Ortega et al. (2021)
Valorisation	Valorisation of petrochemical-based plastic mulching films through CO2-assisted catalytic pyrolysis using nickel catalyst (5 wt% Ni/SiO_2)	**Environmental benefits:** production of value-added products (syngas and hydrocarbons); prevention of landfilling; prevention of accumulation of microplastics in soil emerging from improper waste disposal practices	Jung et al. (2022)
Valorisation	Application of pyrolysis in agricultural waste under the design of an optimal supply network to produce commercial products in Scotland	**Environmental benefits:** diversion from landfill; production of added-value products **Economic benefits:** energy source for agricultural facilities increasing farmers' income	Rentizelas et al. (2018)
Valorisation	Co-pyrolysis of wine manure with plastic mulching films	**Environmental benefits:** concurrent management of two waste streams; production of value-added products; energy source that can be used for local operations; use of manure without dewatering pre-treatment – with **economic** (operational cost) improvements	Ro et al. (2014)
Innovation (technological)	Production of recycled plastic granules from covering films for agricultural applications such as pipes and films	**Environmental benefits:** reduced use of primary feedstock; support of local administrators to achieve circular economy goals; mitigation of agriplastic waste exports	Cascone et al. (2020)
Policy	Introducing information campaigns for farmers Construction of consortium structures (e.g., a network of local municipal authorities, cooperative farmer organizations and agricultural supplies stores (Marnasidis et al., 2018)) in agricultural areas where agriplastic waste can be collected and potentially reprocessed in the field.	**Environmental benefits:** circular waste management practices; creation of an effective waste management network (Marnasidis et al., 2018) – with **economic** (logistical) improvements **Social benefits:** prevention of improper waste management practices; increased behaviour change	Galati et al. (2020) (Galati et al., 2020; Marnasidis et al., 2018; Lakhiar et al., 2024)

(*continued on next page*)

Table 3 (*continued*)

MM category	Description	Sustainability benefits	Ref.
Innovation (technological)	Modelling the technical performance of agriplastics considering regional external conditions and chemical formulation	**Technical benefits:** increased lifetime; optimised correlation of chemical addition with technical performance; improved control of feedstock quality at recycling stage (i.e., use of model indicators to evaluate the ageing of post-consume agriplastics) – extending to **environmental** and **economic** benefits	Picuno (2014)
Innovation (technological and design)	The construction of a greenhouse covering an area of 60 m^2 from recycled composite plastic rods made by mixing discarded fishing nets and car bumpers is feasible.	**Environmental benefits:** use of recycled plastics in agriculture sector; EoL fate of plastics within circular economy – extending to **economic** and **social** benefits	Yang et al. (2022)

et al., 2021).

Implementing the above-mentioned strategies (Tables 3 and 4) may entail significant barriers in developing countries and/or small-scale farmers due to financial constraints and insufficient infrastructure that often limit access to new technologies. Additionally, the lack of education and training can prevent farmers from effectively adopting innovative solutions, while policy challenges, such as inadequate regulatory support and market access, further complicate efforts to transition to sustainable practices. Furthermore, cultural resistance to change and the limited availability of alternative materials can hinder progress. Overcoming these obstacles will require targeted interventions that combine education, financial assistance, and supportive policies to foster sustainability in agriculture.

Another important aspect that needs consideration in future research is smart agriculture, which encompasses a suite of technologies that aim to establish a more efficient, sustainable, and responsive food production system that integrates precision crop cultivation techniques, data-driven decision-making, and automation with elements like robotics, artificial intelligence, and blockchain for holistic resource management (Sharma et al., 2022). This can enhance targeted application practices through systems optimised for accuracy, ensuring consistent implementation while promoting more efficient resource use (Piya, 2024), including agriplastics. By leveraging data-driven insights, smart technologies can optimise agricultural operations, reduce input costs, and contribute to a safer, more reliable food supply through continuous monitoring of crop health and the use of technology for effective disease detection (Sharma et al., 2022). Moreover, this will empower farmers to make informed decisions regarding crop management, resource allocation, and market opportunities by providing access to real-time data and advanced analytical tools (Sharma et al., 2022). However, existing challenges in the adoption of smart agricultural practices, such as the collection and processing of datasets in real-time environments, along with issues related to internet connectivity, security, cost, and high computational demands, must be addressed. Despite its potential, the application of smart agricultural practices in enhancing the sustainability of the agriplastics value chain has not yet received much research attention.

4. Conclusions

This paper sheds light on the complex value of agriplastics from a sustainability perspective, underlining their benefits while highlighting the challenges associated with their production, use and end-of-life (EoL) management. Several blind spots in the current agriplastics system need further investigation to fully understand the long-term implications of their use, disposal and (mis)management. A central dilemma arises from this study's systematized evidence mapping and systemic analysis: Can agriplastics be effectively reduced or eliminated from agricultural systems, given their multiple functions at low cost, and undeniable contributions to food security? While this question was not the primary focus of the study, it deserves deeper exploration, as evidence consistently shows that agriplastics play a crucial role in enhancing crop yields and water efficiency, thereby boosting agricultural productivity, while bio-based, biodegradable agriplastics alternatives, often exhibit inferior quality and functionality. Meanwhile, the costs associated with the management of agriplastic waste, particularly through recycling, present additional challenges. A forced transition to agriplastics alternatives could create unintended consequences while it could raise costs, impacting food prices and security over time. Therefore, sustainability efforts must avoid coming in conflict with the core principles of sustainable development. Additional key findings reveal that:

- Agriplastics pose significant environmental and societal risks, such as microplastic accumulation and the leaching of phthalates into the soil, which require urgent attention. Addressing these challenges demands a coordinated effort across the entire agriplastics value chain to promote long-term sustainable agricultural practices and minimise adverse environmental impacts, with repercussions extending to the economic and social domains.
- Current evidence on the sustainability of agriplastics is limited and fragmented, primarily due to inadequate data and the absence of infrastructures, training, education systems and efficient policy instruments. This has resulted in widespread mismanagement of agriplastic waste, exacerbating sustainability challenges. Despite the focus on EoL management, it remains the least addressed in terms of interventions, delaying progress in managing an ever-growing waste stream with far-reaching consequences. The reliance on polymer-based LCA without context-specific considerations further limits a comprehensive understanding of multidimensional impacts as it offers a partial view of agriplastics sustainability.
- The potential of biopolymers as alternatives to petrochemical-based agriplastics remains underexplored from a holistic and multidimensional perspective, spanning feedstock acquisition, production, use and EoL. Further research is needed to evaluate their mechanical properties and durability, EoL implications, and production costs. Most innovations are still at the laboratory stage, with low technology readiness and limited market availability. These challenges need to be urgently addressed before the provision of subsidies to encourage the use of bio(agri)plastics.
- The success or failure of policies designed to address agriplastic waste is often determined by factors such as infrastructure, economic incentives, availability of alternatives, and compliance mechanisms. Effective implementations often involve supportive measures and stakeholder engagement, while failures reflect the complexities of transitioning away from established practices. Intervention strategies are urgently needed to mitigate agriplastic waste and support a shift toward sustainable practices.

These findings emphasise the importance of adopting a holistic approach that addresses the sustainability challenges of agriplastics across the entire value chain, ensuring that agricultural productivity is balanced with long-term sustainability goals. To address the identified challenges and promote sustainable agriculture practices, future research should focus on:

Table 4
Mitigation alternatives to agriplastics use as obtained from eligible studies.

Material	Description	Innovation/achievement	Ref.
Waste almond shell	Waste almond shell as hydroponic growing media for lettuce production compared to the use of recycled plastic drainage plank and perlite as control	(−) Lower production yields under by 52% in almond shells due to the shell's high salinity and 72% in plastic planks due to impeded root growth and low water-holding capacity. (+) Under minor alterations, almond shells could be used as a sustainable growing media alternative to perlite	Kennard et al. (2020)
Protein hydrolysates from residues of leather industry and natural fillers	Replacement of LDPE mulching films with hydrolysed protein-based biodegradable mulching coatings by the means of spray technique	**Technical benefits:** same agronomic performance (i.e., rate of plant growth and dry matter accumulation); release of nutrients during the decomposition of mulching coatings **Environmental benefits:** valorisation of waste residues from leather industry; no waste generation; biodegradability potential of hydrolysed protein-based coating (<5% of its initial weight after 2 months after tillage) – extending to **economic benefits**	Sartore et al. (2018)
Antireflective-glass and ethylene tetrafluoroethylene (ETFE) films	Replacement of polycarbonate rooftop greenhouse urban agriculture with these alternative covering materials for tomato crops	**Technical benefits:** increased solar energy gains (up to 21%); higher lifetime tomato productivity (up to 41%) – extending to **environmental** and **economic benefits** **Environmental benefits:** lower impact in 7 out of the 8 impact categories in a range of 24–29% per m^2 per year or in a range of 34–42% per kg of tomato	Munoz-Liesa et al. (2022)
Barley straw	Replacement of petrochemical-based PE mulching in Mediterranean greenhouse for organic tomato crop	**Technical benefits:** similar performance to the PE film **Environmental benefits:** prevention of agriplastics waste generation and disposal **Economic benefits:** reduced cost for waste management of mulches	Marín-Guirao et al. (2022).
Compost	Replacement of petrochemical mulching films with organic mulches from animal or plant residues	**Pros (+) and Cons (−) across all domains:** (+) promotes organic recycling; (+) affordable; (+) commercially available; (+) potential increase of organic content in soil and crop yield; (−) phytotoxicity risk due to high nitrogen content; (−) promotes pests and disease-causing organisms; (−) potential soil pollution depending on its content (e.g., heavy metals and microplastics)	Mansoor et al. (2022)
Straw and husk		**Pros (+) and Cons (−) across all domains:** (+) long life span; (+) suitable for vegetable cultivation during the winter; (+) affordable; (+) commercially available; (+) effective in soil moisture preservation; (+) potential to increase crop yield; (−) soil contamination by weed seeds; (−) attract harbour pests	
Sawdust		**Pros (+) and Cons (−) across the economic and technical domains:** (+) suitable for acid loving plants cultivation; (+) commercially available; (+) effective in soil moisture preservation; (+) prevention of soil erosion; (−) ineffective is controlling weed growth; (−) hardens over time and does not allow water to seep into the soil; (−) consumption of soil nitrogen during its decomposition due to its low nitrogen content	
Grass clippings		**Pros (+) and Cons (−) across all domains:** (+) effective control of weed growth; (+) affordable; (+) commercially available; (−) development of root systems that compete with plant for nutrients; (−) careful selection of the layer thickness, i.e., thicker prevents air penetration resulting in rotten and odorous clippings, more thin layers results in fast decomposition; (−) contribution to soil temperature increase affecting the plant growth especially in warm climates	
Paper		**Pros (+) and Cons (−) on the environmental and technical domains:** (+) natural biodegradation; (+) promotes circularity of papers such as newspaper with black in; (−) impractical due to rips and tear apart during application; (−) unsuitable for long-term cultivation due to its fast biodegradation	
Wood/bark chips		**Pros (+) and Cons (−) on the technical domain:** (+) effective in soil moisture preservation; (+) effective in soil aeration; (+) contribution to organic content in soil; (−) reduce soil pH causing phytotoxicity and therefore suitable for crops that need an acidic pH for growth; (−) release of phenolic acids during its degradation leading to soil acidification	
Glass	Replacement of plastic mulching films by non-plastic synthetic mulches	**Pros (+) and Cons (−) across the environmental and technical domains:** (+) aesthetically appealing; (+) promotes glass recycling; (−) low efficiency in controlling weed growth; (−) disruption of soil physico-chemical characteristics affecting plant growth; (−) prevention of sunlight penetration into soil affecting soil moisture	Mansoor et al. (2022)
Rubber		**Pros (+) and Cons (−) across the environmental and technical domains:** (+) promotes rubber recycling; (−) hazard of fire; (−) low efficiency in controlling weed growth; (−) high amounts of zinc release in soil promoting zinc toxicity in plants	

- Conducting comprehensive sustainability assessment studies that take contextual factors into account to better understand the multi-dimensional impacts of agriplastics.
- Investigating the technological advancements necessary for the successful market adoption of biopolymers, ensuring they meet the mechanical and durability requirements of agricultural applications.
- Exploring viable alternatives to both petrochemical-based and biobased-biodegradable agriplastics and assessing their overall sustainability performance.
- Implementing long-term field studies to better understand the implications of agriplastics, addressing identified blind spots, and assessing trade-offs between food security and sustainability.
- Quantifying the economic trade-offs associated with agriplastics recycling versus alternative solutions to understand their effects on food prices and broader sustainability initiatives in agriculture.

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CRediT authorship contribution statement

Spyridoula Gerassimidou: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eleni Iacovidou:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization, Formal analysis, Visualisation

Declaration of competing interest

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Data availability

Data will be made available on request.

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