Food and Agriculture
Organization of the
United Nations

BIOECONOMY

ENVIRONMENT
AND NATURAL
RESOURCES
MANAGEMENT

State of research on the impacts of plastic pollution on soil health and crops

WORKING
PAPER
111

ISSN 2226-6062

ENVIRONMENT
AND NATURAL
RESOURCES
MANAGEMENT

WORKING
PAPER

111

State of research on the impacts of plastic pollution on soil health and crops

AUTHORS

Luca Nizzetto
Norwegian Institute for Water Research (NIVA)

Rachel Hurley
Norwegian Institute for Water Research (NIVA)

France Collard
Norwegian Institute for Water Research (NIVA)

Richard H. Thompson
International Marine Litter Research Unit, University of Plymouth

and

Giulia Carcasci
Food and Agriculture Organization of the United Nations, Rome

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO)

Rome, 2025

Required citation:
Nizzetto, L., Hurley, R., Collard, F., Thompson, R.H. & Carcasci, G. 2025. *State of research on the impacts of plastic pollution on soil health and crops*. Environment and Natural Resources Management Working Paper, No. 111. Rome, FAO.
https://doi.org/10.4060/cd6407en

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

ISSN 2226-6062 [Print]

ISSN 2664-6137 [Online]

ISBN 978-92-5-139996-5

© FAO, 2025

Some rights reserved. This work is made available under the Creative Commons Attribution- 4.0 International licence (CC BY 4.0: https://creativecommons.org/licenses/by/4.0/legalcode.en).

Under the terms of this licence, this work may be copied, redistributed and adapted, provided that the work is appropriately cited. In any use of this work, there should be no suggestion that FAO endorses any specific organization, products or services. The use of the FAO logo is not permitted. If a translation or adaptation of this work is created, it must include the following disclaimer along with the required citation: "This translation [or adaptation] was not created by the Food and Agriculture Organization of the United Nations (FAO). FAO is not responsible for the content or accuracy of this translation [or adaptation]. The original [Language] edition shall be the authoritative edition."

Any dispute arising under this licence that cannot be settled amicably shall be referred to arbitration in accordance with the Arbitration Rules of the United Nations Commission on International Trade Law (UNCITRAL). The parties shall be bound by any arbitration award rendered as a result of such arbitration as the final adjudication of such a dispute.

Third-party materials. This Creative Commons licence CC BY 4.0 does not apply to non-FAO copyright materials included in this publication. Users wishing to reuse material from this work that is attributed to a third party, such as tables, figures or images, are responsible for determining whether permission is needed for that reuse and for obtaining permission from the copyright holder. The risk of claims resulting from infringement of any third-party-owned component in the work rests solely with the user.

FAO photographs. FAO photographs that may appear in this work are not subject to the above-mentioned Creative Commons licence. Queries for the use of any FAO photographs should be submitted to: photo-library@fao.org.

Sales, rights and licensing. FAO information products are available on the FAO website (www.fao.org/publications) and print copies can be purchased through the distributors listed there. For general enquiries about FAO publications please contact: publications@fao.org. Queries regarding rights and licensing of publications should be submitted to: copyright@fao.org.

Contents

Table and figures

FIGURES

TABLE

Acknowledgements

This publication was prepared by Luca Nizzetto (Norwegian Institute for Water Research, and RECETOX, Research Centre for Toxic Compounds in the Environment, Masaryk University); Rachel Hurley, France Collard (Norwegian Institute for Water Research), Richard H. Thompson (Thompson Environmental Consulting Ltd), and Giulia Carcasci, Food and Agriculture Organization of the United Nations (FAO).

This publication was made possible by the valuable contributions of many people from a variety of backgrounds, from both within and outside FAO. The authors sincerely thank Sergejus Ustinov, Marta Arnés García, Carmen Bullón Caro, Alexandre Meybeck, and Huimin Zhang (FAO); Defu He (School of Ecological and Environmental Sciences, East China Normal University); Marie-France Dignac (French National Institute for Agriculture, Food and the Environment (INRAE)); Richard C. Thompson (International Marine Litter Research Unit, University of Plymouth); and Joe Yates (Agriculture, Nutrition & Health Academy, London School of Hygiene & Tropical Medicine).

The report was prepared under the overall leadership of Kaveh Zahedi, Director, FAO Office of Climate Change, Biodiversity and Environment (OCB), and with the guidance of Lev Neretin, Environment Team Leader, OCB.

Abbreviations

CIDAPA	Ibero-American Committee for the Development and Application of Plastics in Agriculture
EU	European Union
FAO	Food and Agriculture Organization of the United Nations

Plastics and chemicals used in their formulation

HDPE	high density polyethylene
LDPE	low density polyethylene
PAEs	Phthalic acid esters
PBAT	polybutylene adipate-co-terephthalate
PBSA	poly(butylene succinate-co-adipate)
PFAS	perfluoroalkyl and polyfluoroalkyl substances
PLA	polylactic acid
PPC	polypropylene carbonate

Executive summary

An estimated 13.4 million tonnes of agricultural plastics are used annually, but comprehensive data on agricultural plastics remains limited.

A systematic review of peer-reviewed scientific articles documenting the presence of plastic residues or microplastics in soils that have been exposed to various types of agricultural plastics confirms that these plastics are a source of pollution in soils. There is evidence of residues or microplastics in soils that have similar physical and chemical characteristics of the agricultural plastics used in fields. Several important uncertainties remain about the extent to which agricultural plastics represent the dominant source of pollution, and the processes that lead to plastic pollution in the soil.

Data indicate that plastic concentrations in soils range from 0.000001 percent to 0.3 percent depending on the type of agricultural plastics and the location. Mulching films, greenhouse systems, and encapsulated fertilizers are known contributors, but the degree of pollution from these sources varies significantly across studies. The lack of standardized methodologies and inconsistent reporting makes it difficult to fully quantify the extent of soil plastic pollution. This situation underscores the need for improved data collection and analysis in this area.

Soil plastic pollution is unlikely to be fully reversible. Some processes (e.g. degradation or the export of plastic through erosion and runoff) may reduce the amount of plastic in soils. However, these processes are generally slow and incomplete, especially for conventional plastics. Microplastics and smaller particles can persist in soils for long periods, and current remediation methods are impractical or too costly at scale. Biodegradable plastics may offer some potential for reversibility, but their in-field degradation rates vary significantly. Overall, once microplastics enter soils, they are likely to accumulate, making complete reversibility challenging. As it ages, plastic in the soil can release the chemicals used in its formulation. There is emerging evidence that plastic-intensive practices may result in increased concentrations of common plastic additives in soil.

Current scientific evidence indicates that plastic pollution in soils is likely to change the physical, chemical, and microbiological properties of the soil. These changes can occur at levels of plastic concentrations that can realistically be expected to be found in the environment (e.g. below 0.05 percent of plastic in the soil). These changes can occur regardless of the type of plastic, the size and shape of the particles, and their origin.

Plastic pollution in soils, even at realistic exposure levels, can lead to significant changes in essential soil properties, affecting the physical structure of the soil, the pH balance, and microbial activity. Studies show that low concentrations of plastic (as minimal as 0.001 percent) in the soil can have an impact on water retention, nutrient cycling, and microbial diversity, all of which affects soil fertility and plant health.

Soil plastic pollution negatively impacts plant health and crop production, even at low, environmentally plausible concentrations. Many studies have documented that plastic particles in soil can inhibit plant growth, alter nutrient uptake, disrupt microbial communities, and increase the bioavailability of heavy metals and other toxic substances. These effects have been observed across a range of exposure levels and study types, from pot and mesocosm experiments to field studies, with significant impacts on crop yield, quality, and food safety.

Current plastic contamination in agricultural soils may already exceed safe thresholds for soil health and plant growth. Over half of studied soils showed concerning levels that may cause effects. This pollution is complex and involves diverse particle types from various sources.

Plastics and plastic-associated chemicals can be transferred from soil to crops, which can potentially have an impact on food safety. Studies confirm that plants can absorb nano- and microplastics, as well as chemicals used in the formulation of these materials, primarily through their roots. Some evidence exists that these substances can be translocated to the edible parts of the plant, but technical challenges limit the analysis for nanoplastics. These findings highlight concerns for both plant health and food safety.

Biodegradable plastics are not necessarily a safer alternative to conventional plastics for agricultural use. They may reduce plastic pollution under certain conditions, but studies show that biodegradable plastic debris can still have an impact soil health and plant growth. These impacts can be observed at levels as low as 0.02 percent of plastic in the soil. Concerns about incomplete degradation, the accumulation of microplastics, the release of chemical additives and their effects on soil and plants indicate that biodegradable plastics require careful management. A precautionary approach that includes more rigorous assessments of long-term effects and realistic exposure scenarios is essential to ensure these materials do not pose an uncontrolled risk for soil and crops.

There are still important knowledge gaps. Global and regional inventories are incomplete. Little is known about the hotspots of agricultural plastic usage and waste management practices. Also, there is limited understanding of the specific emission rates and quantitative contributions agricultural plastics make to soil pollution. Nevertheless, substantial evidence demonstrates that agricultural plastic pollution poses significant risks to soil health, food security, and human health. Agricultural soils now contain substantially higher concentrations of microplastics than marine environments, with accumulation rates increasing over time. Applying the precautionary principle alongside this growing evidence base, policy development is both justified and essential to address the demonstrated risks of plastic pollution in agricultural systems, even while research continues to fill remaining knowledge gaps. Significant developments to improve the design and applications of agricultural plastics are underway, and substantial progress has been made in assessing these efforts through environmental sciences and ecological risk assessment frameworks. Comprehensive global assessments like the 2021 FAO report, *Assessment of agricultural plastics and their sustainability: a call for action*, and major research initiatives, such as the European Union's MINAGRIS project, have provided substantial quantitative data on risks posed by plastic pollution to soil health, fertility, and crop quality. However, knowledge gaps remain regarding the long-term ecosystem impacts, and assessment methodologies are not standardized. Research has documented the uptake of plastic additives by crops and established safety thresholds for biodegradable agricultural plastics, but continued monitoring and research are needed to fully characterize emerging risks and develop comprehensive management strategies.

The priority actions that are recommended in this report to overcome these knowledge gaps will support the design and implementation of policies that can be effective in reducing plastic pollution in soils resulting from the use of agricultural plastics.

© FAO/Giorgio Cosulich

Chapter 1. Introduction

1.1 BACKGROUND AND SCOPE

In 2021, FAO published the first global assessment of plastic use in agriculture: *Assessment of agricultural plastics and their sustainability: a call for action* (FAO, 2021). The report estimated that in 2019, 12.5 million tonnes of plastic products were used in agriculture. Below are the figures for different agriculture subsectors:

- 10.2 million tonnes in crop and livestock production;
- 2.1 million tonnes in fisheries and aquaculture; and
- 0.2 million tonnes in forestry.

The report also noted that only a small fraction of the plastic waste generated from agricultural plastics was recycled. Although record keeping is almost non-existent, it was determined that most of this plastic waste was or burned, buried or landfilled. The FAO report highlighted that a significant portion of the plastic used in agriculture ends up as pollution in soil and water owing to poor design, mismanagement, and lack of adequate end of life management. This plastic pollution poses risks to the environment, human health, biodiversity, food security and food safety.

The FAO report acknowledged that there were significant gaps in knowledge about agricultural plastics and their overall impact. However, the report stressed that the precautionary principle should be followed, which means that action should be taken to prevent harm to human health and the environment even in the absence of full scientific certainty. The report also issued a global call to action to investigate and address the impacts of plastic usage and their alternatives. It also proposed a number of recommendations, including the development of an international voluntary code of conduct, to improve the sustainability of the use of plastic in agriculture.

The objective of this report is to compile and present the available scientific data on the impacts of plastic and microplastic pollution from the use of agricultural plastics on soil health and crop production. It also highlights key findings related to the sustainability of alternative materials, such as biodegradable and bio-based agricultural plastics, and identifies the main knowledge gaps in these areas. By providing an overview of the risks associated with the current use and management of agricultural plastics, as well as the specific issue of plastic pollution in soil, this report contributes to the broader discussion on the sustainability of food systems.

1.2 WHAT ARE AGRICULTURAL PLASTICS?

Plastic is playing an increasing role in terrestrial agriculture. Its use can allow for more efficient and reliable production and create new market opportunities for agricultural producers. The three largest and most rapidly expanding types of agricultural plastics are:

- films for greenhouses and tunnel systems;
- films for covering the soil (mulching); and
- materials used for fodder production (e.g. silage films).

Other types of agricultural plastics include:

- geotextiles;[1]
- irrigation and drainage pipes;
- protection and collection nets, bags, sacks and crates for agricultural products;
- trays and pots for seedlings and plants;
- twines, tags and clips for plants and animals;
- guards and shelters for tree saplings; and
- containers for pesticides and fertilizers (Briassoulis, 2023).

The use of a range of newer polymer-based products is also becoming more widespread in agriculture. These include polymeric micro-encapsulations for slow-release pesticides and fertilizers, seed coatings, and hydrogels to enhance soil water retention.

BIODEGRADABLE PLASTICS

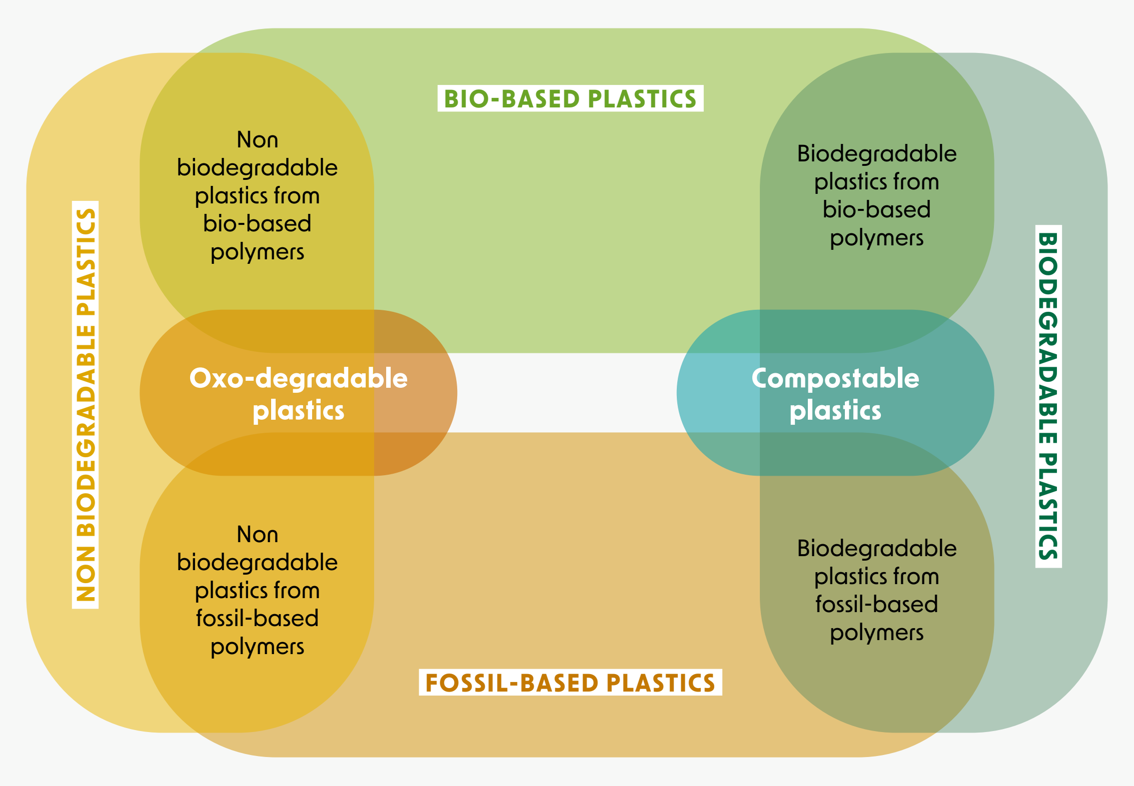
Alternatives to conventional, durable fossil-based plastics include a broad range of materials that share similar mechanical properties but can degrade more quickly in environmental conditions or be processed to complete degradation in composting facilities. These materials can be collectively referred to as 'biodegradable plastics'. Biodegradable and compostable plastics are mainly used for mulching film, plant clips, and seed coatings, and in slow-release pesticides and fertilizers.

These plastics vary greatly in their composition, source materials, and degradability, and there is no generally accepted global standard for their labelling and certification. Consequently, it is important to clarify some key terminology and properties of these materials. Figure 1 illustrates the relationship between different types of biodegradable and non-biodegradable plastic materials. The classification and terminology is consistent with that provided in technical reports (Vert *et al.*, 2012; European Commission Directorate-General for Research and Innovation, 2020) and recommended by the Scientists' Coalition for an Effective Plastic Treaty (Scientists' Coalition for an Effective Plastic Treaty, 2024).

---

[1] Geotextiles are durable, permeable synthetic fabrics used in agriculture to stabilize soil, control erosion, and suppress weeds.

FIGURE 1. **Classification of plastic materials based on their degradability and source of feedstock**



Source: **FAO.** 2021. Assessment of agricultural plastics and their sustainability: A call for action. FAO. https://doi.org/10.4060/cb7856en

- **Bio-based plastics**
  These plastics are composed of or derived, in whole or in part, from renewable, biological feedstocks, including plant/forestry, animal, and marine biomasses. They are not necessarily biodegradable or compostable, as this depends on the chemical structure of the polymers and the types of chemical additives included in the formulation (in green in Figure 1) (Vert *et al.*, 2012).
- **Biodegradable plastics**
  These plastics may or may not be bio-based plastics. They often are formulated from feedstocks from renewable biological sources. However, they can also be entirely made from fossil carbon sources. These plastics are intended to biodegrade more rapidly than conventional plastics under certain conditions and in specific environments, mainly through biological processes (European Commission Directorate-General for Research and Innovation. 2021). Biodegradable plastics specifically designed for degradation in soil are used in agricultural applications, especially for the production of mulching films (Nizzetto *et al.*, 2024).
- **Compostable plastics**
  These plastics are a subset of biodegradable plastics. They can also be made of renewable or fossil feedstocks. However, they require specific composting conditions to degrade effectively, which are typically met in industrial composting facilities. Some compostable plastics are intended to be 'home compostable', but most need to be collected and transferred to appropriate industrial composting facilities (European Commission, n.d).

- **Oxo-degradable plastics**
  Some conventional non-biodegradable plastics can be designed to degrade rapidly in the environment. This is achieved with chemical additives that favour photooxidative and thermal degradation processes. This degradation process is of a physical nature and does not depend on biological processes. This process quickly produces large numbers of micro and nanoplastics that may persist for a long time in the recipient environments. Oxo-degradable plastic cannot be assimilated to biodegradable plastic and is generally not included under the term 'bioplastics', unless the product contains renewable feedstocks.

Because of the complexity and variability of these materials, the term 'bioplastic' lacks specificity and overlooks fundamental differences in their functionality and properties. The term is sometimes not used consistently, which leads to confusion (Aubin *et al.*, 2022). Also, although some jurisdictions have introduced standards for compostable and biodegradable in-soil plastics, the labelling and certification of these materials are often insufficient to guarantee their correct use. Similarly, there is insufficient clarity and controls on the claims that are made about their degradation performance in operational environments.

1.3 BENEFITS OF AGRICULTURAL PLASTICS

Agricultural plastics provide multiple benefits for crop and livestock production and forestry. They can increase yields and at the same time reduce the amount of inputs needed for production. For example, irrigation that uses plastic can reduce the amount of water used for crops and increase the efficiency of water use. By protecting crops from pests, agricultural plastics can reduce the need to apply chemical pesticides that can leach into soil and water. Agricultural plastic can also make agricultural production more reliable by controlling soil temperatures and protecting crops from adverse weather conditions. Producers have used agricultural plastics to become less dependent on climate and geographic conditions and grow valuable crops in a broader range of environments. Because of these benefits, agricultural plastics have been promoted as a way of adapting to some of the negative impacts of climate change and reducing the release of agrochemicals into the environment.

Plastic materials used in irrigation and protected cultivation systems have been on the market for several decades, and the international market for agricultural plastics has expanded considerably over the years. Between 2018-2023, the annual growth rate ranged between 3 percent and 6 percent for the period (FAO, 2021; Data Intelligence, 2023). Agricultural plastics are now used globally, but they were first adopted in China and member countries of the Organisation for Economic Co-operation and Development (OECD), where their use remains most widespread. The market, however, is projected to expand significantly in low and lower-middle income countries.

1.4 THE THREAT OF PLASTIC POLLUTION

Although agricultural plastics can deliver benefits to agricultural producers, there is an emerging awareness that the use of agricultural plastics and their mismanagement are sources of pollution that poses risks to terrestrial and aquatic ecosystems (Ng *et al.*, 2018; Qi *et al.*, 2020a). This pollution could negatively affect soil fertility and plant growth, which would in turn threaten food production, farmers' livelihoods and food security and nutrition (Iqbal *et al.*, 2020; Zhou *et al.*, 2021).

Plastic debris may directly disturb soil structures and organisms. There is also a concern about the large amounts of chemical substances used in the formulation of plastics. In some plastic materials, these chemicals can make up to 60 percent of the total mass (Viljouen *et al.*, 2023). Thousands of different chemical substances are used as plastic additives, and some of these substances have recognized toxic properties (Gou *et al.*, 2012; Net *et al.*, 2015; Zimmerman *et al.*, 2020).

Agricultural plastics are not the only source of plastic pollution in agricultural soils. However, a growing body of research has shown that agricultural plastics that have been damaged, degraded, discarded or inappropriately used, and the intentional release of polymer-coated agrochemicals have contaminated soils and water bodies in many parts of the world struggling to achieve the United Nations' Sustainable Development Goals (SDGs(Viljoen *et al.*, 2023; Gou *et al.*, 2012). The use of agricultural plastics also generates large volumes of waste that is distributed across the broader rural landscape (Briassoulis *et al.*, 2013; Scarascia-Mugnozza, Sica and Russo, 2011). Waste management is a serious challenge for agricultural plastics, especially in areas where there is a lack of capacity in waste collection and processing. This challenge is compounded by the fact that many agricultural plastics are difficult to recycle because of the wide variety of polymers and additives they contain.

Most countries lack specific regulatory frameworks for the use of agricultural plastics and the management of the waste they generate. This situation increases the risks that the use of agricultural plastics will have negative impacts on the environment and agriculture. With the rapid growth in the use of plastics in the agricultural sector, the need for regulatory frameworks becomes even more urgent.

Several knowledge gaps still need to be addressed to ensure that policies and regulatory frameworks for the use of agricultural plastics can be effective in promoting sustainability. These gaps are related to:

- the impact of macro-, micro-, and nanoplastic pollution and associated chemicals on soil health, water quality, and biodiversity;
- the potential transfer of microplastics to plants and animals;
- the implications for food safety and human health; and
- the effectiveness and the economic viability of sustainable options (e.g. biodegradable plastics, alternative materials, and alternative practices), as well as the willingness of agricultural producers to adopt these options.

Many of the sustainability issues associated with plastics are common across all agricultural sub-sectors (crops, livestock, forestry, fisheries, and aquaculture). Plastic pollution in marine environments and sustainability issues associated with plastics used in fisheries have been subject to more studies and are better understood than those related to terrestrial agriculture. Consequently, this report focuses on scientific findings related to the sustainability of plastics and their alternatives in terrestrial agricultural production (crop and livestock production, and forestry). The scope of this report does not extend to the plastic used in the post-production stages of the agricultural value chain (e.g. packaging used in transport and retailing).

1.5 METHODOLOGY

This report presents the results of a series of systematic literature reviews that focused on several aspects of soil plastic pollution. The reviews considered the use of agricultural plastics, the occurrence of plastic pollution in soils resulting from the use of agricultural plastics, and the effects of plastic pollution on soil ecosystems. The outcomes of the reviews were used to provide an analysis of the current state of the available scientific knowledge on these areas and identify research gaps.

The reviews comprised the screening of 2 283 scientific papers in English published in international peer-reviewed journals indexed by Web of Science, with no geographic regions excluded. The report considered original research papers and excluded re-analyses of review papers (about 30 percent of the total). In total, 505 studies met the inclusion and quality criteria, which included an assessment of the quality of the described methodology and the reporting of results. The analysis was limited to papers published during the last 10 years, with topic-specific cut-off dates detailed in Table A1 . Over 80 percent of all the studies were published three years before the publication of this report. A detailed description of the review methodology, including the Boolean search strings and the criteria for eligibility and exclusion, is presented in Appendix 1.

1.6 STRUCTURE OF THE REPORT

Chapter 2 presents the results of the systematic review of the state of knowledge on the sources and occurrence of plastic pollution in agricultural soils resulting from the use of agricultural plastics and other sources, and the impacts of this pollution on soil health and crops. It also looks at the potential reversibility of soil plastic pollution, and its potential effects on plant health and crop yields. The chapter also considers whether current plastic levels in soils fall below the levels used in controlled studies to produce significant effects; the potential transfer of plastic debris or chemicals to crops and food; and the safety of biodegradable plastics for use in agriculture.

Chapter 3 presents a synopsis of persistent knowledge gaps on the ecological and agricultural risks posed by plastic pollution in soils. This list is drawn from a meta-analysis of the scientific works analysed by the systematic literature review. Priority measures to address these knowledge gaps are proposed, and their implications for policy are considered.

Chapter 2. The impact of plastic pollution from agricultural plastics on soil health and fertility

2.1 HOW MUCH PLASTIC IS USED IN TERRESTRIAL AGRICULTURE?

The 2021 FAO report, *Assessment of agricultural plastics and their sustainability: a call for action*, estimated that 10.2 million tonnes of agricultural plastics are used every year for crops and livestock, globally (FAO, 2021). This assessment was largely based on data from Europe and scaled up, in first approximation, to derive global estimates.

Data from the European agricultural plastic industry, which were last updated in 2019 were instrumental for drawing up FAO regional and global estimates (APE Europe, 2024). These data have not yet been updated, and data from other regions are still lacking. Since the publication of the 2021 FAO report, there has been little substantial progress towards improved national inventories of agricultural plastics and the waste they generate. Consequently, the data provided by the 2021 FAO report remain the most reasonable reference.

If a five percent yearly expansion (Le Moine, 2018) is applied since 2019, it can be assumed that about 13.4 million tonnes of agricultural plastics are currently used every year in terrestrial agriculture, with agricultural films accounting for about 40 percent of this total.

Data on the geographical distribution of agricultural plastics usage and waste generation are essential to estimate the sources of plastic pollution and identify potential hotspot sources from the sector. These data are also instrumental to plan waste management infrastructures, such as collection points and recycling locations, which are key measures to prevent mismanagement and other practices that can result in pollution (Morsink-Georgali *et al.*, 2021). In the regional breakdown, data from African countries, Australia and United States are largely missing.

Asia

Asia is the largest consumer of agricultural plastics in the terrestrial farming sector, accounting for perhaps over 60 percent of the global total (FAO, 2021). Unfortunately, data for plastic use in farming in China and Asian countries are fragmentary and mostly unavailable. Given the lack of an accurate assessment of temporal trends in Asia, the updated global figure of 13.4 million tonnes of plastic use in terrestrial agriculture is likely an underestimate.

China, where plastic films are extensively used in farming, is believed to be among the largest consumer of agricultural films. It is estimated that 2.6 million tonnes of agricultural films were used in 2021. There has been a historical average annual increase rate of 6 percent (Yang *et al.*, 2023a). Over half of these films are used for soil mulching applications (Xiong *et al.*, 2019). In some parts of the country, their mismanagement has resulted in serious and extensive soil contamination. To reduce pollution, China is adopting a measure to increase of thickness of agricultural films, which will make them more resistant to embrittlement. This measure could lead to a dramatic increase (possibly more than 30 to 50 percent) in the tonnage of plastic used throughout the country and could potentially rapidly increase the total regional and global inventory of agricultural plastics. However, a more comprehensive and up-to-date inventory for other types of agricultural plastics in China is currently not available or accessible. A similar lack of accessible data applies to the rest of the world.

Europe

The first comprehensive effort to estimate agricultural plastic inventories in Europe was carried out in 2013 (Briassoulis *et al.*, 2013). Country-level estimates of usage and waste generation were calculated for major agricultural plastic products in 27 European Union (EU) countries and the United Kingdom. The estimates included plastic films, irrigation and drainage pipes, nets, and agrochemical containers. The estimated total was between three and four million tonnes. These estimates, which were produced less than a decade earlier, are more than twice as high as the data provided by the European agricultural plastic industry, which were used to extrapolate global estimates in the 2021 FAO report. The variability between different sources of data or estimation methodologies can stem from a range of factors. The estimates calculated in research studies combine data on cultivated lands by crop type with information on typical production systems in each country.

More holistic approaches to produce updated estimates of agricultural plastic that are not visible from aerial photos utilize a combination of modelling of agricultural practices, land cover data, multistakeholder surveys and interviews and validation through aerial observations. Through the effort of international research initiatives such as the PAPILLONS project[2] and the MINAGRIS project,[3] which seeks to understand the harmful impacts of plastic debris on soil biodiversity, functions, ecosystem services, agricultural productivity, and socio-economic outcomes at the farm level, the use of agricultural plastics and waste generation inventories are being prepared with a subnational level resolution. To date, however, only partial results are available from three studies (Blanco *et al.*, 2018; Hachem *et al.*, 2024; Hachem, Vox and Convertino, 2023).

The PAPILLONS project has produced estimates of the amount of agricultural waste generated annually in Greece, Italy, Portugal and Spain. Together, these four countries have produced 1.8 million tonnes. Films for covering, mulching or low-tunnel applications accounted for nearly 300 000 tonnes (Hachem *et al.*, 2024).

---

[2] PAPILLONS website: www.papillons-h2020.eu

[3] MINAGRIS website: https://minagris.eu/about/

By the mid of 2025, a complete map of agricultural plastics usage from the EU is expected. Greece, Italy, Portugal and Spain alone represent about half of the total European estimates from 2013 (Briassoulis *et al.*, 2013). The use of agricultural plastics in Europe varies significantly from country to country. Southern countries are the largest users. The new estimates also include additional agricultural plastics products (e.g. clips) that were not accounted for in previous assessments. However, despite small variations in estimation methods, the updated figures align with previous assessments, with an expansion in use occurred during the past decade.

The Americas

Using a similar methodology, a 2021 report estimated that in Canada the total annual use of agricultural plastic is about 61 700 tonnes, with low density polyethylene (LDPE) bale tubes and wraps representing the most abundant item (15 000 tonnes) (Cleanfarms, 2021).

The Ibero-American Committee for the Development and Application of Plastics in Agriculture (CIDAPA), an initiative from the agricultural plastics industry, has published inventories on agricultural plastics use in Latin America, with accessible data available for 2017. These inventories report data aggregated for main plasticulture product categories, including protected cultivation systems (mainly films for greenhouses and tunnels), mulching films, irrigation pipes, silages, and covers. Data are expressed as land area treated with the different applications, and cannot therefore be directly compared with European data, unless detailed information on agricultural practices and turnover of materials in use are provided. CIDAPA also published a series of reports with focus on national inventories based on data provided by industries. Available reports include assessment for: Chile (Castellon Petrovich, 2022a), Guatemala (Bran Shaw, 2022), and Uruguay (Castellon Petrovich, 2022b). Also, in most of these reports data are reported as treated land area.

WHY IS IT SO DIFFICULT TO OBTAIN DATA ON THE AMOUNT OF PLASTIC USED IN AGRICULTURE?

Detailed and quality-assured data on how much, where and how agricultural plastics are used in different countries and regions remain either unavailable, undisclosed, or inexistent. There is also a lack of data on the polymers and chemical compositions used in many types of agricultural plastics. The paucity of data is due to a number of factors including:

- the shortcomings of reporting requirements throughout the agricultural sector;
- the lack of disclosure by producers, retailers and users; and
- the lack of regulation and policies calling for these data to be tracked.

The fact that only marginal progress has been made in building agricultural plastic inventories also reflects the fact that the scientific community has not focused on developing methodologies and studies that could fill data gaps. Only a limited number of research studies or policy initiatives have attempted to collect data to accurately estimate agricultural plastic inventories.

Generating these estimates requires gathering, mining, and compiling many kinds of data from multiple sources. This process includes interviewing a range of stakeholders and organizations involved in the agricultural plastics value chain in different countries.

Also, inconsistency between production data provided by the industry and data on the use of agricultural plastic and waste generation may be influenced by fluctuations in imports and exports. In general, available estimates, regardless of their methodologies and sources, are affected by substantial uncertainties.

Consolidating methodologies for indirect estimation of agricultural plastics inventories is fundamental to address the fragmentation or lack of data affecting most countries. Confidence in indirect estimate methodologies can be increased through partial validation based on field observations, or the use of aerial and remote sensing data. In particular, aerial survey techniques can provide a valid support to assess the use of films or other large items (Lanorte *et al.*, 2017; Blanco *et al.*, 2018). The application of machine learning for identification of agricultural plastics is another promising approach. Pilot studies that combine machine learning with data from aerial observations or satellite-based remote sensing have been appearing in scientific literature, mostly during the last few years. (e.g. Feng *et al.*, 2021; Niu *et al.*, 2023; Chen *et al.*, 2021). These approaches are important for consolidating global inventories on agricultural plastics.

© FAO/Vincent Tremeau

2.2 IS THE USE OF AGRICULTURAL PLASTICS A SIGNIFICANT SOURCE OF POLLUTION TO FARMED SOILS?

Most of the studies included in the systematic review focus partially or entirely on the use of mulching films. Several studies report that the use of mulching film leads to significantly higher plastic pollution in soils compared to fields with no history of mulching film use (e.g. Steinmetz and Schröder, 2022; Zhou *et al.*, 2020; Cusworth *et al.*, 2024; Wang *et al.*, 2021; He *et al.*, 2023; Wang *et al.*, 2024a; Yan *et al.*, 2022). Other studies report that plastic pollution in fields increases significantly with the number of years the mulching film has been used (e.g. Huang *et al.*, 2020; Zhang *et al.*, 2023a). Findings from other studies indicate that there is a significant correlation between levels of plastic pollution in the soil and the amount of mulching film applied Huang *et al.*, 2020; Huang *et al.*, 2021).

These findings indicates that mulching films are a source of plastic pollution to soils in the fields examined. Many studies have concluded that mulching films are the dominant source, or a major contributor, of plastic pollution based on the occurrence data. However, several studies report no statistically significant difference between fields where mulching film has been used and fields where it has not been used. (e.g. Liu *et al.*, 2023a; Zhou *et al.*, 2023; Liu *et al.*, 2022a; Yu *et al.*, 2021).

An examination of the significant variability in the findings raised a number of points. First, in several studies where a statistically significant difference was reported, film residues or particles resembling mulching film did not contribute 100 percent of the microplastics observed in the studied fields. This finding calls for a more in-depth statistical assessment based on the types of particles. For example, Zhou *et al.* (2020) utilized data on the shapes of film microplastic to assess the role of mulching film as a source of microplastics. In their study, a significant difference for film particles was reported. In other cases, microplastics from mulch film may not have an overall predominance in soils where it was used compared to other types of microplastics. This suggests that other processes can contribute to the presence of microplastics in the soil. This might include other agricultural practices associated with the use of mulch films or even contamination that occurred before mulched practices had begun on those fields. Zhou *et al.* (2020) observed a significant increase in plastic fibres in fields where mulch film was used compared to unmulched fields, even though these fibres were not being released from the mulching film in question. Moreover, there were differences in the usage of the terms 'film' and 'fragment' to denote the residues of mulching film in soils across the studies that were included in the systematic literature review. A common terminology is required to improve the comparability and coherence of published data.

Second, the fate of the residues of mulching film also requires further investigation. For example, Liu *et al.* (2023a) report a lack of statistical significance between fields where mulch film was used and adjacent fields where it was not. Film microplastics in the soil increased for both fields. Further research is needed to determine the extent to which mulching film residues may be transferred to nearby unmulched fields and compare this with other sources of soil microplastics.

Finally, soil environments and the agricultural practices associated with the use of mulching film are extremely diverse. This diversity can introduce substantial variability in findings. For example, Liang *et al.* (2023a) reported the highest levels of plastic contamination in fields where mulching film was used, but other fields where mulching film was also applied were among the least contaminated.

Far fewer articles have examined the role of other types of agricultural plastic types as potential sources of soil pollution. In these studies, greenhouse systems are the most well-represented. However, it should be noted that greenhouse systems are typically associated with simultaneous use of mulching films inside the greenhouses (e.g. Chen, 2022a). As a result, it can be difficult to separate these two types of agricultural plastic as distinct sources of plastic pollution. In the Republic of Korea, Kim *et al.* (2021) observed statistically higher plastic levels inside and outside of greenhouse systems compared to fields where only mulching film had been used. Their findings indicate that in some cases the use of greenhouses can be a more important source of plastic pollution in soils than mulching film. On the other hand, Qi *et al.* (2023) compared the use of mulching film and greenhouses in three regions in China and found no significant difference between practices in terms of the concentration of microplastic in the soil. Fields with greenhouses were among the least contaminated in the study of Lui *et al.* (2022a). This indicates that plastic levels in soils associated with greenhouse use may also be subject to similar variability and uncertainty as is observed for mulching film.

Katsumi *et al.* (2021) reported the occurrence of polymer-encapsulated controlled release fertilizers in Japanese paddy soils. This was the only study included in the systematic review that specifically investigated this type of agricultural plastic.

Several other studies also mention other types of agricultural plastic that were typically associated with the most contaminated fields in the given study. For example, grape fields, where anti-bird nets and fruit bagging are used, had the highest levels of plastic contamination in Chen *et al.* (2022a); non-mulching plastic covers (e.g. fleeces and nets) caused soil contamination in Cusworth *et al.* (2024); and in the Chinese province of Taiwan, the use of foams and plastic wrappings in guava production caused the highest levels of plastic contamination in the soil compared to other practices considered in the same study (Fakour *et al.*, 2021). Altogether these findings underscore the challenge of identifying specific agricultural plastic products and practices as the main sources of soil pollution. While this is sometimes possible, the task is often hindered by the confounding factor of the diversity of the contamination profiles in the soil. Different contamination profiles can be associated with a range of processes that could be responsible for the plastic pollution; processes that can be both ubiquitous and continuous (e.g. atmospheric depositions) or associated with previous agricultural practices.

A number of other studies that address the occurrence of plastic pollution in soils linked to the use of agricultural plastic investigate other sources of plastic pollution. The application of sewage sludge or other types of contaminated organic fertilizer on fields was identified as a source in several studies (e.g. Wang *et al.*, 2024a; Hao *et al.*, 2023; Guo *et al.*, 2023; Jia *et al.*, 2024); atmospheric deposition is mentioned in several cases (e.g. Li *et al.*, 2022); and contaminated irrigation water from various sources was also noted as an important source (e.g. Zhou *et al.*, 2020; Wang *et al.*, 2024a; Chen *et al.*, 2022a; Zhang *et al.*, 2022a; Lang *et al.*, 2022). There is a growing body of literature on the occurrence of plastic pollution in fields that are subject to these sources of pollution and other sources. This literature lay outside the scope of the current systematic literature review, which prioritized studies that include at least one field where agricultural plastics were used. Nevertheless, it must be acknowledged that along with agriculture plastics there are other important sources of plastic pollution in agricultural soils (UNEP and GRID-Arendal, 2021).

An important finding of this literature review is the poor comparability of the findings presented by occurrence studies.[4] This situation makes it difficult to directly rank different sources in terms of their contribution to soil pollution and represents a major shortcoming in the field. Where studies compare agricultural plastics with other sources, significant variability is again reported. In some cases, sources other than agricultural plastics were associated with a greater presence of plastic in the soil than pollution caused by agricultural plastics. For example, in Chinese small-scale vegetable farms, the use of organic fertilizer, along with other differences in agricultural practices, lead to plastic levels in the soil that were twice as high as those found in larger-scale farms typically characterized by the intensive use of mulching film (Hao *et al.*, 2023). Some studies place other sources of plastic pollution in the soil within a similar magnitude as agricultural plastic use (e.g. Lang *et al.*, 2022; Zhang *et al.*, 2022b; Liao, Tang and Wang, 2023; Luo *et al.*, 2024). Other studies identify agricultural plastics as the dominant source (e.g. Xu *et al.*, 2022a; van Schothorst *et al.*, 2021; Ling *et al.*, 2023). Many studies included in the review reveal variabilities in the presence of plastic in the soil from a single source that are of several orders of magnitude. These finding reinforce the high degree of heterogeneity associated with soil plastic pollution; a characteristic that makes it difficult to conclude which sources are the most responsible for plastic pollution in different settings.

Almost all studies reviewed in this report suffer from insufficient descriptions of specific agricultural practices related to the application, use, maintenance, and retrieval of agricultural plastics. This is likely due to a lack of available data or the unwillingness of farmers to divulge information on mismanagement. This situation hinders research.

Several occurrence studies included in the literature review indicate that agricultural practices are likely to be important factors in plastic pollution in soils. However, there is insufficient evidence to rank or fully evaluate these practices. For example, Wang *et al.* (2022) recorded significantly higher levels of microplastics in soils where greenhouses had been abandoned than in fields where greenhouses remained operational. The age of the mulching films used in greenhouse systems was identified as the main control on soil microplastic abundance by Chen *et al.* (2022a) who also noted that the method of film recovery and the frequency of ploughing also revealed a positive correlation. Liang *et al.* (2024a) noted that recovery of mulching films and the resulting residues left in fields was linked to the thickness of the film. Finally, Liu *et al.*, (2022b) found that the type of crop that was grown was linked to the efficiency of the recovery of mulching film with taller crops anchoring the mulching film close to their stem-root systems.

The systematic literature review considered the processes through which agricultural plastics may fragment and release (micro)plastic pollution. Studies have revealed that photodegradation and mechanical abrasion are important processes in this regard (Yang *et al.*, 2022a; Liang *et al.*, 2024b; Ouyang *et al.*, 2023). Occurrence studies rarely provide the level of detail required

---

[4] Occurrence studies aim to measure the concentration, distribution, and types of plastics found in soil samples, helping to assess the extent of plastic pollution in soils.

to evaluate whether these processes have occurred or do occur in the studied fields. Also, agricultural practices characterized as mismanagement (e.g. burial, burning, or ploughing into fields) have not yet been specifically investigated for the amount, types, or characteristics of the plastic pollution that they may generate. As such, the extent to which best practices contribute to plastic pollution in soils compared to the mismanagement of agricultural plastics in not known.

Mismanagement practices that contribute to plastic pollution in the soil can occur at all stages of the life cycle of the plastic materials, from design to disposal. On farms, some mismanagement practices that can lead to soil pollution during and after the use of agriculture plastics include:

- using inadequate plastic products (e.g. excessively thin and brittle materials);
- improperly storing new plastic products and waste;
- abandoning waste in fields, marginal lands or the wider environment; and
- using tilling, ploughing, burying, or open burning to dispose of waste plastic.

It is reasonable to expect that the local mismanagement of agricultural plastics represents an important source of soil pollution. However, this does not imply that the use of agricultural plastics in itself leads unavoidably to the involuntary release of plastic debris in the soil.

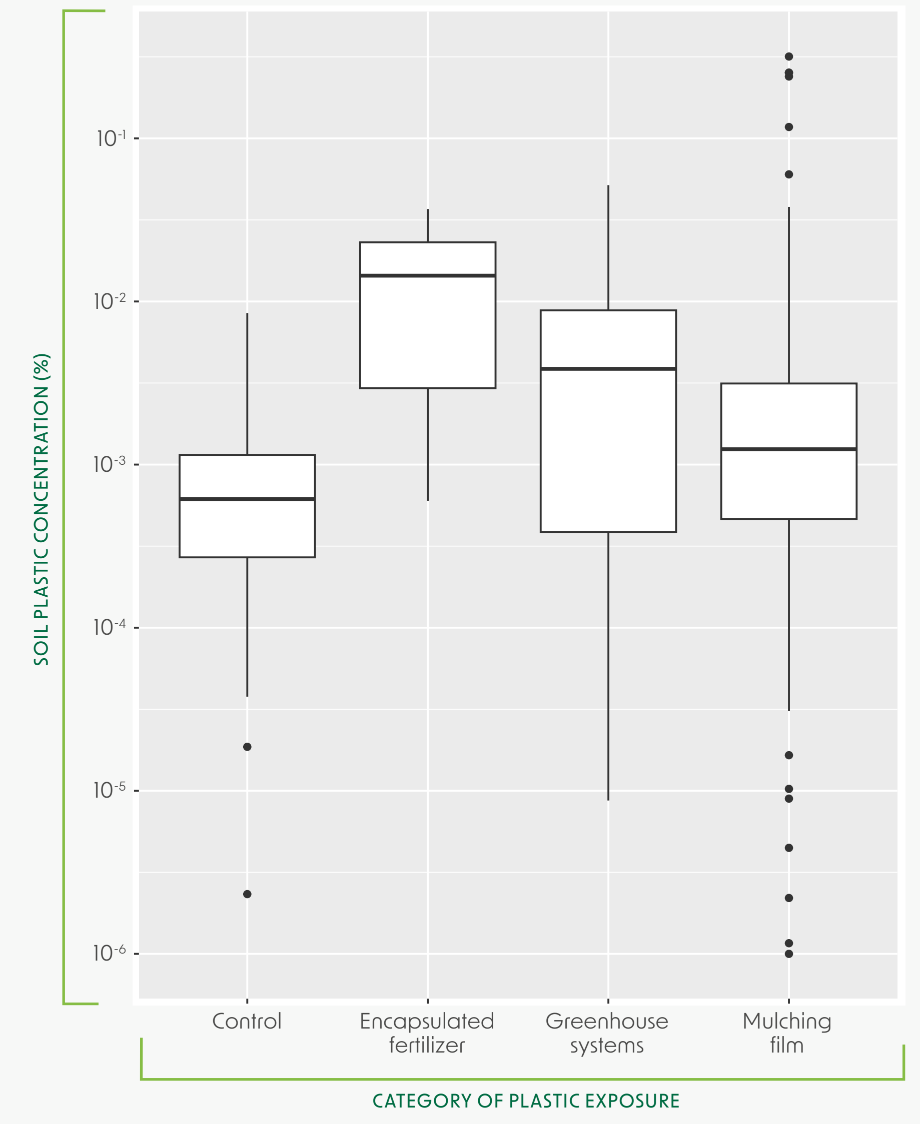
Lack of systematic research on the frequency and the types of agricultural plastic mismanagement and how different mismanagement practices lead to quantifiable quantities of microplastic emissions is an important knowledge gap that requires attention. These mismanagement practices are often described in studies but not quantitatively assessed. Further research is needed to characterize the different ways in which agricultural plastics are being mismanaged or could be mismanaged; the magnitude of current mismanagement; the spatial and temporal scales over which mismanagement currently occurs; and the processes linked to mismanagement that may release plastic pollution to the soil.

Finally, a significant feature of all the occurrence studies included in the review is their uneven geographic distribution. Most of the occurrence studies (55 studies or 82 percent of the total) were conducted on soils in China. This research constitutes an important body of literature and may serve to identify trends in plastic pollution in soils that are associated with particular agricultural plastic materials or practices. However, the wider geographic significance of these findings requires an urgent assessment. There remains a paucity of data on the role of agricultural plastics as sources of plastic pollution in agricultural soils globally. The review undertaken for this publication includes six studies that were conducted in Europe; five studies from Asian countries other than China; and a single study from South America. There is almost no data available for the occurrence of soil plastic pollution associated with agricultural plastic use in Africa and North America. International research and monitoring efforts are necessary to evaluate the extent to which agricultural plastics release pollution to soils and the practices or processes associated with this release.

2.3 HOW MUCH PLASTIC IS PRESENT IN AGRICULTURAL SOILS?

The studies identified in the systematic literature review were analysed for the availability and quality of their estimates of the levels of plastic contamination in soils. A total of 47 studies provided documented data on the concentration of plastic in fields and were included in a dataset of observations. The box plots represented in Figure 2 summarize the data from the meta-analysis that was undertaken with all the studies (47 papers) included in the systematic review. This meta-analysis included all the studies cited in section 2.2 of this report.

FIGURE 2. Estimated levels of soil plastic contamination in fields exposed to different categories of agricultural plastic use



Source: Authors' own elaboration.

To provide an overview of observed plastic levels that is compatible with exposure levels used in effects studies, the data were converted to estimated concentrations and expressed as percentages. Figure 2 illustrates these concentrations by category of plastic exposure, based on the specific use of agricultural plastic described in each study. Plastic levels in soils vary widely, ranging from 0.000001 percent to 0.3 percent. Data were available for only three categories of agricultural plastic: mulching films, greenhouse systems, and encapsulated slow-release fertilizers. A fourth category, representing control fields, is also shown in Figure 2.
The use of encapsulated fertilizers results in the highest levels of soil pollution. However, these data come from a single study in paddy soils in Japan (Katsumi *et al.*, 2021) and require further validation. Soils where greenhouse systems were present showed the second highest plastic levels, with levels typically between 0.001 percent and 0.01 percent. On average, soils exposed to mulching films generally had the lower levels of plastic. However, plastic concentrations from mulching film showed the largest range of levels, registering both the highest and lowest plastic concentrations recorded in this analysis.

The levels of plastic in the soil recorded in many of the fields that were exposed to different types of agricultural plastic overlap with the levels found in many fields that were used as controls. Figure 2 shows that the use of agricultural plastic is generally associated with elevated plastic levels in soil, but sites without a history of plastic exposure also exhibit soil pollution. This indicates that sources of plastic pollution to soils other than agricultural plastics, sewage sludge, and compost or fertilizers are present. Candidate sources for this pollution should be identified and investigated. This would include estimates on the role of atmospheric transport and deposition of plastic as a contributor to plastic pollution to soils.

METHODOLOGICAL CHALLENGES IN ASSESSING SOIL PLASTIC CONTAMINATION

It should be noted, however, that the pollution levels provided in Figure 2 represent a crude estimate. This is because the available studies vary widely in their methodology and in the quality and completeness of data reporting. Few studies had a broad geographic scope that consistently analysed soils from different regions that could produce comparable data (e.g. Hu *et al.*, 2022). No two studies utilize the same sampling and analytical approach, or report data in the same manner. As a result, it is difficult to assess whether any two studies have conducted comparable measurements in the soil. In addition, the description of the methodology by several of the studies was insufficient to guarantee a complete evaluation of the quality of the analysis. This represents a knowledge gap that needs to be urgently addressed by harmonizing sampling and analytical methodologies and putting in place more stringent quality controls for the publication of occurrence data.

Among the studies reviewed for this report, only a small number define the precise size range of plastic particles detected. In many cases, an upper limit is well-defined (typically 5 mm), but the lower size limit of detection is not provided. Several studies simply define the target range as greater than 5 mm. In some studies where a description of the size distribution of particles identified through their analytical methodology, the size distributions vary significantly.
As a result, it is often difficult or impossible to tell whether it is the method in question or the actual size of plastic in the soil at that location that determines the observed size distribution.

For example, for mulching film sites, the average size of the particles described vary across two orders of magnitude.

From the current approach used to describe methodologies and reporting data, it is not possible to discern if difference in size of plastic debris in the soil relates to different practices related to the use of mulching film or differences in the sensitivities of analytical detection methods. Where two studies utilize a different method that imposes a different lower size limit of detection, these studies report overlapping but different proportions of the total plastic pollution. Where these studies do not clearly define their lower size limits, the data they report suffer from poor comparability. Given the high prevalence for failing to report the specific size fraction analysed, this factor is likely to explain a large proportion of the variability in Figure 2.

Also related to the issue of size is the fact that most of the studies focus specifically on the microplastic fraction of soil plastic pollution. The focus on microplastics is important when investigating the presence of plastic pollution in soil. Sampling for microplastic analysis typically take smaller subsamples of soil (usually a few tens of grams). Several studies describe how soils are sieved to remove larger debris (e.g. at 5 mm), but there is often no mention of whether the larger pieces of plastic are incorporated into the reported data, and if so, how. These details are important for determining how the plastic pollution in the soil is described, assessed, and compared. Many effects studies[5] focus on microplastic particles in soil subsamples, and it is also important to carry out field studies to measure the concentration of microplastics in real soils to assess the potential risk. However, field studies that only look at levels of microplastics in soil, are likely to underestimate of the total plastic pollution.

Effects studies have also utilized macro-fragments of agricultural plastic and observed impacts on soil ecosystems. The overwhelming focus on microplastics may exclude important parts of the overall picture of plastic pollution in soils. There is a need for greater clarity on the specific size of the plastic fractions in the soil that are investigated by each study and the main objectives for monitoring plastic in the soil.

The methodological approaches for sampling and analysis vary widely across the studies included in the systematic literature review. The approaches include visual sorting and counting for the largest particles and spectroscopic methods that determine the composition of particles through Fourier-Transform Infrared Spectroscopy (FTIR). Differences in approaches also relate to the extent to which the sampling is representative of a defined area, the size of the plastic, and the types of polymers. These differences are also connected to the total proportion of particles that are likely to be isolated during sample processing and the proportion that is accurately detected during sample analysis. All these factors have implications on the reporting of the final concentrations

The wide range of observed concentrations likely also contributes to the wide-ranging plastic levels observed in Figure 2. During the literature review, the assessment of these differences was substantially hindered by the under-reporting of the methodological approach. In general, the reproducibility of the studies is low. In addition, very few studies satisfy important quality criteria.

---

[5] Effect studies assess the impacts of a substance or condition (e.g. microplastics)on organisms, ecosystems, or specific biological or environmental functions.

For example, there were often mistakes in the published articles, over-application of statistics to datasets, and an over-interpretation of results with limited evidence to substantiate conclusions. There is an urgent need for higher standards for the publishing of studies on the occurrence of plastic in soils and a coordinated approach to data reporting.

2.4 IS SOIL PLASTIC POLLUTION REVERSIBLE?

The fate of plastic pollution in soils has short- and long-term consequences on soils. It is important to understand to what extent plastic pollution is either retained or lost from soils. If plastic particles accumulate in soils, the successive uses of agricultural plastic (or plastic inputs from other sources) will lead to higher concentrations over time. These concentrations could exceed effects thresholds and have negative impacts upon soil ecosystems. On the other hand, if soils can facilitate the export or complete degradation of plastic, soil pollution would be theoretically reversible. However, if the plastics are exported from the soil, they become a source of pollution to connected environments. Remediation of soils through clean-up activities is likely to have limited efficacy as the size of the plastic particles decrease. Removing microplastic-sized debris from even the surface of soils in fields would be unfeasible in terms of cost, practicality, and environmental protection. Already the effective removal of macro-sized mulching film debris has become a significant cost to farmers (Zhang *et al.*, 2022c). Given this situation, there is a need to better understand the environmental fate of soil plastic pollution derived from the use of agricultural plastic and evaluate the extent to which this pollution is reversible.

To establish the current state of knowledge, a systematic literature review on this topic was conducted. Only a small number of studies specifically address the fate of residues from agricultural plastic. Consequently, the literature review was widened to include other, more general, sources of plastic pollution to determine potentially relevant fate processes.

Complete degradation of plastic is one potential mechanism through which pollution could be reversible in soils. Conventional polymer types are not considered to be biodegradable in soils. As the plastic particles age (e.g. through photodegradation or mechanical abrasion) they are expected to generate fragments of decreasing size over time. The degradation of residues derived from agricultural plastic (e.g. mulching films) has been confirmed be zero percent after two years under field conditions (Zhao *et al.*, 2021). For these types of conventional polymers, complete degradation is expected to occur over hundreds of years (Feuilloley *et al.*, 2005). Degradation does not, therefore, represent a viable mechanism for reversing plastic pollution from conventional polymers.

In contrast, several polymers have been certified as biodegradable in the soil and are being used in different agricultural plastic applications, including mulching films, encapsulation or coatings and other products. International standards, such as EN 17033 (Plastics - Biodegradable mulch films for use in agriculture and horticulture - Requirements and test methods),[6] which was developed in 2018 by the European Committee for Standardization, require materials to achieve 90 percent mineralization to carbon dioxide within two years at ambient condition (20 to 28°C). The plastic pollution in soils created by these products is therefore theoretically

---

[6] EN-17033 is available at https://standards.iteh.ai/catalog/standards/cen/b09b1982-efd3-45fe-9d87-7798699e5c3c/en-17033-2018

reversible. However, the actual in-field biodegradation rate has been shown to vary significantly (Francioni *et al.*, 2022). For example, a study carried out by Li *et al.* (2014) found that in-field degradation rates ranged from two percent to 89 percent within two years across different geographic locations. Biodegradation in fields follows more closely that observed in the laboratory when thermal time[7] is considered, instead of calendar time (Sintim *et al.*, 2020). Soil type, soil moisture, and the size of plastic fragments generated through tilling also affect the biodegradation ratebut adoption has been slow, in part because of uncertainties about in-field degradation. The international biodegradability standard EN-17033 requires 90% degradation within 2 years in an aerobic incubation at constant temperature (20–28 °C (Griffin-LaHue *et al.*, 2022). Regular use of mulching film (e.g. annually or during multiple cycles of production per year) could lead to an accumulation plastic in the soil and eventually the establishment of a pseudo steady-state scenario[8] with relatively constant presence of high quantity of bioplastic residues in soil (Griffin-LaHue *et al.*, 2022). This has been observed in occurrence studies that identified microplastic-sized fragments of mulching films in soils treated with biodegradable films (Qi *et al.*, 2021; Ranneklev *et al.*, 2019). In these cases, the biodegradation of these products never results in the complete clearance of these residues from soil. Temporary cessation of the use of these products would be required to full reverse this pollution.

Research into the environmental fate of soil plastic pollution has uncovered a number of important processes that affect both the mobilization and immobilization of particles. Several processes may facilitate the export of plastic particles from soils. Plastic pollution on the soil surface can be carried away through runoff (Han *et al.*, 2022), erosion (Rehm *et al.*, 2021), and the wind (Rezaei *et al.*, 2019; Rezaei *et al.*, 2022; Abbasi *et al.*, 2023; Yang *et al.*, 2022b). These processes transfer the pollution to connected environments. There is, however, some variability in the reported efficacy of these processes in mobilizing plastic particles. Some studies have reported minimal influence, for example in the case of surface runoff (Schell *et al.*, 2022) or entrainment by wind where aggregate stability is high (Yang *et al.*, 2022b) . Questions remain, therefore, about the specific role of these processes in environments where soil properties are very different. Some of the processes that have been studied, for example the adsorption of dissolved organic matter onto plastic surfaces, which can reduce their hydrophobic properties and make them more mobile in soil (Ivanic *et al.*, 2023). Other factors, such as soil pH and the presence of iron and aluminium oxides, can also enhance the transport of plastic particles by influencing how they interact with soil minerals (Ren *et al.*, 2021a; Wu *et al.*, 2020; Xu *et al.*, 2024).

Other processes may facilitate the transport of plastic pollution to deeper soil layers, which would reduce the potential to remove this pollution through surface processes. Bioturbation (Heinze et al, 2021; Rillig, Ziersch and Hempel, 2017), particularly connected to deeper burrowing organisms (e.g. anecic earthworms), and the influence of rainfall intensity (Zhang *et al.*, 2022d), irrigation (Liu *et al.*, 2023b), and wet-dry cycles (O'Connor *et al.*, 2019) have been shown to initiate the vertical migration of plastic pollution in soils. Plastic particles at deeper layers of the soil are typically less mobile due to higher soil compaction, but may still be exported from soils

---

[7] Thermal time is the accumulation of temperature over time, usually measured in degree-days. It accounts for how heat influences temperature-dependent processes like biodegradation, providing a more accurate prediction than calendar time alone.

[8] A steady-state scenario is a condition in which all variables within a system – such as plastic debris concentration or soil moisture – remain constant over time because the inputs and outputs are balanced, resulting in no net change in the system's state. Researchers often control experimental conditions to maintain a steady state in key variables, such as soil nutrients or moisture, allowing the study of dynamic systems under stable conditions and reducing potential confounding factors.

through groundwater transfer (Heerey *et al.*, 2023). Other processes may actually result in the upward movement of plastic particles, as was demonstrated in a study that investigating the role of crop roots on the fate of microplastic in the soil (Li *et al.*, 2021a).

Overall, research on the environmental fate of plastic in the soil reveals wide variabilities. For example, two studies that looked at the fate of microplastics that were added to the soil from sewage sludge in different environmental conditions reported completely opposite results. One study found that more that 99 percent of the microplastics were exported from soils (Crossman *et al.*, 2020) and other found that more than 99 percent were retained by soils (Schell *et al.*, 2022).

More recent evidence shows that the level of microplastics in soils tends to increase over time following repeated additions (e.g. Colombini *et al.*, 2024; Colombini *et al.*, 2022). There are persistent knowledge gaps regarding control scenarios that can better characterize the processes that determine the environmental fate of plastic in the soil. Control scenarios can be used to improve projections about whether fields with different environmental conditions and soil types would effectively retain or export plastic particles of different sizes, shapes, or composition. At present, there is insufficient evidence to determine the likely reversibility of soil plastic pollution in the range of environmental settings.

An important additional point relates to the range of soil plastics that expose agricultural fields to pollution. As has already been highlighted, fields with no documented history of plastic exposure also exhibit soil plastic pollution. It has been suggested that atmospheric transport and deposition of plastic plays an important role in contributing this additional load of small plastic particles. Control fields in studies that have looked into the impact of the continuous use of mulching film over a number of years have found increasing levels of microplastic contamination over time (Liu *et al.*, 2023a). This increase could be due to confounding factors associated with cross-contamination of microplastics through lateral transport by runoff or atmospheric drift. Several studies have highlighted agricultural plastics as significant sources of plastic pollution in soils, but it is important to be recognize that agricultural plastics are not the only contributors to plastic pollution in agricultural soils. Assessments need to be made about the reversibility of the plastic pollution from these additional sources.

Like other conventional and biodegradable plastic products, agricultural plastics contain a mixture of chemical additives, but data on the typical chemical composition of different agricultural plastics products are limited. Recent studies have focused on the role of agricultural plastics as a source of common chemical additives in soil and crops. Phthalic acid esters (PAEs) are among the most frequently studied substances. Several studies consistently reported relatively high levels of PAEs in soils where agricultural plastics had been used, but due to confounding factors or study limitations, these studies could not establish a statistically significant link between the use of agricultural plastics and the increased levels of PAEs in the soil (e.g. Wang *et al.*, 2021a; Sun *et al.*, 2021a; Wang *et al.*, 2016a; Li *et al.*, 2016; Li *et al.*, 2020a).

In some cases, however, this link was convincingly and statistically proven. A 2019 field experiment study from China (Shi *et al.*, 2019), showed that the concentration of PAEs tended to increase in soils covered with plastic mulch. This trend was not statistically significant in the soil, but grains of wheat from these fields did show a significant increase in PAE concentrations compared to grains from control fields. Another monitoring study in the Xuzhou region of China (Li *et al.*, 2021b) demonstrated a positive correlation between plastic concentration in soil and PAEs, but this correlation did not hold across all soil types or environmental conditions.

The assessment of the contribution of agricultural plastic as sources of plastic chemical additives to soil and crops is difficult because there are no chemical additives that can be used as specific markers for agricultural plastic (i.e. chemicals that are used only agricultural plastics). Most plastic chemical additives are produced in very large volumes from diffuse sources. These additives can enter the atmosphere as gases or as particles. Soils and crops can therefore be contaminated directly from atmospheric depositions by diffuse non-specific sources. Despite these confounding factors there is evidence that some agricultural soils have relatively high levels of some plastic chemical additives, and that agricultural plastics are among the most important sources for this pollution (Chen *et al.*, 2024). Research on the role of the mismanagement practices of agricultural plastics in increasing the exposure of soils and crops to plastic-borne chemicals is still at a relatively early stage. Increasing the knowledge base in this area should be seen as a priority.

2.5 IS PLASTIC POLLUTION A CONCERN FOR THE HEALTH OF AGRICULTURAL SOILS?

The claim that plastic pollution in soils is likely to change the physical, chemical, and microbiological properties of the soil is supported by a large number of scientific studies published during the last eight years. The systematic review revealed 213 scientific studies from international academic peer-reviewed journals that reported the results of experimental assessments. Review papers (31 percent of the total number of retrieved publications) are excluded from this number. Over 80 percent of the experimental studies were published in 2022 or later. Even though this area of research is very new, the unfolding body of evidence is already conspicuous.

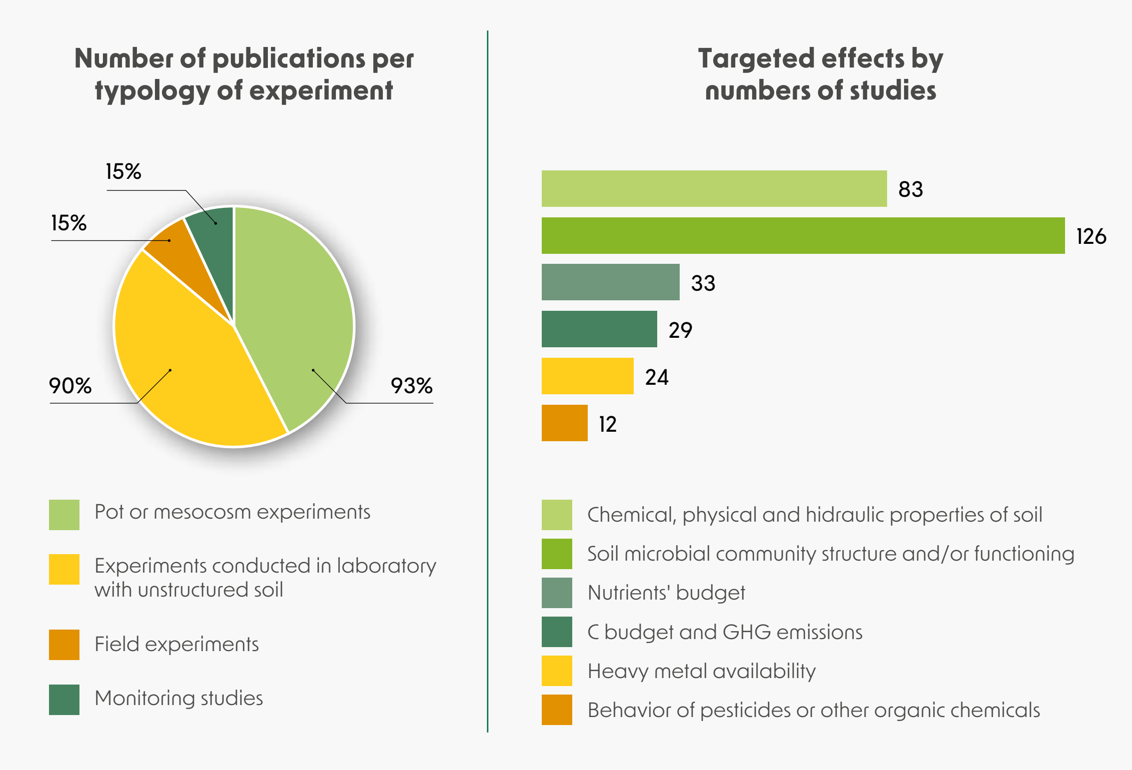
The studies covered a broad range of approaches and examined a wide spectrum of effects. Ninety of these studies focused on experiments conducted on batches using unstructured soil samples; 92 studies carried out pot or mesocosms experiments; and 16 studies ran field experiments where plastic pollution was added to natural or agricultural soils. Fifteen papers described monitoring approaches that attempted to identify the correlations between the level of plastic pollution in soils and some soil property or function across sites with differing levels of soil plastic contamination.

From these numbers in can be seen that nearly 70 percent of the studies (182 in total) focused on controlled experiments to establish a causal link between the addition of plastic debris to soil and changes in some soil properties (Figure 3). Tested materials were mostly microplastics or mesoplastics (e.g. plastic debris larger than 2.5 cm in at least one dimension). However, some studies focused specifically on the effects of the debris from mulching films and used larger plastic residues artificially generated by manually cutting the source materials. As illustrated in Figure 3, most of these studies focused on measuring changes in the physical and hydraulic properties of the soil (83 studies), the structure and functions of soil microbiota functions (126 studies), or both types of effects. Other studies investigate the effects of plastic debris on the carbon budget (12 studies); macronutrient budgets and availability (24 studies); heavy metal speciation[9] (21 studies): and the behaviour of pesticides and other organic chemicals (6 studies).

---

[9] Speciation refers to the different chemical forms in which a substance (e.g. a metal or pollutant) can exist in the environment.

FIGURE 3. Typology of experimental works and studied effect endpoint in the analysis of plastic pollution impacts on soil health

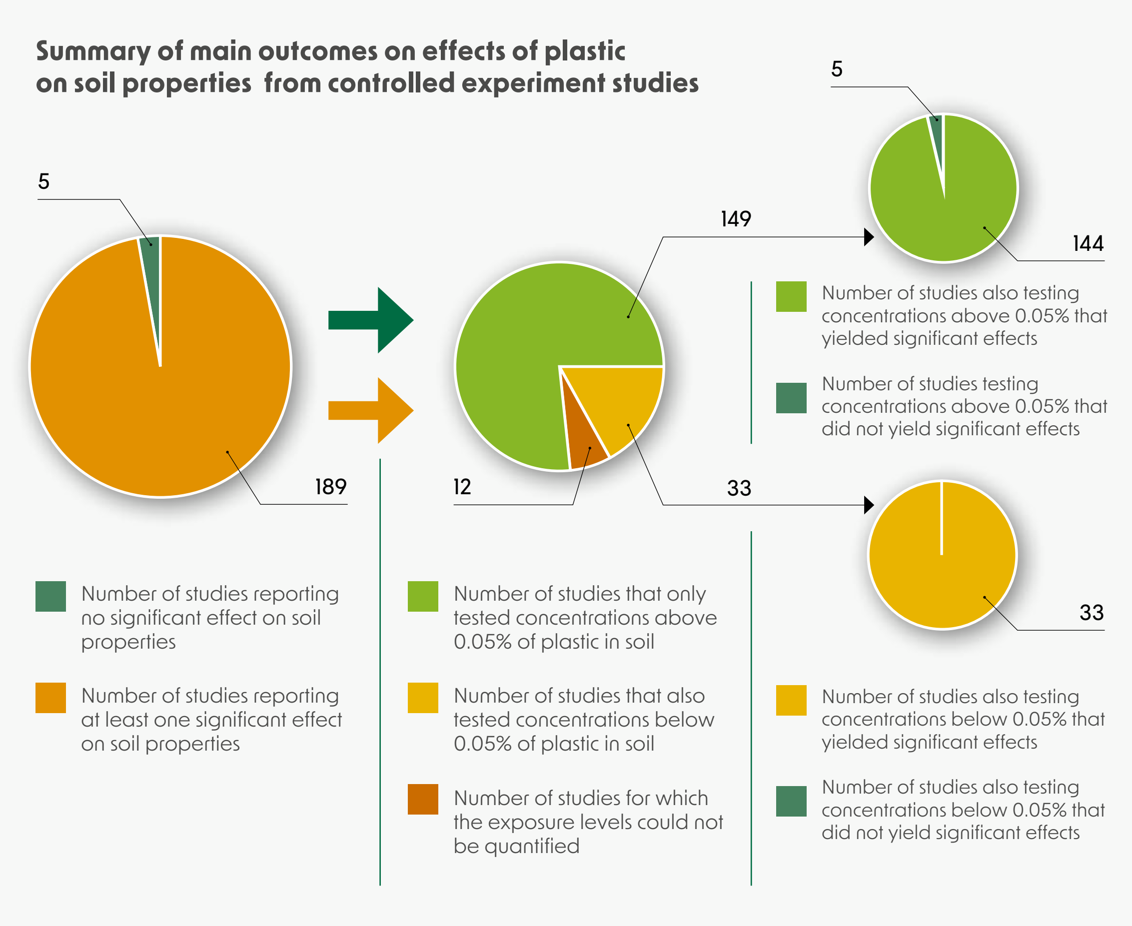


Source: Authors' own elaboration.

The studies utilized a broad range of different test materials in terms of composition, size, shape, and origin of the plastics that were added to soils during the experiments. This can make direct comparisons of the results challenging. Often, virgin plastics (e.g. microspheres or grinded new pellets) were used as test materials. However, many studies utilized debris obtained from cutting or grinding agricultural plastics, especially mulching films based on high density polyethylene (HDPE), polylactic acid (PLA) and polybutylene adipate-co-terephthalate (PBAT). Other tested materials included debris, microspheres, or fibres made of polypropylene, polyvinyl chloride (PVC) and polystyrene.

Most of the studies (182 or. 85 percent) observed a statistically significant effect of plastic on at least one endpoint among those considered (Figure 4). These effects were observed regardless of the type and scale of the experiments; the targeted effects; the size, type, and source of the tested materials the soil type; and the applied dose. Only four studies observed no significant effects. The remaining studies were based on environmental monitoring aimed at identifying correlations between levels of plastic in soils and soil properties changes. Environmental monitoring, in principle, does not allow for the identification of causal relations between the variables.

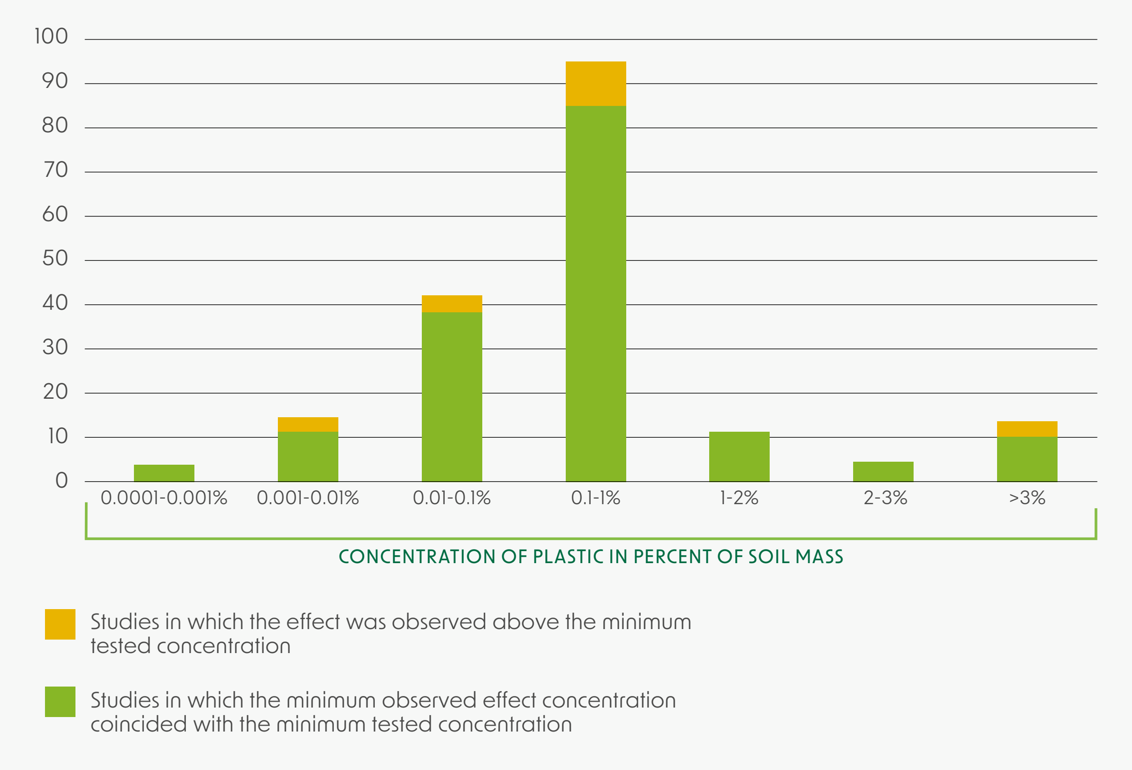
FIGURE 4. Effects of plastic pollution on soil properties from experimental studies



Source: Authors' own elaboration.

The very high frequency of observable effects (Figure 4) in experimental studies is remarkable. These results raise the question of whether the studies were conducted using unrealistically high exposure doses. Figure 5 depicts the number of studies that tested for effects on soil properties at any given value of the concentration gradient, regardless of the type, shape, and size of the plastics added to soil. Most of the studies focus on concentrations of plastic in the soil that range between 0.1 and 1 percent. This range is often considered as representative of extreme pollution scenarios, for example scenarios typical of severe mismanagement of agricultural plastics. There are some studies that address lower concentration ranges. Eighty-two studies (38 percent) focused on a single level of concentration. Other studies considered two or three levels, typically covering two or three orders of magnitude in the concentration gradient. Regardless of the approach, significant effects were observed at the lowest tested concentrations in about 90 percent of the studies. This indicates that the safety thresholds given by the non-observable-effect concentration of plastic in soil could not be identified in most of the studies and that such thresholds are relatively low.

FIGURE 5. Number of studies that observed an effect of plastic pollution on soil health along a concentration gradient



Source: Authors' own elaboration.

Identifying the order of magnitude of a safety threshold (i.e. the maximum level of plastic pollution that can be tolerated by soil before exhibiting any significant change in chemical, hydraulic, or physical properties or in soil macrobiotic community structure and function) remains challenging. Determining an estimate of such a threshold is pivotal for assessing ecological risks and protecting natural and agricultural soils.

To better understand safety thresholds, it is useful to consider the studies that investigated the lower range of plastic concentrations. To date, 33 studies have tested concentrations below 0.05 percent of plastic in soils. This level can be viewed as representative of agricultural soils, including soils that were not subject to intense inputs of microplastics or extreme cases of agricultural plastic mismanagement. This particularly informative subset of studies, which encompasses a wide range of approaches and tested materials, includes 16 experiments conducted in laboratory conditions using unstructured soil samples; 16 pot or mesocosms experiments; and 6 field-scale experiments that considered micro-, meso- and macroplastics from different origins and with different chemical compositions that included conventional polymers and biodegradable materials based on PLA and PBAT. The examined effect endpoints of these experiments covered the full spectrum of parameters and processes, including the physical and hydraulic properties of the soil; the structure and functioning of the microbiota community structure and functioning; the carbon budget; the availability of macronutrient, metal speciation and the behaviour of pesticides and other organic chemicals in the soil.

These studies that focused on the lower range of the exposure gradient all provided evidence of one or more significant effects. The lowest concentration yielding observed significant effects on any soil property was 0.001 percent of plastic in soil. Significant effects at this lower-end range of exposure were observed in four studies (three pot experiments[10] and one field experiment). One of these pot experiment (Ren *et al.*, 2021b) used polystyrene nano-microplastics ranging in size between 70 nanometres and 5 microns; the second pot experiment (Boots, Russel and Green, 2019) used both conventional (HDPE) and degradable (PLA) microplastics, as well as synthetic textile fibres (the latter tested at the 0.001 percent concentration); the third pot experiment (Xu *et al.*, 2023) focused on polystyrene nanosphere (500 nanometres). The field experiment (Koskei *et al.*, 2021) used both conventional (HDPE) and degradable (PLA) mulching film residues in the macroplastic range (5 cm hand-cut squares) that were mixed into agricultural soil.

Plastic products can release chemical substances used in their formulation into the soil, and these chemicals poses risks to soil health. Agricultural plastics may contain a range of substances added during manufacturing to achieve specific properties and durability. These substances include plasticizers (e.g. PAEs and bisphenols), antioxidants, UV filters, surfactants (e.g. perfluoroalkyl and polyfluoroalkyl substances - PFAS), processing aids, metals, metalloids and other substances.

As plastic ages in soil, it is believed these substances can migrate from the polymer to the soil and soil water. The rate at which chemicals are released from the polymer will depend on the polymer's characteristics, the extent of ageing, the chemical and physical properties of the substances, and environmental conditions.

Biodegradable plastics also contain chemical additives. These plastics degrade more quickly, so the chemicals additives are likely to be released into the soil at faster rates than for conventional plastics. In this area of research, plasticizers are the most studied chemicals additives. Depending on the type of polymer and their intended function, plasticisers can represent between 10 percent and 70 percent of the plastic's total weight. Agricultural plastics could potentially represent an important source of plasticizers in the soil. Plasticisers typically make up to 20 to 60 percent of mulch films (Viljoen *et al.*, 2023). Some plasticizers are known to have endocrine-disruptive effects on humans and other animals. They also potentially have properties that are mutagenic (causing genetic mutations), teratogenic (causing developmental malformations or birth defects in a developing foetus) and carcinogenic (Guo *et al.*, 2012; Net *et al.*, 2015). Several substances that are classified as PAEs are now considered priority pollutants by the EU and the United States Environmental Protection Agency (Viljoen *et al.*, 2023).

However, the extent to which agricultural plastics contains hazardous chemicals is not well known. Apart from limited provisions for biodegradable plastics certified for soil use under regulatory standards (e.g. EN 17033 in Europe) regulations do not specify any requirements for the formulation of agricultural plastics because they are not considered to be materials that come in contact with food.

---

[10] Pot experiments are studies that focus on the effects of specific factors (e.g. plastic concentration in soil)on plant growth or health, conducted in pots. These studies are similar to mesocosm experiments, but generally lack the use of structured soil columns. Artificial watering and controlled nutrient addition are typically applied to observe plant responses under regulated conditions.

Additionally, PAEs and other chemicals that are used as plastic additives are released into the atmosphere from various sources, not only agricultural plastics. Once airborne, these chemicals can enter the soil through atmospheric depositions. The transfer of plastic to soils through practices such as biowaste fertilization, wastewater irrigation, and littering can also contribute to the presence of chemical additives in soils. Consequently, establishing a direct link between chemicals in agricultural plastics and risks to soil health is difficult. Some evidence has linked agricultural plastics to high levels of certain plastic additives in soil or crops (Shi *et al.*, 2019; Li *et al.*, 2021b). However, this remains a poorly understood risk factor for environmental and human health, and warrants the prioritization of further research.

NAVIGATING THE COMPLEXITY OF RISK THRESHOLDS, AND PLASTIC INTERACTIONS WITH SOIL

Plastic pollution consists of a complex range of materials that have a wide range of sizes, properties, and chemical compositions (Koelmans *et al.*, 2022). The size of the plastic particles is a particularly important in the determining the interactions between plastic debris in the soil, the natural structures of the soil and soil biota.

The smallest habitats for organisms in the soil consists of micro-sites ranging of 2 to 250 microns (Rillig, 2012). Most processes that sustain the cycling of organic matter in the soil and maintain soil fertility are carried out by microorganisms in these micro-sites and associated biofilms. Micro- and nanoplastics have the same dimensions as these micro-sites. As a result, these materials may interfere with these processes, for example by occluding micropores, which affects biofilm composition, or by introducing exotic microbiota (Rillig, 2012).

Soils are self-organizing complex systems and their responses to disturbances caused by the presence of plastic pollution can be highly variable, non-linear and difficult to predict. Effects cascading from the initial interactions of plastic with the soil can have far-reaching indirect consequences at different scales and on various components of the soil. Depending on the size and shape of the plastic, in particular, impacts can result from alteration of soil properties (e.g. affecting formation of aggregates and porosity) or directly from histological (microplastic) and cellular (nanoplastics and chemical additives) interactions (Hurley and Nizzetto, 2018).

Microplastics are relatively large pollutants compared to chemical contaminants. Plastic debris larger than 100 nanometres are hardly ever taken up into crops and the bodies of other living organisms (Zantis *et al.*, 2023). Organisms exposed to particles of this size are unlikely to exhibit any direct physiological responses. However, macroplastics and larger plastic debris can modify the habitats of soil organisms, which can have indirect impacts on different soil properties and biota.

When plastic pollutants have indirect habitat-mediated effects on soil organisms, a linear dose-response relationship should not be expected. This situation complicates the definition of risk thresholds. In contrast, micro- and nanoplastic debris and chemical additives, both of which can be generated or released by larger particles of plastic, can penetrate the protective layer of cells (epithelial tissue) and cause direct physiological responses. These responses may exhibit a more typical linear dose-effect relationship. Because plastic pollution in the soil includes particles of different dimensions and chemical composition that interact with the soil ecosystem at multiple scales, assessing risk thresholds for soil health in relation to plastic pollution requires a holistic ecosystem approach, which has not yet been fully developed. The lack of an established approach to address this question is an important knowledge gap.

2.6 WHAT CHANGES CAN PLASTIC POLLUTION CAUSE IN SOILS PROPERTIES AND MICROBIOTA UNDER REALISTIC EXPOSURE SCENARIOS?

Several studies have analysed the responses of soil ecosystems to the addition of plastic debris. Most of these studies focus on high, but plausible and exposure scenarios (e.g. 0.1 to 1 percent of plastic in the soil) that have been observed in both laboratory and field studies. However, to determine whether and how plastic pollution represents a generalized concern for soil health, it is important to delve specifically into the results recently obtained by studies conducted in pot or mesocosms experiments, or better yet field experiments, under relatively low dosage (e.g. greater than 0.05 percent of plastic in the soil). These studies better reflect the exposure of soils affected by agricultural plastics, as well as the range of other possible sources of plastic pollution. It is also important to concentrate on studies that examine the responses of soil properties that are critical for soil fertility and sustainable agricultural production.

Among the soil characteristics that have been screened for responses to plastic pollution are physical and hydraulic properties (e.g. porosity, bulk density and soil aggregate stability). These are fundamental indicators of the ability of the soil to retain water. This ability in turn affects the energy balance in the soil, and the broader regulation of water chemistry and the microbial community. The physical structure of the soil is also critical for plant germination, root development and primary agricultural production.

Studies have shown that several properties that are critical for soil functionality and fertility respond to stress caused by plastic debris in soil. Examples of the soils properties that were affected include soil aggregation processes and aggregate size and stability (e.g. de Souza Machado *et al.*, 2018; Lozano *et al.*, 2021) soil porosity (e.g. Jiang et al,. 2017), and soil moisture dynamics (e.g. hydraulic conductivity, water holding capacity, and surface desiccation) (e.g. Wan *et al.*, 2019; Qi *et al.*, 2020b).

More recent studies have revealed the sensitivity of different soil properties to low concentrations of plastic. Experiments in which microplastics particles of varying sizes (e.g. 5 microns) and shapes were added to structured soil columns at low concentrations (0.05 percent) found that the water holding capacity of soil was reduced and the water infiltration rate increased (Gu *et al.*, 2023).

A long-term field-scale experiment that involved the controlled addition of mulching film residues (two to three cm in size) showed significant effects on water storage and water in the soil of fields that had been under cotton cultivation for over two years. In this study, the concentration of plastic in the soil was very low (0.006 percent) (Wen *et al.*, 2023).

A similarly designed multi-year study that investigated the effects of the residues of conventional and degradable mulching film (5 cm in size) in the soil of a maize field showed significant effects on soil bulk density,[11] porosity, and soil water storage. These effects were especially pronounced two years after the addition of the plastic debris. The concentrations of both types of plastic was between 0.002 and 0.004 percent (Koskei *et al.*, 2021).

This experiment was repeated under similar environmental conditions and focused on the effects of residues of polyethylene mulching film of different sizes (from 4mm to 10 cm) over a three-year period. This study used higher concentrations of plastic (between 0.02 and 0.04 percent). Results revealed similar responses in soil hydraulic properties, bulk density and soil aggregate size distribution, especially caused by the smaller debris. It was observed that after 30 days of exposure to synthetic microfibres, the aggregate structure of the soil was affected by small particles of microplastic at concentrations as low as 0.001 percent (Boots, Russell and Green, 2019).

Another key property considered in a number of effect-focused studies is soil pH (e.g. Boots, Russell and Green, 2019; Qi *et al.*, 2020b). The pH scale measures soil acidity, which is associated with a number of properties and functions that are pivotal for soil fertility. These include nutrient availability, microbial activity, and organic matter decomposition. Changes in soil pH can affect plant physiology by altering nutrient availability, reducing root uptake efficiency, or causing direct toxic effects. Modifications in soil pH can also increase the bio availability and toxicity of metals present in soil. Increased acidity can lead to leaching of minerals that help maintain soil structure.

Studies showed that the addition of plastic particles to the soil can cause a change of up to one point in soil pH. Such a change, especially when it occurs in the central neutrality range of the pH scale, can have a substantial effect on nutrient availability and the bioavailability of toxic metals.[12] This type of response has been induced in experimental work following treatments with HDPE, PLA or PBAT particles or film residues such as those that can be released by mulching films, at concentrations as low as 0.01-0.05 percent, especially in mesocosm experiments (Zimmerman *et al.*, 2020) or even field experiments (e.g. Boots, Russell and Green, 2019; Zhang *et al.*, 2023b; Greenfield *et al.*, 2022; Dong *et al.*, 2024).

Biological processes regulated by the soil microbiota have also been observed to be sensitive to the addition of plastics in soil (Huang *et al.*, 2019; Fei *et al.*, 2020; Rong *et al.*, 2021). The composition and functioning of the soil microbial community are closely connected to several soil properties. These processes drive nutrient cycling, contribute to the degradation of organic matter, and influence the amount of carbon in the soil. They also affect the speciation, fate and bioavailability of toxic metals, pesticides and chemical additives, including those released from the plastic itself.

The mechanisms and the full extent to which agricultural plastic residues and the chemicals they contain can interfere with soil microorganisms and the causal relations that determine their co-variance with other soil properties are not yet fully understood. Nevertheless, all the studies

---

[11] Soil bulk density is a measure of the mass of soil per unit volume, typically expressed in grams per cubic centimeter (g/cm^3). Soil bulk density includes both solid particles (minerals and organic matter) and the pore spaces between them. It is a critical parameter linked to essential processes (e.g. water movement, root penetration, and soil aeration) often used as an indicator of overall soil health. Higher bulk density values often indicate compacted soil, which may restrict root growth and reduce water infiltration and aeration, whereas lower bulk density suggests a looser soil structure, generally favorable for plant growth.

[12] Bioavailability refers to the extent a substance becomes available to living organisms for uptake.

that looked at the effects of plastic residues on soil microbial communities have yielded significant results, even at relatively low concentration of plastic. For example, an increase of 0.1 percent HDPE or PLA in the soil decreased bacterial diversity and richness, and changed the composition and activity of bacteria that support the cycling of nitrogen in the soil (Zhang *et al.*, 2023b; Lian *et al.*, 2022) Also, conventional plastics (e.g. polyethylene) and biodegradable plastics (e.g. PBAT-based) mulching film residues at concentrations estimated around 0.1 percent of plastic in soil were shown to affect the microbiome. Concentrations at this low level were also shown to increase nitrogen fixation and organic nitrogen degradation. Plastic at these concentrations also affect the plants synthesis genes, and decrease their nitrification genes, leading to higher ammonium concentrations and depletion of nitrite and nitrate in the soil (Rüthi *et al.*, 2023). A field study on the use of microplastics of conventional and degradable polymers added at levels that were ten time lower (i.e. 0.01 percent) also concluded that plastic residues induced a change in nitrogen cycling. The total nitrous oxide emissions were altered, especially by the occurrence of conventional film residues, which caused a two-thirds decrease compared to the cumulative flux in control settings. In this case, however, no significant changes in the composition of the microbial community were detected (Greenfield *et al.*, 2022). The addition of 0.005 percent of conventional microplastics (polypropylene and polyethylene) at the submicron scale (i.e. 0.7-5 microns) significantly increased the activity of nitrogenase (a bacterial enzyme that is crucial for fixing biological nitrogen in the soil) and changed the taxonomic profile of rhizosphere bacteria and had an especially notable effect on the abundance of bacteria involved in nitrogen cycling. Similar results at low microplastic exposure levels have also been confirmed by other studies conducted with different types of soils and plastic residues (e.g. Xu *et al.*, 2023).

Researchers have also studied the effect of relatively low levels of soil plastic pollution on other important processes driven by soil microbes. For example, the addition of 0.01 percent of polyethylene microplastics in rice paddy soil altered the succession of the bacterial community during the decomposition of soil organic matter, which affected the carbon dioxide emissions from the soil (Xiao *et al.*, 2022).

One question that has been under investigation is whether plastic contamination in the soil and the chemical additives they contain can affect the availability and distribution of toxic substances (e.g. pesticides, heavy metals, metalloids, or other organic contaminants). Of the twenty-seven scientific papers that have looked into this question, 18 focus on heavy metal speciation and bioavailability, and the remainder focus on pesticides or organic contaminants. Significant effects on speciation and availability of toxic metals in soils have been observed at plastic concentrations as low as 0.01 percent in pot and mesocosm experiments (Chen *et al.*, 2022b). These effects have noteworthy implications for soil properties, plant growth, and microbial communities, as reported across several studies, including Chen *et al.* (2022b). Studies conducted with environmentally plausible concentrations of plastics in soils showed that microplastics can either reduce or increase the mobility and availability of heavy metals (e.g. cadmium, copper, and zinc) depending on the types of plastics (and including both conventional and biodegradable plastics), their degradation status, soil typology, and the presence of other contaminants (Li *et al.*, 2023a; Sun *et al.*, 2024; Wen *et al.*, 2022; Wang *et al.*, 2024b; Liu *et al.*, 2023c).

THE EFFECTS OF MICROPLASTICS ON SOIL ORGANISMS

An important new area of research focuses on the impacts of microplastics on soil invertebrates (e.g. earthworms, arthropods). This research was not part of the systematic review on microplastics effects on soil fertility and crops addressed by this report. Nevertheless, results of recent studies conducted under realistic or prolonged exposure conditions are noteworthy. Soil invertebrates are important for determining soil properties and maintaining soil health. Most of the available studies were conducted in laboratory settings and focused on how exposure to microplastics affects groups of individual species. They have typically considered exposure to particle types that were not specifically related to agricultural plastics. Most available studies also focused on high levels of concentration. Some of these studies have highlighted significant effects on mortality, reproductions and other physiological or behavioural responses (e.g. Qiu *et al.*, 2022). However, only a limited number of studies have focused on more complex exposure and experimental scenarios (e.g. field or mesocosms experiments). A study conducted under realistic exposure condition (0.05 percent of plastic in soil) showed that earthworms exposed to weathered microplastics originating from polyethylene mulching films, suffered tissue lesions other conditions and had increased levels of pathogenic bacteria in the gut. These effects also appeared to impact the metabolism of the earthworms. The study showed in particular that aged microplastics, with the same characteristics as those found in the environment, have greater toxicity than pristine microplastics typically used in ecotoxicological tests (Jiang *et al.*, 2023). Other studies showed that prolonged (e.g. several weeks) exposure to conventional mulching film residues at realistic concentrations[13] can affect the composition of the soil invertebrate community (Huang *et al.*, 2023), and that earthworms can drag plastic mulch residues into their burrows. This can result in a redistribution of plastics in the soil profile, which could accelerate the ageing and fragmentation processes of these residues (Zhang *et al.*, 2018). One study exposed springtails (class Collembola) to conventional and biodegradable mulching films-derived microplastics under a broad range of concentrations that reflected both realistic exposure scenarios for soils and highly contaminated soils. These organisms did not experience effects on reproduction, survival, endocrine disruption, mutagenesis or developmental toxicity in any of the five generations tested (van Loon *et al.*, 2024).

Knowledge on the effects of plastic residues and microplastics on soil invertebrates under realistic and prolonged exposure scenario remains limited. Given the important role of soil invertebrates for soil health and fertility, addressing this knowledge gap through carefully designed mesocosms or field-scale experiments is important.

The total number of available studies addressing effects of microplastics originating from the use agricultural plastics on soil invertebrates is still limited, but it is an expanding research area. Plastic debris in soil can act as habitat modifiers and can interact directly with these organisms causing effects that are not lethal (Figure 6). Future studies need to focus on both the indirect and direct effects of plastic on soil invertebrates through prolonged multigeneration studies.

---

[13] Refers to the actual levels of plastic pollution found in real-world environmental conditions, rather than in laboratory or experimental settings.

EFFECTS OF MICROPLASTICS ON POLLINATORS

Pollinators, especially bees, are exposed to microplastics through contaminated nectar, pollen, water, airborne particles, and nesting materials. Laboratory studies on honeybees show that microplastics can accumulate in the gut, tracheae, and even the brain, causing intestinal damage, oxidative stress, altered gut microbiota, and behavioural changes such as impaired learning and food intake. Nanoplastics may pose even greater risks due to their small size and ability to cross biological barriers. Most evidence comes from studies using high concentrations and focuses on honeybees, while effects on wild pollinators like bumblebees or hoverflies remain largely unknown. Microplastics may also indirectly affect pollinators by altering floral resources, soil conditions, or pesticide exposure. Field studies are needed to understand the implications for pollination services and food security (Sheng *et al.*, 2024).

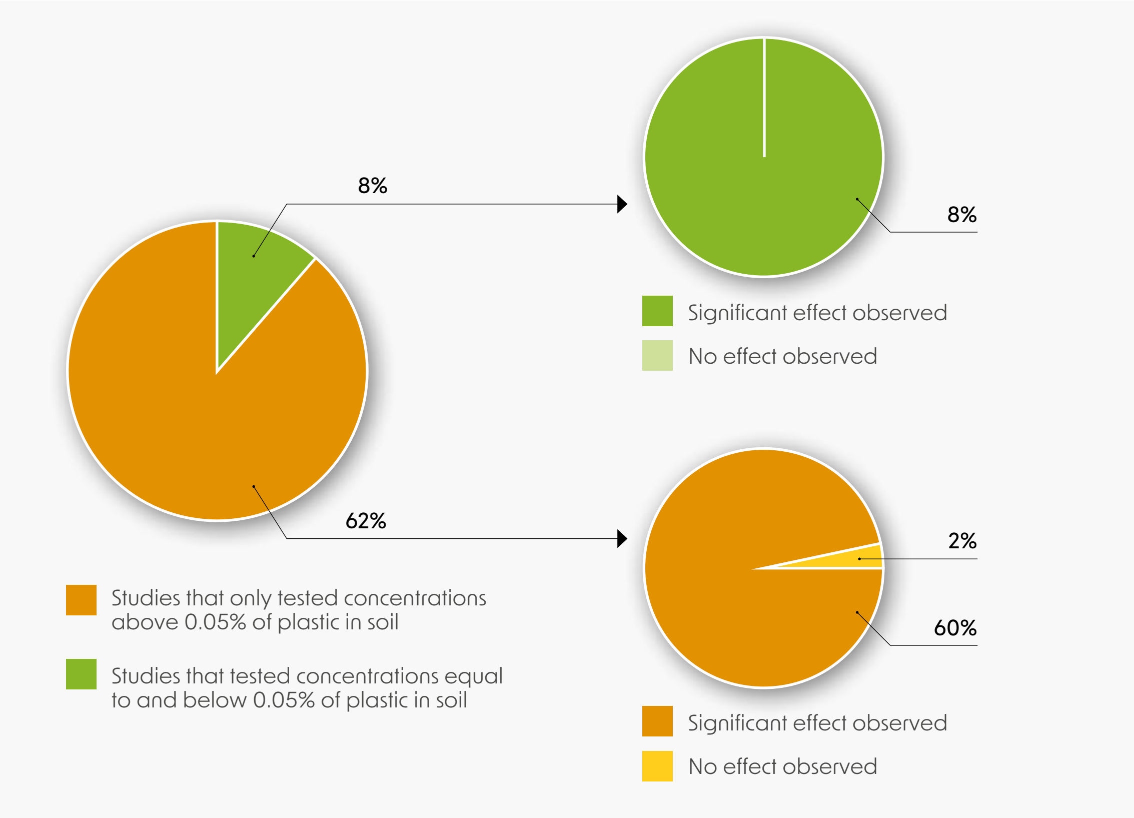
2.7 DOES SOIL PLASTIC POLLUTION AFFECT PLANT HEALTH AND CROP PRODUCTION?

Plastic pollution in the soil is likely to affect plant growth, crop quality and quantity, and the uptake of toxic substances from the soil. These effects have been observed at environmentally plausible concentrations. The systematic review revealed that, since 2016, 114 scientific studies from international peer-reviewed journals had addressed this question. Review papers (32 percent of the total number of retrieved publications) are excluded from this number.

As observed for the literature on soil effects, 80 percent of the experimental studies were published during and after 2022. Nearly all reviewed studies show that exposure to plastic debris in a range of configurations (nano-, micro- or macroplastics) affect one or more aspect of plant growth and quality. Only two studies (van Loon *et al.*, 2024; Chu *et al.*, 2023) that reported on experiments with low exposure levels of plastic concentrations in field conditions reported non-significant effects produced by either conventional or biodegradable plastics. Four other similar field-scale experiments conducted with addition of microplastics made of conventional polyolefins to real agricultural soils, reported instead adverse effects on plant growth and crop yield and quality, including at levels as low as 0.01 percent of plastic in soil (Zhou *et al.*, 2023a; Guo *et al.*, 2024; Palansooriya *et al.*, 2024; Wu *et al.*, 2022). Two additional field-scale experiments show that large debris of both conventional and biodegradable plastic films can affect distribution and growth of non-agricultural plants on sandy littoral soils (Menicagli *et al.*, 2023; Menicagli *et al.*, 2020).

Most of the studies included in the systematic review were conducted under realistic conditions for plant growth: 68 studies focused on experiments conducted in pot or mesocosms; 10 were field experiments; and 22 studies described experiments conducted in hydroponic conditions. The remaining studies were either laboratory experiments, monitoring studies or modelling studies (Figure A2.1 in Appendix 2.). Thus, over 70 percent of the studies (81 in total) focused on controlled experiments to establish a causal link between the addition of plastic debris to soil and observed changes in plant growth, physiology, or health. For 70 of these studies, the exposure level was indicated in percentage of plastic mass in soil (or could be translated into these units) and this enabled the contextualization of the exposure scenario in terms of its environmental plausibility (Figure 7). This type of analysis highlights the prevalence of studies conducted at concentrations above 0.05 percent of plastic in soils. Only eight studies addressed low exposure levels.

FIGURE 7. Proportion of studies on plant effects conducted in realistic exposure scenarios



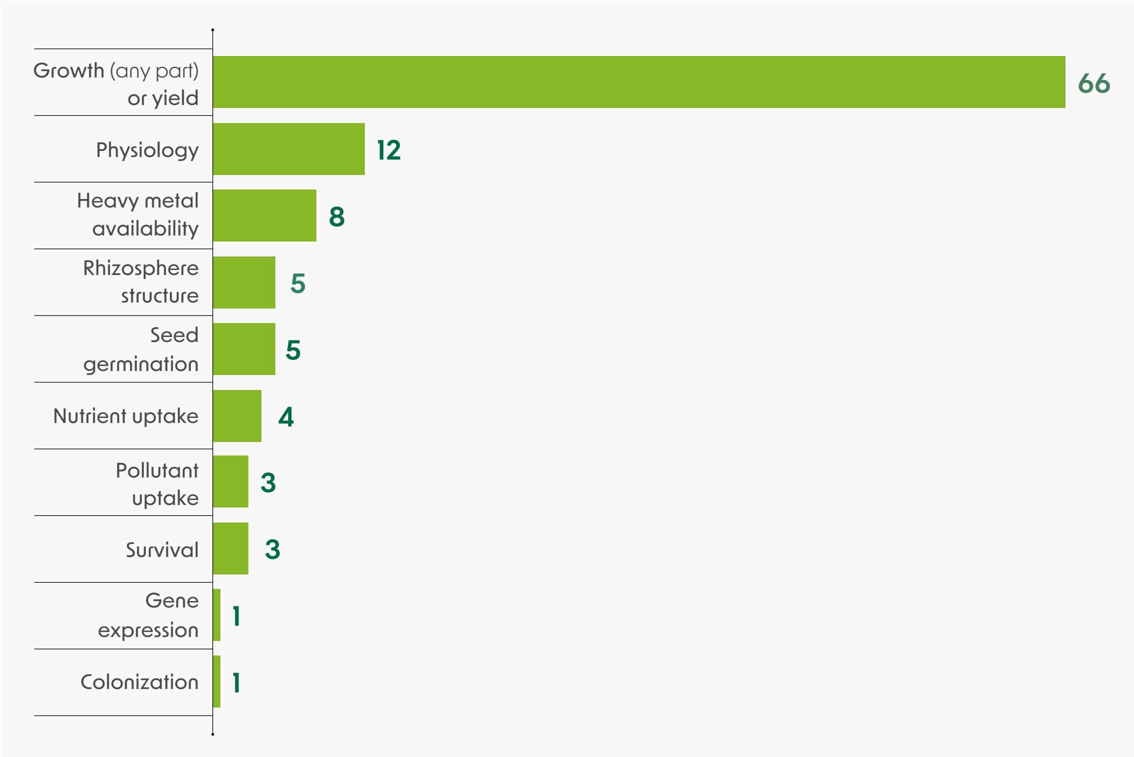
Source: Authors' own elaboration.

Figure A2.2. in Appendix 2 details the number of studies addressing effects on plants of plastic in soil, organized by typology of experiment. Regardless of exposure levels in the different studies, in about 90 percent of the experiments, significant effects on plant growth or quality were observed at the lowest tested concentrations. This finding indicates that the currently available body of evidence is inadequate to draw an accurate assessment of a safety threshold to protect plants from soil plastic pollution. Figure A2.3 and A2.4 in Appendix 2 provides an overview of the frequency at which different plastic concentration ranges have been included in the reviewed studies. Regardless of characteristics and composition of plastic pollution, such a threshold can be estimated to lay below the 0.05 percent level.

Tested materials included mostly microplastics or mesoplastics (e.g. plastic debris larger than 2.5 cm in at least one dimension). Some studies that focused on the effects of mulching film debris, utilized larger residues that were artificially generated by manually cutting the source materials. These residues were obtained from both conventional mulch film (e.g. LDPE) and a range of biodegradable films (primarily based on PLA or PBAT).

As for soils, research on the effects of plastic pollution on plants also focused on multiple effect endpoints (Figure 8). Studies that focused on effects on growth or crop yield accounted for over 60 percent of the studies.

FIGURE 8. Targeted effect endpoints by number of studies



Source: Authors' own elaboration.

Looking more in detail into the studies conducted under more realistic exposure scenarios (field, mesocosms, or pot experiments, and plausible plastic concentrations, such as lower than 0.1 percent) reveals a broad range of observed responses by plants growing in plastic contaminated soils. These included:

- **Growth inhibition**
  There is a prevalence of observed inhibitory effects on individual plant growth or crop yield (e.g. Wu *et al.*, 2022; Wang *et al.*, 2024c; Zhang *et al.*, 2023b; Zhang *et al.*, 2023c; Tong *et al.*, 2022). On the other hand, some studies indicated that microplastic at low concentrations might promote growth in some parts of plants (e.g. Lozano *et al.*, 2021; Wu *et al.*, 2022; Lian *et al.*, 2021; Grifoni *et al.*, 2024). These findings showcase a complex relationship between the characteristics of microplastics and plant response, which can be mediated by changes in the soil habitat induced by the plastic debris.
- **Physiological stress responses**
  Plants exhibit defensive responses to plastic pollution in soil through altered antioxidant enzymes activity (e.g. Zhang *et al.*, 2023b; Sun *et al.*, 2023a; Pehlivan and Gedik, 2021; Li *et al.*, 2024).
- **Altered rhizosphere microbial community structure and activity**
  Both biodegradable and non-biodegradable microplastics can alter the structure and diversity of soil microbial communities, including arbuscular mycorrhizal fungi (AMF), which play a critical role in plant health and nutrient uptake (e.g. Tong *et al.*, 2022).

- **Nutrient uptake**
  Different types of plastic mulch residues were observed to significantly affect the total nitrogen and magnesium uptake by plants, with potential impacts on plant nutrition and health. Such an effect can potentially be mediated by changes induced by plastics in the soil (e.g. Dewi *et al.*, 2024).
- **Soil-plant contamination dynamics**
  The presence of microplastics can enhance the bioavailability and mobility of heavy metals in the soil, influencing the absorption and accumulation in plants (e.g. Lin *et al.*, 2002; Wang *et al.*, 2020).

Based on this evidence, the burgeoning plastic contamination in agricultural soils should be considered as a concern for both food safety and security.

2.8 ARE CURRENT LEVELS OF PLASTICS MEASURED IN AGRICULTURAL SOILS SAFELY BELOW THE EFFECT THRESHOLD FOR SOIL HEALTH AND PLANTS?

A meta-analysis encompassing a critical assessment of the full body of evidence from scientific literature on exposure and effect studies, reveals that several agricultural soils may already be in the 'risk zone' and may already face adverse impacts on both soil health and plant production and quality (Figure 9). The meta-analysis aggregates a high level of variability and uncertainty, nested in the different methodologies and experimental approaches adopted by researchers around the world to analyse plastic contamination in soils and assess effects produced by different types of plastic debris on soil and plant health. The analysis therefore enables the elaboration of a truly evidence-based critical overview aggregating, in this case, data from 371 studies.

The results suggest that:

- All agricultural soils analyzed so far by different studies appeared to be diffusely contaminated not only with debris released by agricultural plastics but also from plastics of different origins and typologies.
- Current contamination levels observed in over 50 percent of agricultural soils analysed fall within the range of concern for adverse effects on soil health and plant production and quality.
- The mismanagement of mulching film, which is prevalent in some regions of the world, is reflected in the characteristic profile of soils contaminated by these plastic materials. However, plastic pollution in agricultural soils is typically heterogeneous, encompassing a mix of macro-, meso-, micro- and possibly nanoparticles in a variety of shapes and compositions. The effects are mediated by this complex mix of materials in soils rather than by specific interactions of one or several types of particles.
- Because of the complexity and diversity of plastic soil contamination, risk assessment approaches should be designed to capture the multiple types of interactions that plastic debris can have on soil components and biota, in order to consolidate knowledge on safety thresholds.

Plastic pollution in agricultural soils is widespread and is not easily reversible. Soil plastic concentrations are likely to increase over time because of use and mismanagement of agricultural plastics, atmospheric depositions, and other sources. Immediate actions are therefore necessary to limit further plastic pollution in agricultural soils, safeguarding food safety, quality, and security. Preventing releases of agricultural plastic into soils and the environment is essential to protect agricultural production and food quality, but it is a challenging undertaking. Addressing the diversity of processes that lead to plastic accumulation in soils will require ambitious policies and a fundamental shift in how plastic is used and managed in agriculture and other sectors.

Few studies have examined the longer-term effects of plastic debris accumulation in soil from agricultural plastics, particularly mulching films. Seventeen studies address the effects of plastic residues on soil properties and/or plant growth and quality under field conditions (Koskei *et al.*, 2021; Wen *et al.*, 2023; Greenfield *et al.*, 2022; Schöpfer *et al.*, 2022; Chu *et al.*, 2023; Zhou *et al.*, 2023a; Wu *et al.*, 2023; Uzamurera *et al.*, 2023; Liu *et al.*, 2023d; Sun *et al.*, 2023b; Bian *et al.*, 2022; Xiang *et al.*, 2024; Ma *et al.*, 2023; Brown *et al.*, 2022; Hu *et al.*, 2020; Ding *et al.*, 2023; Yang *et al.*, 2023b; Zhang *et al.*, 2023c; Quan *et al.*,2024; Tan *et al.*, 2015; Zhang *et al.*, 2022e). However, only four had a time frame that extended beyond 3 years (Ding *et al.*, 2023; Yang *et al.*, 2023b; Quan *et al.*, 2024; Tan *et al.*, 2015; Zhang *et al.*, 2022e). These studies presented

FIGURE 9. Overlap between measured plastic levels in agricultural soils and the concentrations of plastic observed to affect soil properties and plant growth or quality

Source: Authors' own elaboration.

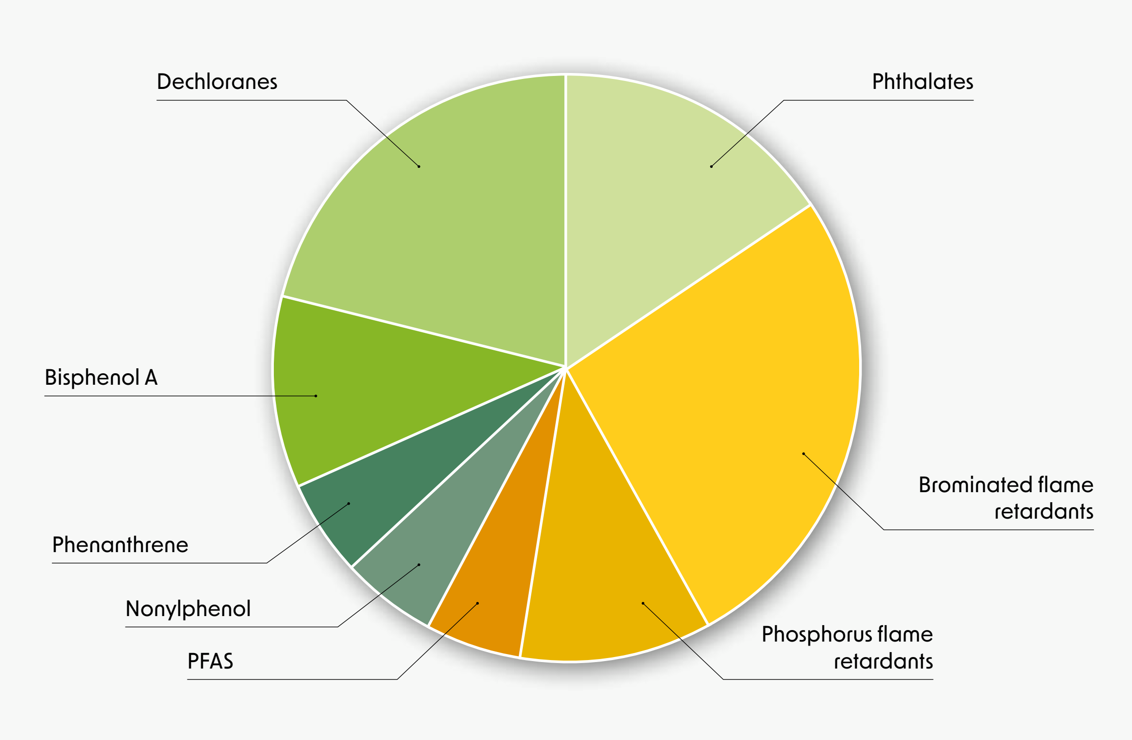
varying conclusions, reporting both positive effects and long-term negative impacts on soil fertility. These apparently contrasting outcomes likely derive from the different experimental conditions adopted, different plastics, differences in measured endpoints and especially different approaches in framing the research questions, the context, and definitions of positive or negative effects. Hence, knowledge on the long-term impacts of agricultural plastics used in fields remains insufficient.

2.9 CAN PLASTICS DEBRIS OR CHEMICALS PRESENT IN PLASTIC BE TRANSFERRED FROM SOIL TO THE CROP AND FOOD?

Thirty-three studies investigated the uptake of nano- and microplastics or of plastic-related chemicals by crops. Nearly all of them produced evidence that both plastic-related chemicals and very small plastic debris (e.g. in the nanoscale range) are taken up by plants in experimental conditions, including hydroponic conditions and soil-based cultivation (e.g. Liu *et al.*, 2022c; Wang *et al.*, 2016; Xu *et al.*, 2021; Kim *et al.*, 2024; Sun *et al.*, 2021). Several widely consumed plants were targeted in the studies. Five crop species received the most attention: maize, wheat, rice, lettuce, and cabbages. These crop species were investigated for plastic and/or related chemical uptake in 78 percent of the studies screened. Figure 10 summarizes the chemicals considered in the crop uptake studies. Among the chemicals used for exposure experiments, dechloranes, phthalates, and brominated flame retardants were investigated in more than half of the studies. Several studies focused on the uptake in roots. Six of these studies also looked at the plants' edible parts, (Kim *et al.*, 2024; Dong *et al.*, 2021; Li *et al.*, 2023b; 2023c; Tang *et al.*, 2023; Abdolahpur Monikh *et al.*, 2022) and demonstrated the possibility of translocation following uptake by the roots. Four of these studies were conducted in pot or mesocosm experiments under realistic growth conditions (Kim *et al.*, 2024; Li *et al.*, 2023b; 2023c; Abdolahpur Monikh *et al.*, 2022). It is noteworthy that the uptake of both plastics and related chemicals within the same exposure experiment was never investigated.

Evidence shows that nanoplastics or, more generally, plastic debris smaller than 1 micron can be taken up by plants. In a recent review paper, which described various mechanisms through which particles of different sizes can enter both root and aerial plant tissues, model simulations aligned well with experimental observations (Liang *et al.*, 2023b). So far, the evidence of the translocation of nanoplastics to edible plant parts is mostly confined to root vegetables. However, some preliminary studies seem to confirm that nanoplastics can also be translocated to above ground edible parts of plants, for example in lettuce and cereals (Li *et al.*, 2023b; 2023c; Tang *et al.*, 2023; Abdolahpur Monikh *et al.*, 2022).

FIGURE 10. Prevalence of plastic chemical additives in studies on uptake in edible plants



Source: Authors' own elaboration.

Technical challenges still affect the analysis of nanoplastics (Pei *et al.*, 2023). However, the existing evidence of uptake and translocation of plastic and plastic-associated chemicals are a source of concern for plant health and food safety. Thousands of chemicals are associated with plastic materials and their fate in plants and through the food chain is still poorly understood. According to most of the analysed studies, both chemicals and small plastic debris are first taken up through the roots (Li *et al.*, 2020b; Bonato *et al.*, 2022), but absorption through the leaves from the air is possible for chemicals typically used as plastic additives (Zeng *et al.*, 2022). Roots, shoots, or stems are usually collected for chemical or plastic quantification, but half of the studies did not analyse the edible parts of those crops. A complete understanding of the implications of soil plastic pollution for food safety is far from available. Nevertheless, more recent studies are paving the way for future research to focus on this aspect (e.g. Liu *et al.*, 2022c).

It is well known that certain practices expose farm animals to ingestion of agricultural plastics, especially chopped net wrap used in haybales (Pizol *et al.*, 2017; Gaylon *et al.*, 2023). Feeds produced from food waste can also be heavily enriched by residues from plastic food packages. A high occurrence of phthalate plasticizers was observed in a 2022 study in China (Xu *et al.*, 2022b). Beyond this evidence, and despite the rising concerns among farmers and practitioners, knowledge of the implications for both animal health, trophic transfer, and food safety is conspicuous by its absence.

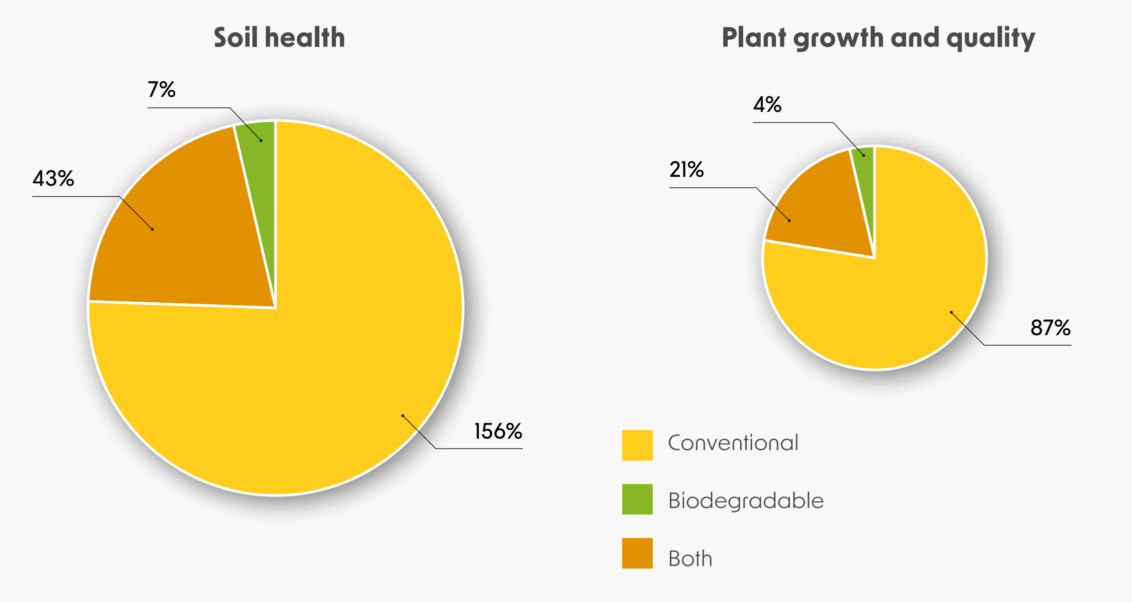
2.10 ARE BIODEGRADABLE PLASTICS A SAFER ALTERNATIVE FOR AGRICULTURAL APPLICATIONS?

Biodegradable and compostable plastics have been proposed as potential options for addressing the pollution and issues of waste generation and handling that are associated with the use of conventional non-degradable plastics in agriculture. After use, these materials are generally left in the field and often mixed into the soil where they degrade. However, compostable plastics need to be collected and processed in a composting facility.

For biodegradable plastics, the biodegradation rate depends on the conditions of the natural environment (e.g. soil) or composting environment. Particularly important factors are the temperature, moisture, and pH, the microbial community composition, and the physical and chemical characteristics of the materials. These characteristics include shape, the type of polymers, and the type and abundance of the mix of chemicals and filler materials added in the formulation. A given biodegradable plastic can degrade at different rates under different conditions. Biodegradation converts the materials into carbon dioxide, water, mineral salts, new microbial biomass, and in some cases, methane. During degradation, the mix of chemicals and fillers present in the formulation (which can be as complex and toxic as that of non-degradable plastics) (Zimmerman *et al.*, 2020) can be released from the polymer matrix. In this case, their fate and behaviour can be uncoupled from that of the source material (European Commission Directorate-General for Research and Innovation. 2021). Biodegradable plastics are also subject to the same physical processes that causing the embrittlement of conventional plastics (e.g. mechanical stress, temperature variations, solar radiation, and fragmentation by animals). They however appear to be generally more susceptible to these processes compared to conventional plastics (Nizzetto *et al.*, 2024). Large items made of biodegradable plastics can therefore break down easily and become source debris (including microplastics) in the soil or the composting environment, which can eventually be biodegraded if the conditions allow. For oxo-degradable plastics (see Figure), this degradation process, which is of a physical nature and does not depend on biological processes, rapidly produces large numbers of micro and nanoplastics that may persist for a long time when mixed in the recipient environments.

To date, scientific evidence from controlled experimental studies on the effects of plastic debris, mulching film residues, and microplastic in soils and plants under realistic contamination levels does not indicate that biodegradable plastics are safer than conventional plastics. In the scientific literature, most studies address the effects of plastic debris made of conventional plastics. However, the number of studies that also tested biodegradable plastics has rapidly expanded in recent years (Figure 11). The main types of bioplastics included in these studies are PLA, poly(butylene succinate-co-adipate) (PBSA), and PBAT. These bioplastics often take the form of microplastics or mulching film residues and are typically generated by cutting the source materials (e.g. mulching films) by hand or by mechanically reducing plastic particles to the micron range (micronization).

FIGURE 11. Number of studies addressing effects of plastic pollution on soil health and plant growth and quality, by type of tested plastics



Source: Authors' own elaboration.

It is important to recognize that biodegradable agricultural plastics currently in use worldwide are made from a variety of polymeric compositions and formulations. Materials based on PLA and PBAT, for example, are commonly used in mulching applications. A broader range of bioplastics is also employed in polymeric microencapsulations for agrochemicals and seed coatings. Different polymeric compositions vary significantly in their degradability in soil. For example, PLA requires treatment in composting facilities for complete degradation. Unfortunately, due to mislabelling and a lack of standardization and certification, materials not certified for degradation in the soil are often left in the soil after use, regardless of their actual capacity to degrade under those conditions. As a result, toxicological studies have correctly focused attention on both soil biodegradable and compostable materials with variable compositions. This reflects how these materials are actually used in different regions, even though some of these products are not permitted to be left to degrade in the soil in certain jurisdictions (e.g. European standard EN 17033).

Regardless of typology, shape, or composition of these bioplastics, scientific evidence shows that similarly to conventional plastic pollution, biodegradable and compostable plastic debris can produce significant effects on soil characteristics and plant growth or quality. This was observed in nearly all the studies conducted so far. There were only two exceptions (Schöpfer *et al.*, 2022; Chu *et al.*, 2023). Evidence suggests that these materials can significantly affect soil quality and plant growth at relatively low and plausible levels (e.g. 0.02 percent). For instance, a pot study (Li *et al.*, 2023d) compared the effects on the soil of PBAT and LDPE microplastics obtained by crushing virgin polymers. The results revealed that PBAT could affect several soil chemical properties, such as electrical conductivity and the different forms that nitrogen, phosphorus, and nitrogen can take. Low levels of PBAT enhanced bacterial community richness, while higher levels decreased it. PBAT promoted nitrogen fixation in soil but reduced phosphorus content.

In another study using similar low exposure levels (Lin *et al.*, 2022), biodegradable polypropylene carbonate (PPC) and PLA microplastics were found to have contrasting effects on cadmium uptake in rice plants. PPC decreased this toxic metal accumulation in both the roots and aerial parts of rice, while PLA increased its concentration in the roots. Changes in the soil bacterial community were observed, with PPC mitigating and PLA exacerbating the stress on bacteria caused by cadmium.

Another recent study looked at the impact of polycaprolactone microplastics on soil microbes and plant growth, particularly oilseed rape and lettuce (Li *et al.*, 2024). This study found that a concentration of 0.02 percent of polycaprolactone microplastics in the soil did not significantly alter the overall structure and diversity of soil microbial communities or affect plant growth in a lasting way. However, there was a temporary effect on soluble protein in plant leaves and a permanent reduction in levels of malondialdehyde (an organic chemical compound known to be mutagenic and carcinogenic) in lettuce.

Similar studies that have investigated slightly higher levels of plastic exposure and used more realistic test materials have yielded similar results. For example, impacts of the debris of PBAT mulching films (in microplastic form) on root growth and soil enzymes in soybeans and maize have been documented at 0.1 percent of plastic in soil after the controlled addition of artificially generated particles (Yu *et al.*, 2023).

These findings indicate that PBAT microplastics in the soil can inhibit root development and affect soil enzyme activities involved in the carbon/nitrogen balance. These changes could have a negative impact on crop yields. The study suggests caution in using biodegradable plastics.

In an 8-week pot study (Zhang *et al.*, 2024), a concentration of 0.3 percent microplastics derived from PBAT-based mulching film in the soil was shown to affect the soil carbon cycle by decreasing particulate organic carbon and increasing dissolved organic carbon. At the same time, concentrations of phthalate esters (a group of common plastic additives) in soil also increased in the soil.

A two-year-long field study (Uzemurera *et al.*, 2023) compared the effect of tilling of various types of plastic films, including thick and thin polyethylene and biodegradable residues, in a semi-arid maize field. The thin biodegradable film residues were shown to have a greater effect on soil quality and maize productivity than thick film residues in terms of reducing soil water content, increasing soil bulk density, decreasing soil porosity, and altering soil nitrate and ammonium content.

Another multi-year experiment, which was conducted in field conditions (Sintim *et al.*, 2019), focused on repeated mulching applications (rather than on the controlled addition of mulching film residues to soil). The study provided an assessment of the effects produced by mulching practices with a range of different biodegradable plastic films compared to no-mulching, mulching with conventional plastic film, or mulching with biobased cellulose film. The study observed significant effects of some of the mulch treatments on soil aggregate stability, water infiltration, soil pH, electrical conductivity, nitrate-N, and exchangeable potassium, as well as on soil health indicators (hydraulic and biological properties, and fertility) and nutrient cycling. However, these effects were not consistent across all biodegradable plastic mulches and sampling times. This suggests that while biodegradable plastic mulches may be a viable alternative to polyethylene films, an evaluation based on long-term studies is needed.

Some of the observed effects on plants, including several common crops, caused by concentrations equal or lower than 0.1 percent of biodegradable plastic debris in the soil are:

- changes in the uptake of nitrogen (Wang *et al.*, 2024c; Dewi *et al.*, 2024);
- changes in the uptake of magnesium uptake (Dewi *et al.*, 2024);
- reduced root growth (Lian *et al.*, 2022), possibly mediated by responses in enzymatic activity at the level of the rhizosphere (Yu *et al.*, 2023);
- reduction in shoot biomass (Wang *et al.*, 2024c; Liu *et al.*, 2023e);
- changes in the number of leaves (in lettuce) (Wang *et al.*, 2024c);
- changes in chlorophyll content (Wang *et al.*, 2024c; Liu *et al.*, 2023e);
- changes in photosynthetic parameters (Wang *et al.*, 2024c);
- changes in the nitrogen, phosphorus and potassium content in leaves (Wang *et al.*, 2024c; Liu *et al.*, 2023e);
- accelerated accumulation of hydrogen peroxide and superoxide (Lian *et al.*, 2022; Wang *et al.*, 2024c);
- increased malondialdehyde (Wang *et al.*, 2024c; Li *et al.*, 2024);
- a decrease in soluble proteins content in leaves (Li *et al.*, 2024); and
- increased accumulation of cadmium in roots in rice (Lin *et al.*, 2022).

Both negative and positive effects on plant growth have been observed in some studies, depending on the added dose (e.g. Grifoni *et al.*, 2024; Yang *et al.*, 2021). Several of these responses were observed to be similar between treatments with biodegradable plastic and conventional plastic microparticles.

Some evidence suggests an enhanced susceptibility of soil properties and plant health to biodegradable plastic debris in soil compared to conventional plastic. A 2024 study observed that PBAT microplastic have significantly greater impacts on oxidative damage, photosynthetic rate, soil aggregation, microbial activity, and soil ammonium than produced by polyethylene microplastics (Wang *et al.*, 2024c).

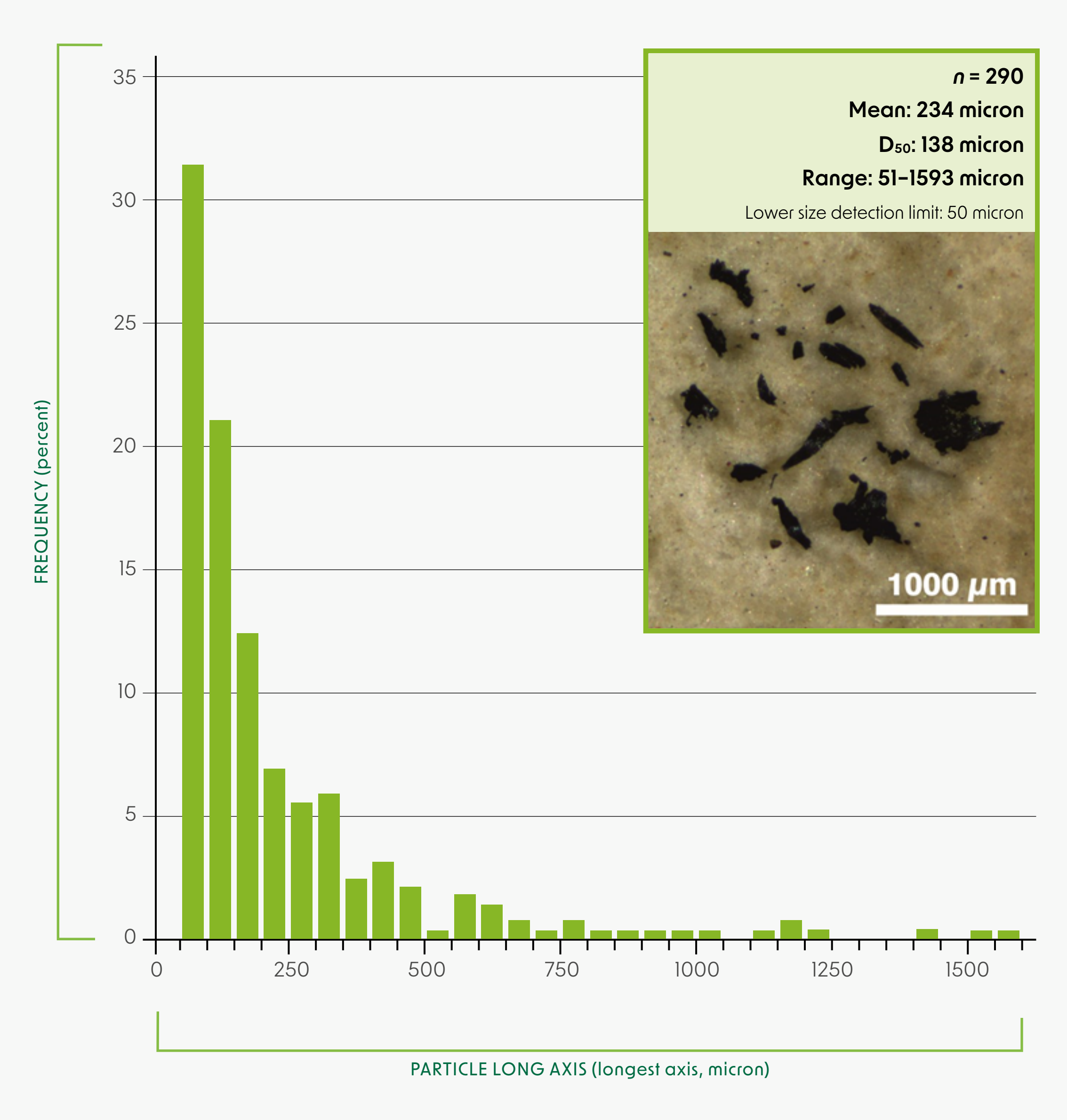
These are still preliminary results. Nevertheless, these studies addressing the effects of bioplastic residues in agricultural soils sound a warning about the need for precautionary risk assessments or risk management approaches when using use of these materials. It must be acknowledged that bioplastic use in agriculture encompasses a broad range of products with varying compositions of polymers and chemical additives. Chemicals substances used as additives in biodegradable plastic can be similar to those used in conventional plastics and can include recognized hazardous substances (Zimmerman *et al.*, 2020). Some bioplastics are not specifically designed to biodegrade in the soil. Proper labelling, traceability, standardization and certifications are instrumental for ensuring the safe use of these materials and preventing long-term soil pollution.

Addressing the ecological risks associated with the use of these materials requires a clear definition of exposure scenarios. For example, data on the characteristics of the residues of biodegradable mulching film and their long-term accumulation in soil are conspicuously scarce. A simplistic approach to estimating exposure concentrations for risk assessments of the residues of biodegradable mulching film have been proposed that assume a single application of the film and complete degradation within one or two years (Degli-Innocenti, 2024). Testing realistic exposure gradients is crucial for the characterization of ecological risk. However, more detailed and cautious estimates are likely needed to develop exposure scenarios. These scenarios should account for the range of test materials and be based on a better assessment of degradation rates in real operational environments. It has been suggested that concentrations of residues of biodegradable mulching films between 0.004 percent and 0.4 percent can be considered as plausible (Nizzetto *et al.*, 2024).

Evidence of the accumulation in the soil of debris of certified biodegradable film is slowly emerging thanks to improvements in chemical analyses (Figure 12). The results show that the residues fall within the microplastic size range and have a distribution pattern similar to that of conventional microplastics in soil. A 2022 field trial (Schöpfer *et al.*, 2022) highlighted the persistence of biodegradable mulching film residues in soil environment. There is concern in the scientific community over the effective degradability of these materials in certain environmental conditions (e.g. water environments formed by soil runoff or cold environments) (Nizzetto *et al.*, 2024). Research is ongoing in this area, but information is currently insufficient to assess the persistence of soil pollution derived from biodegradable agricultural plastics.

© FAO

FIGURE 12. PBAT-based biodegradable mulching film residues in soil sample from a Norwegian farm



The image visualizes the size distribution of 290 particles of PBAT-based biodegradable mulching film residues found in soil samples from a Norwegian farm. The x-axis shows the length of particles (in microns); the y-axis indicates the frequency (percentage of total particles) in each size range. The median particle size (D_{50}) is 138 microns. The image shows a microscope view of selected particles.

Source: **Ranneklev, S.B., Hurley, R., Bråte, I.L.N. & Vogelsang, C.** 2019. Plast i landbruket: kilder, massebalanse og spredning til lokale vannforekomster (Plastland). Norsk insitutt for vannforskning. https://niva.brage.unit.no/niva-xmlui/handle/11250/2632595

Chapter 3. Knowledge gaps, priority measures and policy implications

3.1 SYNTHESIS OF MAIN CONCLUSIONS FROM THE REVIEW OF SCIENTIFIC RESEARCH ON AGRICULTURAL PLASTICS AND SOIL PLASTIC POLLUTION

- Significant international research efforts in recent years have substantially advanced our understanding of the ecological risks posed by agricultural plastics, though knowledge gaps remain in some areas such as long-term ecosystem impacts and standardized assessment methods. Scientific research has consistently and comprehensively documented that plastic pollution in soils is a serious environmental issue with measurable impacts on soil health, crop productivity, and ecosystem function. This situation is demonstrably worsening over time due to increasing plastic use and accumulation rates and has already begun to have significant consequences for food security and safety, with projections indicating these impacts will intensify without intervention. Reported concentrations of plastics (in the form of microplastics) in most agricultural soils analysed to date range from below 0.001 percent to 0.3 percent. However, because quantitative assessments typically only address microplastic debris and overlook larger debris, these figures are likely to underestimate the total level of plastic in soils.
- Data on soil contamination are fragmentary and available only from some regions and some soil types. Nevertheless, soil microplastic pollution is likely to be a problem everywhere. Several laboratory and field studies show that microplastic pollution at concentrations below 0.05 percent of plastic in the soil can affect the physical and chemical properties of the soil as well as plant growth and quality regardless of the composition and size distribution of the plastic particles. Also, the ability of crops to accumulate and translocate small plastic particles and plastic-associated chemical substances into the edible part of the plant has been confirmed by most studies.
- Current levels of plastic pollution in agricultural soils are already in the range in which adverse effects on soil health and plant growth and quality are likely to occur. Agricultural soils appear to be important environmental recipients of plastic pollution.
- Some of the plastics used in terrestrial agriculture or the mismanagement of these plastics are important sources of soil plastic pollution. In some cases, agricultural plastics are responsible for extreme levels of pollution. Soils not directly affected by the mismanagement of agricultural plastics can also contain debris derived from agricultural plastics. Even standard practices for mulching film, the use of micro-encapsulations for seeds, fertilizers or pesticides, and plastic clips and other plastic items used in agriculture can act as a source of plastic pollution in soils.

- Biodegradable plastics have been proposed as safer alternatives. However, their use in agriculture also results in the temporary addition of plastic residues, microplastics, chemical additives or filler materials in soils. These inputs can have similar environmental effects as conventional plastics. Levels of the biodegradable plastic in soils can increase considerably if the rate of application exceeds the rate of degradation. To date, insufficient knowledge exists on the actual degradation rates for biodegradable plastics in real operational environments.

Although an exhaustive risk assessment has not yet been completed, these findings reinforce the fact that that there is an urgent need to take effective measures to preserve the health and productivity of agricultural soils by preventing any further voluntary addition of plastic pollution from agricultural plastics and reducing, as much as possible, unintentional releases of plastic in soils from both agricultural and non-agricultural activities.

There is much that remains unknown about agricultural plastics. These knowledge gaps have important consequences for managing the risks associated with the use of plastic in terrestrial agriculture and implementing the necessary measures to guarantee that the use of these plastics is sustainable. These gaps can be clustered around different aspects of the risk assessment and management (e.g. sources, exposure and impacts) and at different stages of the life cycle of agricultural plastics. The following sections describe in greater detail these knowledge gaps, their implications, and measures that should be prioritized to address them. The insights presented here are based on:

- information and data extracted from the systematic literature review presented in the previous chapter;
- information that has been gathered from stakeholder submissions contributed to the Global Forum on Food Security and Nutrition (FSN Forum) and analysed in a FAO report (Karasik *et al.*, 2024);
- a series of round tables and stakeholder dialogues organized as part of the PAPILLONS and MINAGRIS European stakeholder forum on agricultural plastics;
- a series of international digital round tables organized by the International Knowledge Hub Against Plastic Pollution (IKHAPP);
- an analysis conducted among international stakeholders through a digital survey (Tartiu *et al.*, 2024);
- information extracted from recent academic publications focusing on sustainable management of plastic in agriculture; and (Briassoulis, 2023; Hoffman *et al.*, 2023; Wagner *et al.*, 2024); and
- policy briefs released by scientific organizations (The Scientists' Coalition for an Effective Plastic Treaty, 2024).

3.2. KNOWLEDGE GAPS ON THE DISTRIBUTION AGRICULTURAL PLASTICS ON FARMS AND THEIR WASTE MANAGEMENT

There has been an increased focus by the research community on developing and deploying methodologies for compiling inventories on plastics used in agricultural plastics at local, national and regional levels. However, the validated data that is available remain highly fragmentary. Little progress has been made on global estimates since the 2021 FAO report. Some ongoing research initiatives with national and regional scopes are making advances in this field, and more high-quality data may become available in the next few years. The introduction of new technologies (e.g. aerial surveys, remote sensing and machine learning) is critical for increasing the rate of data generation and expanding the knowledge base. These technologies will support the establishment of agricultural plastics inventories over large geographic scales.

The mismanagement of waste generated by the use of agricultural plastics is a significant driver of plastic pollution. Establishing accurate quantitative estimates of the impact of these environmentally damaging practices is crucial for prioritizing interventions to reduce plastic pollution from agriculture and understanding the relative significance of this source of plastic pollution compared to other sources (e.g. contaminated organic fertilizers, atmospheric deposition).

PRIORITIZED MEASURES TO FILL THE GAP

Measures that should be prioritized to address the lack of a reliable and comprehensive inventory of agricultural plastic use, the waste generated from this use, and waste management practices include increasing data openness from the private sector about production volumes, the distribution of agricultural plastics at the subnational level, and the chemical composition and technical properties of these plastics. This openness would apply to all private commercial enterprises involved in the manufacturing and distribution chain. Developing and applying data mining tools that can enable risk assessors, risk managers, agrifood producers and scientists to extract data and validate its quality is also important. Establishing a network of 'living labs' clustered in different regions where farmers, retailers or waste managers can contribute to providing information on the diffusion of agricultural plastics, the generation of waste, and the reporting of waste mismanagement would also be a step in the right direction. Supporting multistakeholder research projects in different regions to gather quantitative data on waste management practices for agricultural plastics on farms and beyond would also be valuable. Also, environmental or agricultural authorities could support the development and demonstration of innovative surveillance technologies and systems for the detection, reporting and registration of environmentally damaging and illegal practices for managing the waste generated by agricultural plastics.

IMPLICATIONS FOR POLICY MAKING

Increasing the knowledge base about the distribution of agricultural plastics and waste management practices will have important implications for policies and regulatory systems. Tools and measures to assess and manage ecological risks will make it easier to identify potential options for reducing the negative environmental, agricultural, and social impacts of unsustainable practices and inadequate waste management. More information on the distribution and waste management of agricultural plastics will also be instrumental for ensuring the fair allocation of responsibilities among various stakeholders in the sustainable use and management of agricultural plastics through frameworks such as Extended Producer Responsibility (EPR) schemes. Data from surveys and inventories will guide agricultural planning and regulatory actions that can protect soil health, support the design and implementation of soil monitoring activities, and prevent microplastic contamination. Inventories of agricultural plastics would contribute to setting evidence-based policies, building institutional capacities, and creating economic incentives to adopt best practices throughout the life cycle of agricultural plastics. These inventories would provide critical data to facilitate the redesign of products toward more sustainable alternatives, improve waste management infrastructure efficiency, and contribute to creating effective deterrence against illegal disposal practices through enhanced monitoring and enforcement mechanisms

3.3. KNOWLEDGE GAPS ON AGRICULTURAL PLASTICS AS SOURCES OF PLASTIC POLLUTION TO SOILS

There is currently no quantitative assessment of the emission rate of plastic pollution in soils from the routine use of agricultural plastics. Assessments of plastic pollution from agricultural plastics would need to include macro-, meso-, micro-, nanoparticles. Polymer science and agricultural technology researchers have studied the aging process of agricultural plastics. However, research activities to establish a quantitative link between the aging of agricultural plastics during 'normal operations' and the release of plastic debris and chemical additives are largely non-existent. When this knowledge becomes available and is linked to information on agricultural plastics inventories and distribution, it will generate important data for assessment of the role of plastics in agriculture as a source of plastic pollution compared to other types of sources. This is crucial for the prioritization of interventions to protect soils from plastic pollution.

Studies on plastic pollution resulting from agricultural plastics have primarily focused on the correlation between plastic concentrations in soils and the history of using mulching films or other agricultural plastics-based film applications. Few studies have addressed the applications associated with the intentional release of microplastics, such as the use of polymeric encapsulations for agrochemicals. Additionally, there is still a very limited understanding of both the intentional and unintentional releases of substances of concern contained in plastics, which is critical for conducting a comprehensive risk assessment. The role and relevance of other agricultural plastics-based practices as sources of soil pollution, including emerging applications (e.g. hydrogel polymers in superabsorbents) have not been sufficiently explored.

While agricultural plastics, particularly plastic mulch films, appear to represent the dominant source of plastic pollution in many agricultural soils based on emerging evidence, comprehensive quantitative assessments of the relative contribution from all plastic sources remain limited. Multiple plastic inputs to soils have been identified, including sewage sludge application, irrigation systems, and atmospheric deposition, but standardized methodologies for source attribution and system-wide quantitative comparisons are still developing. This situation, combined with significant geographic and system-specific variations, continues to impede fully adequate prioritization of actions to safeguard the health of agricultural soils, though current evidence suggests that addressing agricultural plastic use should be a primary focus. Most studies on the occurrence of plastic pollution related to the use of agricultural plastics have been carried out in China. The applicability of these findings for assessing exposure levels in other parts of the world is uncertain. There is also a general lack of comparability between these studies because of differences in sampling methods, analytical protocols and approaches for reporting data. Consequently, data from different studies cannot be reliably used as part of a regional or global assessment. There is an urgent need to harmonize approaches for carrying out research on plastic pollution related to agricultural plastics so that meaningful comparisons can made in different soils and regions, and monitoring datasets can be established. These harmonized datasets could serve to identify pollution hotspots where there are particularly serious concerns for food production. Furthermore, while there is some evidence that plastic pollution levels in soils tend to increase over time (e.g. as a result of continuous applications of agricultural plastics, atmospheric deposition, the application of contaminated organic fertilizers), the fate and behaviour of micro- and nanoplastic in soils remain uncertain. Understanding the fate of plastics in the soils is essential to evaluate to what extent plastic contamination is reversible and estimate the required recovery time for contaminated soils.

PRIORITIZED MEASURES TO FILL THE GAPS

Measures that should be prioritized to fill knowledge gaps about the relationship between agricultural plastics and soil pollution include promoting practices that enhance cooperation among multiple stakeholders (producers, users, waste managers, scientists, policymakers, and civil society) to rapidly increase the knowledge base about pollution sources from agricultural plastics. This work must cover the design of agricultural plastic products, handling practices, and environmental conditions (including soil type, temperature, and climatic factors) in which they are applied. This should also include developing alternatives and biodegradable substitutes, as well as expanding efforts to characterize the aging and degradation processes of different materials under various environmental conditions. To accomplish this, it is imperative to improve and harmonize analytical methods using systematic frameworks to ensure reliable and comparable data that can support risk assessments and risk management. When these improved and harmonized analytical methodologies have been validated, they should be applied over broad geographic scales using both ground-based monitoring and satellite-based detection technologies. In some regions, this would require building research and monitoring capacities through international collaboration and knowledge transfer programs.

IMPLICATIONS FOR POLICY MAKING

Addressing knowledge gaps about the relationship between agricultural plastics and soil pollution is crucial to raise awareness among the stakeholders about the ecological and agricultural risks associated with the use of these plastics. This is a prerequisite for building the political will to formulate sound policies for environmental protection and sustainable agricultural development.

Quality data gathered from monitoring plastic pollution in agricultural soils, along with new and accurate inventories of pollution sources that have been created through improved analytical capacities are essential for the prioritization of policies and policy instruments at national and regional levels. This data and inventories are also required for establishing baselines and temporal data series that can be used to evaluate policy effectiveness. Quality monitoring data are also necessary for identifying pollution hotspots and designing and adjusting these interventions more effectively. Greater knowledge about the degradation behaviour of agricultural plastics in their operational environment is critical for guiding industrial innovation through initiatives from the private sector and the development of technical and environmental standards in the public policy sphere. The availability of monitoring data on plastic pollution in agricultural soil, and an understanding of the agricultural practices that are responsible for this pollution, are needed to safeguard food security, assess food safety, and manage risks.

3.4. KNOWLEDGE GAPS RELATED TO THE DESIGN AND USE OF AGRICULTURAL PLASTICS

Awareness of the problem of plastic pollution in soils has emerged only recently, and the awareness of agricultural plastics as a source of this pollution is even more recent. The first quantitative estimate was established in the 2021 FAO report. This estimate helped to catalyse innovative measures to develop more environmentally friendly products and practices. A number of research and development initiatives from the independent research community and the private sector have been launched over the past two or three years. These initiatives have included activities to formulate new technical specifications, develop new machinery for clean and safe retrieval, establish labelling and tracing systems, and create extended producer responsibility (EPR) systems for handling waste. To date, none of these innovations or claims have been exhaustively assessed for effectiveness by the scientific community or thoroughly validated. However, this expected to happen soon.

As concern has grown over soil pollution caused by the use of conventional agricultural plastics, claims have been made that suggest that biodegradable plastics may be an environmentally friendly alternative because they do not lead to the accumulation of plastic residues in soil. However, emerging evidence indicates that microplastics and other debris from biodegradable plastic are found in soils. Finding indicate that these materials may degrade slowly in certain environments (e.g. in soils in colder regions). When application rates exceed degradation rates, there is the possibility that concentrations of debris from biodegradable plastics in the soil will increase. These concentrations would continue to increase unless the use of the biodegradable plastics is suspended for a sufficient amount of time to allow for the complete degradation of the material.

PRIORITIZED MEASURES TO FILL THE GAPS

Actions that should be prioritized to fill current knowledge gaps related to the design and use of agricultural plastics include:

- increasing opportunities for collaborative research and development between bioplastic industry and environmental and ecotoxicology researchers, with a focus on the independent testing and evaluation of new designs in operational environments;
- promoting holistic thinking about the design of conventional and biodegradable agricultural plastics that brings together representatives from industry, farmers, waste managers and researchers to establish standards for quality and sustainability (e.g. accounting for the carbon fingerprint of the products), traceability systems, labelling regulations, technical designs, best practices, and dedicated equipment for the safe handling of the materials in field and in post-use; and develop training programmes for stakeholders along the entire value chain to ensure compliance with these specifications;

- establishing validated methodologies for detecting and quantitatively assessing the residues from biodegradable agricultural plastics in the soil, and carrying out monitoring activities to assess the scale of the occurrence of biodegradable plastic debris in agricultural soils so that risk assessments can be done; and
- addressing the knowledge gaps about the presence, fate, behaviour and effects of the chemicals and other components of biodegradable plastics or that result from the partial degradation of polymers.

POLICY IMPLICATIONS

The measures prioritized above can contribute to the development of innovative designs and an expanded knowledge base that could support the implementation of policy initiatives that phase out harmful and obsolete products and practices.

The formulation of more effective standards and regulations on biodegradable agricultural products involves bridging the knowledge gaps on the environmental performance of the materials currently in use in different operational environments, and the testing and evaluation of materials that will enter in the market in future. Gaining a better understanding the potential negative aspects of biodegradable plastics is crucial for properly tailoring incentives and plans for promotion or deterrence measures concerned with the use of these materials.

When planning these mea sures, consideration should be given not only of the immediate agricultural or economic benefits, but also local or regional specific needs. For example, there may be a need to to build resilience to the impacts of climate change impacts through the use of plasticulture in areas where sufficient waste management infrastructure is lacking. A holistic assessment of the social and environmental costs and benefits should be considered. When there is insufficient knowledge to carry out a complete socio-environmental cost-benefit analysis, the precautionary principle should shape decision making to avoid regrettable solutions.

3.5. KNOWLEDGE GAPS ON THE IMPACTS OF AGRICULTURAL PLASTICS POLLUTION ON SOIL AND CROP HEALTH

The body of evidence that shows that plastic pollution in soils can cause adverse impacts on soil health and plants at environmentally plausible and observed levels is expanding. However, significant gaps remain. To date, studies have been unable to draw quantitative conclusions related to risk thresholds and the underlying mechanisms that determine the complex ecological responses to plastic pollution. This inability stems from a range of factors.

- While some soil properties can be affected by the addition of plastic particles (e.g. residues from plastic mulching film), the mechanisms that cause these variations in different soil properties have not yet been clearly delineated. Given this uncertainty, risk assessments should first identify early warning responses from sensitive variables that control fundamental ecological or physiological processes as metrics for the definition of risk.
- The available studies have considered high concentrations of plastic in soils and narrow exposure gradients. For example, in several studies, only one concentration level of plastic was tested. This is not sufficient to characterize the risks of plastic pollution to soil health and plants.

- Regardless of the adopted exposure scenarios, the majority of the studies conducted to date have observed significant effects on one or more soil properties or plants attributes at the lowest tested concentrations. This suggests that most studies have missed the range for exploring non-effect safety thresholds.
- Only a limited number of studies have explored effects under realistic field conditions where responses may be different from those observed in laboratory conditions.
- There are no studies measuring the long-term effects of the presence of micro and nanoplastics and their associated chemicals in soils.
- There is not a clear understanding of the mechanisms controlling the direct and/or indirect interactions that link micro and nanoplastics in soils to the impairment of plant growth and physiology.
- The risk components associated with the mix of chemicals released to the soil from plastic is not well enough understood. Given the complexity of this mix, hazard-based prioritization should be employed to identify a first tier of substances of the highest concern. This initial prioritization could be based for example on indicators of persistence, bioaccumulation, mobility, and toxicity (Wagner *et al.*, 2024).

An increasingly large body of evidence suggests that plastic debris and microplastics from biodegradable agricultural plastics can have similar effects as conventional plastics on soil properties and plants. However, there is not sufficient data and knowledge available to assess safety exposure levels for biodegradable agricultural plastics. The exposure scenarios used to assess effects of debris from biodegradable agricultural plastics are potentially affected by a technical bias linked to the difficulty in generating fully representative test materials and the lack of empirical information on environmental concentrations (Hurley *et al.*, 2024). Research on ecological effects has focused so far on test materials in the form of microplastics or larger fragments artificially generated from virgin biodegradable agricultural plastics. These may not directly reflect the characteristics of these materials when they become exposed to real-world conditions. As a result, a detailed assessment of the ecological risks posed by the use of biodegradable agricultural plastics is not yet available. Difficulties in designing proper exposure scenarios for the quantitative assessment of risk also stem from the paucity of data on environmental concentrations. Finally, there is no knowledge on the effects of the long-term use of biodegradable agricultural plastics and the consequent continuous exposure of the soil to their residues, including released chemical additives

The safe and sustainable use of agricultural plastics requires an accurate characterization of risk thresholds. This is essential for adopting an effective risk management approach to manage plastics in agriculture and ensure soil and crop health over the short and long term.

PRIORITIZED MEASURES TO FILL THE GAPS

To address the knowledge gaps related to the impacts of plastic pollution generated by the use of conventional and biodegradable plastics in agriculture on soil and crop health, a number of actions need to be prioritized.

Efforts need to be increased to design and produce tests for the materials that are used in both conventional and biodegradable agricultural plastics. Activities in this area would need to consider the size, shape and chemical composition of these materials. Testing methods that incorporate these materials into the soil to mimic, as much as reasonably and technically possible, 'real-life' conditions also need to be developed. Testing these materials is necessary for the development and validation of methods for extracting and analysing plastic debris and micro and nanoplastics from the soil, and conducting effect studies that can determine safety thresholds (e.g. non-observable effect levels or their equivalent).

- Greater focus needs to be placed on studying the degradability of both conventional and biodegradable plastics in soils and other recipient environments (e.g. water, sediments, the digestive tracts of organisms) under real operational conditions and across different pedoclimatic regions. Field-scale studies, field plots and controlled mesocosms studies are important tools to address this point.
- To improve the design of toxicological experiments, 'range-finding' pilot studies need to be developed to frame the range of exposure levels for debris derived from all products made from conventional and biodegradable agricultural plastic products.
- To design correct exposure scenarios, the knowledge base about the environmental occurrence of debris from biodegradable agricultural plastics in soils needs to be expanded. To do this, improvements in sampling and analytical techniques are necessary.
- When testing the effects of conventional and biodegradable agricultural plastics and 'non-plastic' alternatives on soil ecosystems, plant health, agricultural yields and agricultural practices (e.g. through mid- to long-term field scale or mesocosms experiments) efforts must be increased to consider the real environmental conditions in which these plastics will be used. Also, greater focus needs to be placed on the effects of plastics in the soil on crop yield over multiple years through long-term studies. Effects testing should be directed at identifying risk thresholds for all types of agricultural plastics and alternative materials.
- Correlative studies for monitoring plastics in the soil need to be expanded to address the possible statistical relationships between the level of plastic in soils and soil health along the main gradients of pedoclimatic and agricultural conditions. This would provide a clearer picture of the current state of agricultural soil health and the safe operational space for plastic-based practices in agriculture.
- Research must be directed to understand how plastic residues in soils from both conventional and biodegradable plastics interact with other factors that can potentially affect soil resilience. These factors would include for example soil exhaustion, drought and flooding, erosion, excess salinity, the presence of pesticides residues and the co-presence of other pollutants (e.g. heavy metals, organic conta minants).

POLICY IMPLICATIONS

Overcoming the knowledge gaps related to the impacts of plastic pollution generated by the use of conventional and biodegradable plastics in agriculture on soil and crop health will make it easier to formulate polices to protect the environment and improve agricultural sustainability. Particularly valuable would be a comprehensive understanding of the effects mechanisms and risk thresholds, which would allow for detailed provisions on the safe use of conventional and biodegradable agricultural plastics to be included in national and international policies and their implementing instruments. Existing policies and regulations on the protection of terrestrial and freshwater biodiversity could also include provisions to manage the risks posed by plastic pollution in soils. The development of risk assessments and risk management measures for the safe use of conventional and biodegradable plastics agricultural plastics and the substances they contain are essential for updating chemical safety regulations to cover polymer formulations and their specific use in agriculture.

The effective communication of risk based on a solid base of evidence risk is required to enable the constructive engagement of policy makers, regulators and environmental authorities with farmers, the agricultural plastics industry and other stakeholders, and ensure the acceptance and adoption of guidelines that can safeguard soil quality and increase agricultural sustainability. Effective communication is also instrumental for stimulating agricultural and industrial innovations that can make safer and more environmentally sustainable products and practices available. With a clearer picture of the negative environmental, social and economic externalities associated with plastic pollution, agricultural and technical innovations could include nature-based solutions and other measures that may provide alternatives to the use of plastics.

3.6. KNOWLEDGE GAPS ON POSSIBLE RISKS ASSOCIATED WITH AGRICULTURAL PLASTICS POLLUTION-DERIVED RISKS ON FOOD SAFETY

Plastic debris and the chemicals associated with this debris can directly impair food quality and safety. Physiological responses have been observed in crops that have been exposed to plastics in the soil. Plastic pollution generated by agricultural plastics and other sources can also indirectly alter the nutritional quality and safety of food products. Increased research activities that focus on clarifying these impacts need to be carried out to update food safety criteria and the processes that ensure food is safe.

Plants can take up nanoparticles and chemicals that are present in, or released by, larger plastic items in the soil and translocate them to edible parts. When crops are grown in contaminated soil, understanding the interactions between plant physiology and the uptake of plastic particles and/or chemical additives is crucial to assess the potential direct or indirect risks to food safety. These assessments also apply to livestock production. Farmers and agrifood producers are aware that, under certain conditions, farm animals ingest significant amounts of agricultural plastics (particularly from hay bale nets) or feed contaminated with plastic from various sources (especially feeds derived from the waste of processed food). To date, scientific research has not sufficiently addressed this problem and its implications. Exposure of farm animals to plastics can pose a risk to their health and affect the quality and safety of animal-derived food products. Addressing this knowledge gap should be considered a major scientific priority.

PRIORITIZED MEASURES TO FILL THE GAPS

A fundamental first step in designing measures that can preserve food safety and the health of farm animals is to bring together farmers and other stakeholders operating in the agricultural plastics value chain to jointly identify practices that expose crops and farm animals to plastic pollution. Progress to reduce exposure to plastic pollution and guarantee cleaner and safer operations on farms relies on effective dialogue and cooperation between scientists, agrifood producers, and representatives from of the plastic industry. Greater access to data on the chemical composition of agricultural plastics and their formulation would substantially accelerate the development of risk assessments. These data are currently not disclosed to the scientific community by manufacturers.

To build capacities for assessing the health implications of plastics pollution in food, it is necessary to improve the reliability of methodologies for the detection and measurement of agricultural plastics, including micro- and nanoplastics, and their associated chemical additives in crops. Similarly, increased public and private investments should be directed to research that focuses on investigating the fate of micro- and nanoplastics in soil, and the uptake of plastic chemical additives in plants, animals and people. Efforts in this area would also expand the knowledge base on the potential for plastic and plastic-associated chemicals in crops and feeds to be transferred into farm animals and people.

© FAO/Cristina Aldehuela

Conclusions

The comprehensive analysis presented in this report on plastic pollution from agricultural plastics and its impacts on soil health and crops, which is based on a systematic review of 2 283 scientific papers with 505 meeting inclusion criteria, demonstrates that plastic contamination in agricultural soils represents a critical environmental challenge that requires immediate action. The evidence reveals that agricultural soils have become significant environmental recipients of plastic pollution, with contamination levels ranging from 0.000001 percent to 0.3 percent of soil mass. However, these figures likely underestimate total pollution as they primarily capture the presence of microplastic.

The research findings provide compelling evidence of plastic pollution's pervasive effects on soil ecosystems. Among 213 experimental studies examining soil properties, 85 percent documented significant effects from plastic contamination, and 90 percent of 114 studies on the impacts on plants observed adverse effects at the lowest tested concentrations. These impacts result from changes in fundamental soil properties including pH alterations of up to one point, modifications to water retention and nutrient cycling, the disruption of microbial communities, and the increased bioavailability of heavy metals and toxic substances.

The threshold for observable effects is alarmingly low. Significant impacts were documented at concentrations as minimal as 0.001 percent plastic in soil. Current contamination levels in over half of analysed agricultural soils fall within ranges where adverse effects on soil health and plant production are likely to occur. This finding suggests that many agricultural systems may have already crossed critical risk thresholds.

There are complex interactions between plastic debris and agricultural systems that extend beyond simple physical contamination. Plastic particles can alter soil structure, modify the composition of the microbial community, affect nutrient availability, and influence the bioavailability of contaminants. Of particular concern is the documented uptake and translocation of nano- and microplastics, along with their associated chemical additives, into edible parts of crops. This process has significant implications for food safety.

Chemical additives used in plastic formulations, which can constitute up to 60 percent of total plastic mass, are released into soil as materials age. These substances include plasticizers, antioxidants, UV filters, and other compounds with recognized toxic properties. Their presence in the soil creates additional pathways for environmental and human health impacts.

Contrary to common assumptions, the evidence demonstrates that biodegradable plastics do not represent inherently safer alternatives for agricultural applications. Scientific studies show that biodegradable plastic debris can produce similar effects on soil health and plant growth as conventional plastics. These impacts have been observed at concentrations as low as

0.02 percent. The degradation rates of these materials vary significantly under real operational conditions, and incomplete degradation can lead to microplastic accumulation similar to conventional plastics.

A critical finding is that soil plastic pollution appears largely irreversible under current conditions. Some processes (e.g. degradation or export through erosion) may reduce the quantity of plastic in the soil, but these processes are generally slow and incomplete. Microplastics and smaller particles persist in soils for extended periods, and current remediation methods are impractical or prohibitively expensive at agricultural scales. This irreversibility means that continued plastic inputs will result in progressive accumulation, potentially leading to increasingly severe impacts over time.

Despite the substantial research base, significant knowledge gaps remain that limit comprehensive risk assessments. The geographic distribution of research shows a marked bias. Eighty-two percent of occurrence studies were conducted in China. This imbalance raises questions about the global applicability of findings. Critical uncertainties include the lack of standardized methodologies for detection and quantification; insufficient understanding of long-term impacts; limited knowledge of food safety implications; and uncertainty regarding the relative contribution of agricultural plastics to plastic pollution compared to other pollution sources.

The evidence presented indicates that plastic pollution from agricultural sources poses a fundamental challenge to the sustainability of agrifood systems and pose risks food security and nutrition. The combination of the demonstrated effects at environmentally realistic concentrations, the widespread contamination, and the limited reversibility suggests that current practices may compromise long-term soil productivity and crop quality. The documented uptake of plastic particles and chemicals into food crops raises additional concerns about the implications for human health that require urgent investigation.

The findings in this report demonstrate that agricultural plastic pollution is an urgent environmental and food security challenge that requires immediate and coordinated actions the encompass research, policies, and practices to safeguard soils for future generations.

The FAO Provisional Voluntary Code of Conduct on the Sustainable Use and Management of Plastics in Agriculture (VCoC) provides a crucial framework for addressing these challenges through science-based guiding principles and comprehensive policy guidance (FAO, 2025). The VCoC establishes seven interconnected goals: i) contribute to food security; ii) reduce environmentally harmful plastics; iii) ensure sustainable design and circularity; iv) promote proper waste management; v) eliminating environmental leakage; vi) ensure the fair, equitable and inclusive participation and consideration of the needs of affected populations; and vii) promote international cooperation.

Reaching these goals includes developing improved waste management practices, establishing standardized monitoring protocols, advancing research on safer alternatives, and implementing precautionary policies that account for the irreversible nature of plastic soil contamination. The VCoC specifically addresses the need for comprehensive approaches to address all stages in the life cycle of agricultural plastics, from their design and manufacturing to distribution, use, collection, recycling, and disposal.

The VCoC provides a policy framework to assist governments and stakeholders in developing global, regional, national, and sub-national strategies, policies, regulatory frameworks, and programmes to prevent plastic pollution from agricultural sources. It emphasizes multistakeholder collaboration and includes special considerations for small-scale farmers, women, youth, Indigenous Peoples, and other vulnerable groups in rural areas. The framework, which promotes international cooperation through capacity building and technology transfer, is intended to support low-income and lower-middle income countries achieve their goals for sustainable plastic management and develop safer, more environmentally sound alternatives to plastic.

© FAO/Vincent Tremeau

References

Abbasi, S., Rezaei, M., Mina, M., Sameni, A., Oleszczuk, P., Turner, A. & Ritsema, C. 2023. Entrainment and horizontal atmospheric transport of microplastics from soil. *Chemosphere*, 322: 138150. https://doi.org/10.1016/j.chemosphere.2023.138150

Abdolahpur Monikh, F., Holm, S., Kortet, R., Bandekar, M., Kekäläinen, J., Koistinen, A., Leskinen, J.T.T. *et al.* 2022. Quantifying the trophic transfer of sub-micron plastics in an assembled food chain. *Nano Today*, 46: 101611. https://doi.org/10.1016/j.nantod.2022.101611

APE Europe. 2024. Statistics -plasticulture in Europe. In APE Europe. [Cited 28 April 2024]. https://apeeurope. eu/statistics/.

Aubin, S., Beaugrand, J., Berteloot, M., Boutrou, R., Buche, P., Gontard, N. & Guillard, V. 2022. Plastics in a circular economy: Mitigating the ambiguity of widely-used terms from stakeholders consultation. *Environmental Science & Policy*, 134: 119–126. https://doi.org/10.1016/j.envsci.2022.04.011

Bian, W., An, L., Zhang, S., Feng, J., Sun, D., Yao, Y., Shen, T., Yang, Y. & Zhang, M. 2022. The long-term effects of microplastics on soil organomineral complexes and bacterial communities from controlled-release fertilizer residual coating. *Journal of Environmental Management*, 304: 114193. https://doi.org/10.1016/j.jenvman.2021.114193

Blanco, I., Loisi, R.V., Sica, C., Schettini, E. & Vox, G. 2018. Agricultural plastic waste mapping using GIS. A case study in Italy. *Resources Conservation and Recycling*, 137: 229–242. https://doi.org/10.1016/j.resconrec.2018.06.008

Bonato, T., Beggio, G., Pivato, A. & Piazza, R. 2022. Maize plant (Zea mays) uptake of organophosphorus and novel brominated flame retardants from hydroponic cultures. *Chemosphere*, 287: 132456. https://doi.org/10.1016/j.chemosphere.2021.132456

Boots, B., Russell, C.W. & Green, D.S. 2019. Effects of Microplastics in Soil Ecosystems: Above and Below Ground. *Environmental Science & Technology*, 53(19): 11496–11506. https://doi.org/10.1021/acs.est.9b03304

Bran Shaw, R. 2022. Situación de la plasticultura en Guatemala. Presentation at the XVI Congreso Internacional de Plasticultura.

Briassoulis, D., Babou, E., Hiskakis, M., Scarascia, G., Picuno, P., Guarde, D. & Dejean, C. 2013. Review, mapping and analysis of the agricultural plastic waste generation and consolidation in Europe. *Waste Management & Research*, 31(12): 1262–1278. https://doi.org/10.1177/0734242X13507968

Briassoulis, D. 2023. Agricultural plastics as a potential threat to food security, health, and environment through soil pollution by microplastics: Problem definition. *Science of The Total Environment*, 892: 164533. https://doi.org/10.1016/j.scitotenv.2023.164533

Brown, R.W., Chadwick, D.R., Thornton, H., Marshall, M.R., Bei, S., Distaso, M.A., Bargiela, R. *et al.* 2022. Field application of pure polyethylene microplastic has no significant short-term effect on soil biological quality and function. *Soil Biology and Biochemistry*, 165: 108496. https://doi.org/10.1016/j.soilbio.2021.108496

Castellon Petrovich, H.F. 2022a. *La Plasticultura en Chile y el desarrollo de la producción de frutas para la exportación, la horticultura y la ganadería ante el cambio climático.* https://www.researchgate.net/publication/360264752_La_Plasticultura_en_Chile_y_el_desarrollo_de_la_produccion_de_frutas_para_la_exportacion_la_horticultura_y_la_ganaderia_ante_el_cambio_climatico

Castellon Petrovich, H.F. 2022b. *La Plasticultura en Uruguay: desarrollo agrícola con aporte de los agroplásticos.* https://www.researchgate.net/publication/371755369_La_Plasticultura_en_Uruguay_desarrollo_agricola_con_aporte_de_los_agroplasticos

Chen, L., Yu, L., Li, Y., Han, B., Zhang, J., Tao, S. & Liu, W. 2022a. Spatial Distributions, Compositional Profiles, Potential Sources, and influencing Factors of Microplastics in Soils from Different Agricultural Farmlands in China: A National Perspective. *Environmental Science & Technology*, 56(23): 16964–16974. https://doi.org/10.1021/acs.est.2c07621

Chen, L., Yu, L., Han, B., Li, Y., Zhang, J., Tao, S. & Liu, W. 2024. Pollution characteristics and affecting factors of phthalate esters in agricultural soils in mainland China. *Journal of Hazardous Materials*, 466: 133625. https://doi.org/10.1016/j.jhazmat.2024.133625

Chen, S., Feng, T., Lin, X., Hou, Z., Chao, L., Zhang, X., Liu, Y. & Li, J. 2022b. Effect of Microplastics on the Adsorption and Desorption Properties of Cadmium in Soil. *Bulletin of Environmental Contamination and Toxicology*, 110(1): 33. https://doi.org/10.1007/s00128-022-03669-2

Chen, W., Xu, Y., Zhang, Z., Yang, L., Pan, X. & Jia, Z. 2021. Mapping agricultural plastic greenhouses using Google Earth images and deep learning. *Computers and Electronics in Agriculture*, 191: 106552. https://doi.org/10.1016/j.compag.2021.106552

Chu, J., Zhou, J., Wang, Y., Jones, D.L., Ge, J., Yang, Y., Brown, R.W., Zang, H. & Zeng, Z. 2023. Field application of biodegradable microplastics has no significant effect on plant and soil health in the short term. *Environmental Pollution*, 316: 120556. https://doi.org/10.1016/j.envpol.2022.120556

Cleanfarms. 2021. *Agricultural Plastic Characterization and Management on Canadian Farms.* https://cleanfarms.ca/wp-content/uploads/2021/08/Project-Building-a-Canada-Wide-Zero-Plastic-Waste-Strategy-for-Agriculture.pdf

Colombini, G., Rumpel, C., Houot, S., Biron, P. & Dignac, M.-F. 2022. A long-term field experiment confirms the necessity of improving biowaste sorting to decrease coarse microplastic inputs in compost amended soils. *Environmental Pollution*, 315: 120369. https://doi.org/10.1016/j.envpol.2022.120369

Colombini, G., Senouci, F., Rumpel, C., Houot, S., Biron, P., Felbacq, A. & Dignac, M.-F. 2024. Coarse microplastic accumulation patterns in agricultural soils during two decades of different urban composts application. *Environmental Pollution*, 363: 125076. https://doi.org/10.1016/j.envpol.2024.125076

Crossman, J., Hurley, R.R., Futter, M. & Nizzetto, L. 2020. Transfer and transport of microplastics from biosolids to agricultural soils and the wider environment. *Science of The Total Environment*, 724: 138334. https://doi.org/10.1016/j.scitotenv.2020.138334

Cusworth, S.J., Davies, W.J., McAinsh, M.R. & Stevens, C.J. 2024. A nationwide assessment of microplastic abundance in agricultural soils: The influence of plastic crop covers within the United Kingdom. *PLANTS, PEOPLE, PLANET*, 6(2): 304–314. https://doi.org/10.1002/ppp3.10430

Data Intelligence. 2023. Agricultural Plastics Market Size Share Growth Outlook and Forecast 2024. In: *DataM Intelligence*. [Cited 8 April 2024]. https://www.datamintelligence.com/research-report/agricultural-plastics-market

de Souza Machado, A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R. & Rillig, M.C. 2018. Impacts of Microplastics on the Soil Biophysical *Environment. Environmental Science & Technology*, 52(17): 9656–9665. https://doi.org/10.1021/acs.est.8b02212

Degli-Innocenti, F. 2024. The pathology of hype, hyperbole and publication bias is creating an unwarranted concern towards biodegradable mulch films. *Journal of Hazardous Materials*, 463: 132923. https://doi.org/10.1016/j.jhazmat.2023.132923

Dewi, S.K., Han, Z.M., Bhat, S.A., Zhang, F., Wei, Y. & Li, F. 2024. Effect of plastic mulch residue on plant growth performance and soil properties. *Environmental Pollution (Barking, Essex: 1987)*, 343: 123254. https://doi.org/10.1016/j.envpol.2023.123254

Ding, F., Li, S., Lu, J., Penn, C.J., Wang, Q.-W., Lin, G., Sardans, J. *et al.* 2023. Consequences of 33 Years of Plastic Film Mulching and Nitrogen Fertilization on Maize Growth and Soil Quality. *Environmental Science & Technology*, 57(25): 9174–9183. https://doi.org/10.1021/acs.est.2c08878

Dong, Y., Gao, M., Qiu, W. & Song, Z. 2021. Uptake of microplastics by carrots in presence of As (III): Combined toxic effects. *Journal of Hazardous Materials*, 411: 125055. https://doi.org/10.1016/j.jhazmat.2021.125055

Dong, Y., Gao, M., Qiu, W., Xiao, L., Cheng, Z., Peng, H. & Song, Z. 2024. Investigating the impact of microplastics on sulfur mineralization in different soil types: A mechanism study. *Journal of Hazardous Materials*, 464: 132942. https://doi.org/10.1016/j.jhazmat.2023.132942

European Commission Directorate-General for Research and Innovation. 2021. *Biodegradability of plastics in the open environment*. Publications Office of the European Union. https://data.europa.eu/doi/10.2777/690248

European Commission. n.d. Bio-based, biodegradable and compostable plastics. In: *European Commission | Energy, Climate change, Environment | Topics | Plastics*. [Cited 28 January 2022]. https://ec.europa.eu/environment/topics/plastics/bio-based-biodegradable-and-compostable-plastics_en

Fakour, H., Lo, S.-L., Yoashi, N.T., Massao, A.M., Lema, N.N., Mkhontfo, F.B., Jomalema, P.C. *et al.* 2021. Quantification and Analysis of Microplastics in Farmland Soils: Characterization, Sources, and Pathways. *Agriculture*, 11(4): 330. https://doi.org/10.3390/agriculture11040330

FAO. 2021. *Assessment of agricultural plastics and their sustainability: A call for action*. FAO. https://doi.org/10.4060/cb7856en

FAO. 2025. *A Provisional Voluntary Code of Conduct on the Sustainable Use and Management of Plastics in Agriculture*. Rome._https://doi.org/10.4060/cd3004en

Fei, Y., Huang, S., Zhang, H., Tong, Y., Wen, D., Xia, X., Wang, H., Luo, Y. & Barceló, D. 2020. Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil. *Science of The Total Environment*, 707: 135634. https://doi.org/10.1016/j.scitotenv.2019.135634

Feng, Q., Niu, B., Chen, B., Ren, Y., Zhu, D., Yang, J., Liu, J., Ou, C. & Li, B. 2021. Mapping of plastic greenhouses and mulching films from very high resolution remote sensing imagery based on a dilated and non-local convolutional neural network. *International Journal of Applied Earth Observation and Geoinformation*, 102: 102441. https://doi.org/10.1016/j.jag.2021.102441

Feuilloley, P., César, G., Benguigui, L., Grohens, Y., Pillin, I., Bewa, H., Lefaux, S. & Jamal, M. 2005. Degradation of Polyethylene Designed for Agricultural Purposes. *Journal of Polymers and the Environment*, 13(4): 349–355. https://doi.org/10.1007/s10924-005-5529-9

Francioni, M., Kishimoto-Mo, A.W., Tsuboi, S. & Hoshino, Y.T. 2022. Evaluation of the mulch films biodegradation in soil: A methodological review. *Italian Journal of Agronomy*, 17(3). https://doi.org/10.4081/ija.2021.1936

Galyon, H., Vibostok, S., Duncan, J., Ferreira, G., Whittington, A., Havens, K., McDevitt, J. & Cockrum, R. 2023. Clearance of Biodegradable Polymer and Polyethylene Films from the Rumens of Holstein Bull Calves. *Animals*, 13(5): 928. https://doi.org/10.3390/ani13050928

Greenfield, L.M., Graf, M., Rengaraj, S., Bargiela, R., Williams, G., Golyshin, P.N., Chadwick, D.R. & Jones, D.L. 2022. Field response of N2O emissions, microbial communities, soil biochemical processes and winter barley growth to the addition of conventional and biodegradable microplastics. *Agriculture, Ecosystems & Environment*, 336: 108023. https://doi.org/10.1016/j.agee.2022.108023

Griffin-LaHue, D., Ghimire, S., Yu, Y., Scheenstra, E.J., Miles, C.A. & Flury, M. 2022. In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. *Science of The Total Environment*, 806: 150238. https://doi.org/10.1016/j.scitotenv.2021.150238

Grifoni, M., Pellegrino, E., Arrighetti, L., Bronco, S., Pezzarossa, B. & Ercoli, L. 2024. Interactive impacts of microplastics and arsenic on agricultural soil and plant traits. *The Science of the Total Environment*, 912: 169058. https://doi.org/10.1016/j.scitotenv.2023.169058

Gu, J., Chen, L., Wan, Y., Teng, Y., Yan, S. & Hu, L. 2023. Experimental Investigation of Water-Retaining and Unsaturated Infiltration Characteristics of Loess Soils Imbued with Microplastics. *Sustainability*, 15(1): 62. https://doi.org/10.3390/su15010062

Guo, Y., Zhang, Z., Liu, L., Li, Y., Ren, N. & Kannan, K. 2012. Occurrence and Profiles of Phthalates in Foodstuffs from China and Their Implications for Human Exposure. *Journal of Agricultural and Food Chemistry*, 60(27): 6913–6919. https://doi.org/10.1021/jf3021128

Guo, Z., Li, P., Ma, L., Yang, X., Yang, J., Wu, Y., Liu, G., Ritsema, C.J. & Geissen, V. 2024. Cascading effects from soil to maize functional traits explain maize response to microplastics disturbance in multi-nutrient soil environment. *Geoderma*, 441: 116759. https://doi.org/10.1016/j.geoderma.2023.116759

Guo, S., Zhang, J., Liu, J., Guo, N., Zhang, L., Wang, S., Wang, X. *et al.* 2023. Organic fertilizer and irrigation water are the primary sources of microplastics in the facility soil, Beijing. *Science of The Total Environment*, 895: 165005. https://doi.org/10.1016/j.scitotenv.2023.165005

Hachem, A., Vox, G. & Convertino, F. 2023. Prospective Scenarios for Addressing the Agricultural Plastic Waste Issue: Results of a Territorial Analysis. *Applied Sciences*, 13(1): 612. https://doi.org/10.3390/app13010612

Hachem, A., Convertino, F., Baptista, F., Batista, T., Briassoulis, D., Valera Martinez, D.L., Moreno Teruel, M.Á. *et al.* 2024. GIS mapping of agricultural plastic waste in Southern Europe. *Science of The Total Environment*, In Press.

Han, N., Zhao, Q., Ao, H., Hu, H. & Wu, C. 2022. Horizontal transport of macro- and microplastics on soil surface by rainfall induced surface runoff as affected by vegetations. *Science of The Total Environment*, 831: 154989. https://doi.org/10.1016/j.scitotenv.2022.154989

Hao, Y., Sun, H., Zeng, X., Dong, G., Kronzucker, H.J., Min, J., Xia, C., Lam, S.S. & Shi, W. 2023. Smallholder vegetable farming produces more soil microplastics pollution than large-scale farming. *Environmental Pollution*, 317: 120805. https://doi.org/10.1016/j.envpol.2022.120805

He, X., Qian, Y., Li, Z., Yang, S., Tian, J., Wang, Q., Lei, J., Qi, R. & Feng, C. 2023. Identification of factors influencing the microplastic distribution in agricultural soil on Hainan Island. *Science of The Total Environment*, 874: 162426. https://doi.org/10.1016/j.scitotenv.2023.162426

Heerey, L., O'Sullivan, J.J., Bruen, M., Turner, J., Mahon, A.M., Murphy, S., Lally, H.T. *et al.* 2023. Export pathways of biosolid derived microplastics in soil systems – Findings from a temperate maritime climate. *Science of The Total Environment*, 888: 164028. https://doi.org/10.1016/j.scitotenv.2023.164028

Heinze, W.M., Mitrano, D.M., Lahive, E., Koestel, J. & Cornelis, G. 2021. Nanoplastic Transport in Soil via Bioturbation by Lumbricus terrestris. *Environmental Science & Technology*, 55(24): 16423–16433. https://doi.org/10.1021/acs.est.1c05614

Hofmann, T., Ghoshal, S., Tufenkji, N., Adamowski, J.F., Bayen, S., Chen, Q., Demokritou, P. *et al.* 2023. Plastics can be used more sustainably in agriculture. *Communications Earth & Environment*, 4(1): 1–11. https://doi.org/10.1038/s43247-023-00982-4

Hu, C., Wang, X., Wang, S., Lu, B., Guo, W., Liu, C. & Tang, X. 2020. Impact of agricultural residual plastic film on the growth and yield of drip-irrigated cotton in arid region of Xinjiang, China. *International Journal of Agricultural and Biological Engineering*, 13(1): 160–169. https://doi.org/10.25165/j.ijabe.20201301.5084

Hu, J., He, D., Zhang, X., Li, X., Chen, Y., Wei, G., Zhang, Y., Ok, Y.S. & Luo, Y. 2022. National-scale distribution of micro(meso)plastics in farmland soils across China: Implications for environmental impacts. *Journal of Hazardous Materials*, 424: 127283. https://doi.org/10.1016/j.jhazmat.2021.127283

Huang, B., Sun, L., Liu, M., Huang, H., He, H., Han, F., Wang, X. *et al.* 2021. Abundance and distribution characteristics of microplastic in plateau cultivated land of Yunnan Province, China. *Environmental Science and Pollution Research*, 28(2): 1675–1688. https://doi.org/10.1007/s11356-020-10527-3

Huang, M., Zhu, Y., Chen, Y. & Liang, Y. 2023. Microplastics in soil ecosystems: soil fauna responses to field applications of conventional and biodegradable microplastics. *Journal of Hazardous Materials*, 441: 129943. https://doi.org/10.1016/j.jhazmat.2022.129943

Huang, Y., Zhao, Y., Wang, J., Zhang, M., Jia, W. & Qin, X. 2019. LDPE microplastic films alter microbial community composition and enzymatic activities in soil. *Environmental Pollution*, 254: UNSP 112983. https://doi.org/10.1016/j.envpol.2019.112983

Huang, Y., Liu, Q., Jia, W., Yan, C. & Wang, J. 2020. Agricultural plastic mulching as a source of microplastics in the terrestrial environment. *Environmental Pollution*: 114096. https://doi.org/10.1016/j.envpol.2020.114096

Hurley, R.R. & Nizzetto, L. 2018. Fate and occurrence of micro(nano)plastics in soils: Knowledge gaps and possible risks. *Current Opinion in Environmental Science & Health*, 1: 6–11. https://doi.org/10.1016/j.coesh.2017.10.006

Hurley, R., Binda, G., Briassoulis, D., Carroccio, S.C., Cerruti, P., Convertino, F., Dvorakova, D. *et al.* 2024. Production and characterisation of environmentally relevant microplastic test materials derived from agricultural plastics. *Science of The Total Environment*: 174325. https://doi.org/10.1016/j.scitotenv.2024.174325

Iqbal, S., Xu, J., Allen, S.D., Khan, S., Nadir, S., Arif, M.S. & Yasmeen, T. 2020. Unraveling consequences of soil micro- and nano-plastic pollution on soil-plant system: Implications for nitrogen (N) cycling and soil microbial activity. *Chemosphere*, 260: 127578. https://doi.org/10.1016/j.chemosphere.2020.127578

Ivanic, F.M., Guggenberger, G., Woche, S.K., Bachmann, J., Hoppe, M. & Carstens, J.F. 2023. Soil organic matter facilitates the transport of microplastic by reducing surface hydrophobicity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 676: 132255. https://doi.org/10.1016/j.colsurfa.2023.132255

Jia, Z., Wei, W., Wang, Y., Chang, Y., Lei, R. & Che, Y. 2024. Occurrence characteristics and risk assessment of microplastics in agricultural soils in the loess hilly gully area of Yan' an, China. *Science of The Total Environment*, 912: 169627. https://doi.org/10.1016/j.scitotenv.2023.169627

Jiang, X.J., Liu, W., Wang, E., Zhou, T. & Xin, P. 2017. Residual plastic mulch fragments effects on soil physical properties and water flow behavior in the Minqin Oasis, northwestern China. *Soil and Tillage Research*, 166: 100–107. https://doi.org/10.1016/j.still.2016.10.011

Jiang, X., Cao, J., Ye, Z., Klobucar, G. & Li, M. 2023. Microplastics - Back to Reality: Impact of Pristine and Aged Microplastics in Soil on Earthworm Eisenia fetida under Environmentally Relevant Conditions. *Environmental Science & Technology*, 57(44): 16788–16799. https://doi.org/10.1021/acs.est.3c04097

Karasik, R., Baann, C., Howell, D., Nizzetto, L. & Carcasci, G. 2024. *Analysis of stakeholder submissions towards the development of a Voluntary Code of Conduct on the Sustainable Use and Management of Plastics in Agriculture*. FAO. https://doi.org/10.4060/cd2593en

Katsumi, N., Kusube, T., Nagao, S. & Okochi, H. 2021. Accumulation of microcapsules derived from coated fertilizer in paddy fields. *Chemosphere*, 267: 129185.

Kim, D., Kim, H., Lee, J., Choi, M.-J., Kweon, H.-S. & An, Y.-J. 2024. Evidence of parental transfer of nanoplastics in pea (*Pisum sativum*) plants. *Journal of Hazardous Materials*, 465: 133516. https://doi.org/10.1016/j.jhazmat.2024.133516

Kim, S.-K., Kim, J.-S., Lee, H. & Lee, H.-J. 2021. Abundance and characteristics of microplastics in soils with different agricultural practices: Importance of sources with internal origin and environmental fate. *Journal of Hazardous Materials*, 403: 123997. https://doi.org/10.1016/j.jhazmat.2020.123997

Koelmans, A.A., Redondo-Hasselerharm, P.E., Nor, N.H.M., de Ruijter, V.N., Mintenig, S.M. & Kooi, M. 2022. Risk assessment of microplastic particles. *Nature Reviews Materials*, 7(2): 138–152. https://doi.org/10.1038/s41578-021-00411-y

Koskei, K., Munyasya, A.N., Wang, Y.-B., Zhao, Z.-Y., Zhou, R., Indoshi, S.N., Wang, W. *et al.* 2021. Effects of increased plastic film residues on soil properties and crop productivity in agro-ecosystem. *Journal of Hazardous Materials*, 414: 125521. https://doi.org/10.1016/j.jhazmat.2021.125521

Lang, M., Wang, G., Yang, Y., Zhu, W., Zhang, Y., Ouyang, Z. & Guo, X. 2022. The occurrence and effect of altitude on microplastics distribution in agricultural soils of Qinghai Province, northwest China. *Science of The Total Environment*, 810: 152174. https://doi.org/10.1016/j.scitotenv.2021.152174

Lanorte, A., De Santis, F., Nolè, G., Blanco, I., Loisi, R.V., Schettini, E. & Vox, G. 2017. Agricultural plastic waste spatial estimation by Landsat 8 satellite images. *Computers and Electronics in Agriculture*, 141: 35–45. https://doi.org/10.1016/j.compag.2017.07.003

Le Moine, B. 2018. Worldwide plasticulture - a focus on films. Presentation at 29 May 2018, Bordeaux, France. [Cited 11 February 2024]. https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fcipa-plasticulture.com%2Fwp-content%2Fuploads%2F2018%2F06%2FWorlwide-Plasticulture_Le-Moine_CIPA.pptx&wdOrigin=BROWSELINK

Li, C., Moore-Kucera, J., Miles, C., Leonas, K., Lee, J., Corbin, A. & Inglis, D. 2014. Degradation of Potentially Biodegradable Plastic Mulch Films at Three Diverse U.S. Locations. *Agroecology and Sustainable Food Systems*, 38(8): 861–889. https://doi.org/10.1080/21683565.2014.884515

Li, C., Chen, J., Wang, J., Han, P., Luan, Y., Ma, X. & Lu, A. 2016. Phthalate esters in soil, plastic film, and vegetable from greenhouse vegetable production bases in Beijing, China: Concentrations, sources, and risk assessment. *Science of The Total Environment*, 568: 1037–1043. https://doi.org/10.1016/j.scitotenv.2016.06.077

Li, C., Li, Z., Cui, Q., Hassan, A., Zhang, K., Lu, X. & Zhang, Y. 2023d. Effect of different additions of low-density polyethylene and microplastics polyadipate/butylene terephthalate on soil bacterial community structure. *Environmental Science and Pollution Research International*, 30(19): 55649–55661. https://doi.org/10.1007/s11356-023-26159-2

Li, C., Sun, H., Shi, Y., Zhao, Z., Zhang, Z., Zhao, P., Gao, Q. *et al.* 2023a. Polyethylene and poly (butyleneadipate-co-terephthalate)-based biodegradable microplastics modulate the bioavailability and speciation of Cd and As in soil: Insights into transformation mechanisms. *Journal of Hazardous Materials*, 445: 130638. https://doi.org/10.1016/j.jhazmat.2022.130638

Li, H., Lu, X., Wang, S., Zheng, B. & Xu, Y. 2021a. Vertical migration of microplastics along soil profile under different crop root systems. *Environmental Pollution*, 278: 116833. https://doi.org/10.1016/j.envpol.2021.116833

Li, J., Peng, D., Ouyang, Z., Liu, P., Fang, L. & Guo, X. 2022. Occurrence status of microplastics in main agricultural areas of Xinjiang Uygur Autonomous Region, China. *Science of The Total Environment*, 828: 154259. https://doi.org/10.1016/j.scitotenv.2022.154259

Li, L., Luo, Y., Li, R., Zhou, Q., Peijnenburg, W.J.G.M., Yin, N., Yang, J., Tu, C. & Zhang, Y. 2020b. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. *Nature Sustainability*, 3(11): 929–937. https://doi.org/10.1038/s41893-020-0567-9

Li, M., Ma, Q., Su, T., Wang, Z. & Tong, H. 2024. Effect of Polycaprolactone Microplastics on Soil Microbial Communities and Plant Growth. *Journal of Polymers and the Environment*, 32(3): 1039–1045. https://doi.org/10.1007/s10924-023-03028-0

Li, Q., Zeng, A., Jiang, X. & Gu, X. 2021b. Are microplastics correlated to phthalates in facility agriculture soil? *Journal of Hazardous Materials*, 412: 125164. https://doi.org/10.1016/j.jhazmat.2021.125164

Li, Y., Yan, H., Li, X., Ge, J., Cheng, J. & Yu, X. 2020a. Presence, distribution and risk assessment of phthalic acid esters (PAEs) in suburban plastic film pepper-growing greenhouses with different service life. *Ecotoxicology and Environmental Safety*, 196: 110551. https://doi.org/10.1016/j.ecoenv.2020.110551

Li, Y., Lin, X., Wang, J., Xu, G. & Yu, Y. 2023b. Quantification of nanoplastics uptake and transport in lettuce by pyrolysis gas chromatography-mass spectrometry. *Talanta*, 265: 124837. https://doi.org/10.1016/j.talanta.2023.124837

L**i, Y., Lin, X., Wang, J., Xu, G. & Yu, Y.** 2023c. Mass-based trophic transfer of polystyrene nanoplastics in the lettuce-snail food chain. *Science of The Total Environment*, 897: 165383. https://doi.org/10.1016/j.scitotenv.2023.165383

Lian, J., Liu, W., Meng, L., Wu, J., Zeb, A., Cheng, L., Lian, Y. & Sun, H. 2021. Effects of microplastics derived from polymer-coated fertilizer on maize growth, rhizosphere, and soil properties. *Journal of Cleaner Production*, 318: 128571. https://doi.org/10.1016/j.jclepro.2021.128571

Lian, Y., Liu, W., Shi, R., Zeb, A., Wang, Q., Li, J., Zheng, Z. & Tang, J. 2022. Effects of polyethylene and polylactic acid microplastics on plant growth and bacterial community in the soil. Jo*urnal of Hazardous Materials*, 435: 129057. https://doi.org/10.1016/j.jhazmat.2022.129057

Liang, J., Chen, X., Zha, S., Chen, X., Yu, Y., Duan, X., Cao, Y. & Liang, Y. 2023a. Distribution and Characteristics of Microplastics in Agricultural Soils around Gehu Lake, China. *Water, Air, & Soil Pollution*, 234(8): 517. https://doi.org/10.1007/s11270-023-06546-8

Liang, J., Chen, X., Duan, X., Gu, X., Zhao, X., Zha, S. & Chen, X. 2024b. Natural aging and adsorption/desorption behaviors of polyethylene mulch films: Roles of film types and exposure patterns. *Journal of Hazardous Materials*, 466: 133588. https://doi.org/10.1016/j.jhazmat.2024.133588

Liang, R., Zhu, Z., Peng, C., Bian, Z., Yang, X., Wang, H. & Wang, X.-X. 2024a. Mulch film to plastic debris: A survey of agricultural soils of Hebei Province, North China. *Science of The Total Environment*, 918: 170509. https://doi.org/10.1016/j.scitotenv.2024.170509

Liang, Y., Cao, X., Mo, A., Jiang, J., Zhang, Y., Gao, W. & He, D. 2023b. Micro(nano)plastics in plant-derived food: Source, contamination pathways and human exposure risks. *TrAC Trends in Analytical Chemistry*, 165: 117138. https://doi.org/10.1016/j.trac.2023.117138

Liao, Y., Tang, Q. & Yang, J. 2023. Microplastic characteristics and microplastic-heavy metal synergistic contamination in agricultural soil under different cultivation modes in Chengdu, China. *Journal of Hazardous Materials*, 459: 132270. https://doi.org/10.1016/j.jhazmat.2023.132270

Lin, X., Li, Y., Xu, G., Tian, C. & Yu, Y. 2022. Biodegradable microplastics impact the uptake of Cd in rice: The roles of niche breadth and assembly process. *Science of The Total Environment*, 851: 158222. https://doi.org/10.1016/j.scitotenv.2022.158222

Ling, Q., Yang, B., Jiao, J., Ma, X., Zhao, W. & Zhang, X. 2023. Response of microplastic occurrence and migration to heavy rainstorm in agricultural catchment on the Loess plateau. *Journal of Hazardous Materials*, 460: 132416. https://doi.org/10.1016/j.jhazmat.2023.132416

Liu, H., Wang, X., Shi, Q., Liu, Y., Lei, H. & Chen, Y. 2022b. Microplastics in arid soils: Impact of different cropping systems (Altay, Xinjiang). *Environmental Pollution*, 303: 119162. https://doi.org/10.1016/j.envpol.2022.119162

Liu, R., Xie, H., Xu, Y. & Sun, F. 2022c. Phytotoxicity, uptake, and translocation of two halogenated flame retardants and cadmium in two rice varieties. *Frontiers in Environmental Science*, 10. https://doi.org/10.3389/fenvs.2022.990174

Liu, R., Liang, J., Yang, Y., Jiang, H. & Tian, X. 2023e. Effect of polylactic acid microplastics on soil properties, soil microbials and plant growth. *Chemosphere*, 329: 138504. https://doi.org/10.1016/j.chemosphere.2023.138504

Liu, S., Niu, S.-H., Xiang, L., Liao, X.-D. & Xing, S.-C. 2023d. Effects of the oversized microplastic pollution layer on soil aggregates and organic carbon at different soil depths. *Journal of Hazardous Materials*, 450: 131014. https://doi.org/10.1016/j.jhazmat.2023.131014

Liu, X., Tang, N., Yang, W. & Chang, J. 2022a. Microplastics pollution in the soils of various land-use types along Sheshui River basin of Central China. *Science of The Total Environment*, 806: 150620. https://doi.org/10.1016/j.scitotenv.2021.150620

Liu, Y., Cui, W., Li, W., Xu, S., Sun, Y., Xu, G. & Wang, F. 2023c. Effects of microplastics on cadmium accumulation by rice and arbuscular mycorrhizal fungal communities in cadmium-contaminated soil. *Journal of Hazardous Materials, 442: 130102.* https://doi.org/10.1016/j.jhazmat.2022.130102

Liu, Y., Zhong, Y., Hu, C., Xiao, M., Ding, F., Yu, Y., Yao, H. *et al.* 2023a. Distribution of microplastics in soil aggregates after film mulching. *Soil Ecology Letters*, 5(3): 230171. https://doi.org/10.1007/s42832-023-0171-9

Liu, Y., Liu, Y., Li, Y., Bian, P., Hu, Y., Zhang, J. & Shen, W. 2023b. Effects of irrigation on the fate of microplastics in typical agricultural soil and freshwater environments in the upper irrigation area of the Yellow River. *Journal of Hazardous Materials*, 447: 130766. https://doi.org/10.1016/j.jhazmat.2023.130766

Luo, Q., Zhang, X., Wang, C., Yang, N., Sun, Z. & Feng, L. 2024. Characteristics of microplastics in dryland soils after long-term film mulching and the effect of cropping type in western Liaoning Province, China. *Land Degradation & Development*, 35(4): 1466–1476. https://doi.org/10.1002/ldr.4999

Lozano, Y.M., Lehnert, T., Linck, L.T., Lehmann, A. & Rillig, M.C. 2021. Microplastic Shape, Polymer Type, and Concentration Affect Soil Properties and Plant Biomass. *Frontiers in Plant Science*, 12. https://doi.org/10.3389/fpls.2021.616645

Ma, R., Xu, Z., Sun, J., Li, D., Cheng, Z., Niu, Y., Guo, H., Zhou, J. & Wang, T. 2023. Microplastics affect C, N, and P cycling in natural environments: Highlighting the driver of soil hydraulic properties. *Journal of Hazardous Materials*, 459: 132326. https://doi.org/10.1016/j.jhazmat.2023.132326

Menicagli, V., Balestri, E., Vallerini, F., Castelli, A. & Lardicci, C. 2020. Combined effect of plastic litter and increased atmospheric nitrogen deposition on vegetative propagules of dune plants: A further threat to coastal ecosystems. *Environmental Pollution*, 266: 115281. https://doi.org/10.1016/j.envpol.2020.115281

Menicagli, V., Balestri, E., Giommoni, F., Vannini, C. & Lardicci, C. 2023. Plastic litter changes the rhizosphere bacterial community of coastal dune plants. *Science of The Total Environment*, 880: 163293. https://doi.org/10.1016/j.scitotenv.2023.163293

Mihai, F.-C., Gundogdu, S., Markley, L.A., Olivelli, A., Khan, F.R., Gwinnett, C., Gutberlet, J. *et al.* 2022. Plastic Pollution, Waste Management Issues, and Circular Economy Opportunities in Rural Communities. *SUSTAINABILITY*, 14(1): 20. https://doi.org/10.3390/su14010020

Morsink-Georgali, P.-Z., Afxentiou, N., Kylili, A. & Fokaides, P.A. 2021. Definition of optimal agricultural plastic waste collection centers with advanced spatial analysis tools. *Cleaner Engineering and Technology*, 5: 100326. https://doi.org/10.1016/j.clet.2021.100326

Net, S., Sempéré, R., Delmont, A., Paluselli, A. & Ouddane, B. 2015. Occurrence, Fate, Behavior and Ecotoxicological State of Phthalates in Different Environmental Matrices. *Environmental Science & Technology*, 49(7): 4019–4035. https://doi.org/10.1021/es505233b

Ng, E.-L., Lwanga, E.H., Eldridge, S.M., Johnston, P., Hu, H.-W., Geissen, V. & Chen, D. 2018. An overview of microplastic and nanoplastic pollution in agroecosystems. *Science of the Total Environment*, 627: 1377–1388. https://doi.org/10.1016/j.scitotenv.2018.01.341

Niu, B., Feng, Q., Su, S., Yang, Z., Zhang, S., Liu, S., Wang, J., Yang, J. & Gong, J. 2023. Semantic segmentation for plastic-covered greenhouses and plastic-mulched farmlands from VHR imagery. *International Journal of Digital Earth*. https://www.tandfonline.com/doi/abs/10.1080/17538947.2023.2275657

Nizzetto, L., Binda, G., Hurley, R., Baann, C., Selonen, S., Velmala, S. & van Gestel, C.A.M. 2024. Comments to "Degli-Innocenti, F. The pathology of hype, hyperbole and publication bias is creating an unwarranted concern towards biodegradable mulch films" [J. Hazard. Mater. 463 (2024) 132923]. *Journal of Hazardous Materials*: 133690. https://doi.org/10.1016/j.jhazmat.2024.133690

O'Connor, D., Pan, S., Shen, Z., Song, Y., Jin, Y., Wu, W.-M. & Hou, D. 2019. Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles. *Environmental Pollution*, 249: 527–534. https://doi.org/10.1016/j.envpol.2019.03.092

Ouyang, D., Peng, Y., Li, B., Shao, F., Li, K., Cai, Y., Guo, T. & Zhang, H. 2023. Microplastic formation and simultaneous release of phthalic acid esters from residual mulch film in soil through mechanical abrasion. *Science of The Total Environment*, 893: 164821. https://doi.org/10.1016/j.scitotenv.2023.164821

Palansooriya, K.N., Withana, P.A., Jeong, Y., Sang, M.K., Cho, Y., Hwang, G., Chang, S.X. & Ok, Y.S. 2024. Contrasting effects of food waste and its biochar on soil properties and lettuce growth in a microplastic-contaminated soil. *Applied Biological Chemistry*, 67(1): 3. https://doi.org/10.1186/s13765-023-00851-w

Pehlivan, N. & Gedik, K. 2021. Particle size-dependent biomolecular footprints of interactive microplastics in maize. *Environmental Pollution*, 277: 116772. https://doi.org/10.1016/j.envpol.2021.116772

Pei, W., Hu, R., Liu, H., Wang, L. & Lai, Y. 2023. Advanced Raman spectroscopy for nanoplastics analysis: Progress and perspective. *TrAC Trends in Analytical Chemistry*, 166: 117188. https://doi.org/10.1016/j.trac.2023.117188

Pizol, J.V., Dennis, R.R., Thorson, J.F. & Prezotto, L.D. 2017. *Distribution and Clearance of Chopped Net Wrap in the Digestive Tract of Beef Cattle*. Montana State University.

Qi, R., Jones, D.L., Li, Z., Liu, Q. & Yan, C. 2020a. Behavior of microplastics and plastic film residues in the soil environment: A critical review. *Science of the Total Environment*, 703: 134722. https://doi.org/10.1016/j.scitotenv.2019.134722

Qi, R., Jones, D.L., Liu, Q., Liu, Q., Li, Z. & Yan, C. 2021. Field test on the biodegradation of poly(butylene adipate-co-terephthalate) based mulch films in soil. *Polymer Testing*, 93: 107009. https://doi.org/10.1016/j.polymertesting.2020.107009

Qi, R., Tang, Y., Jones, D.L., He, W. & Yan, C. 2023. Occurrence and characteristics of microplastics in soils from greenhouse and open-field cultivation using plastic mulch film. *Science of The Total Environment*, 905: 166935. https://doi.org/10.1016/j.scitotenv.2023.166935

Qi, Y., Beriot, N., Gort, G., Huerta Lwanga, E., Gooren, H., Yang, X. & Geissen, V. 2020b. Impact of plastic mulch film debris on soil physicochemical and hydrological properties. *Environmental Pollution*, 266: 115097. https://doi.org/10.1016/j.envpol.2020.115097

Qiu, Y., Zhou, S., Zhang, C., Zhou, Y. & Qin, W. 2022. Soil microplastic characteristics and the effects on soil properties and biota: A systematic review and meta-analysis. *Environmental Pollution*, 313: 120183. https://doi.org/10.1016/j.envpol.2022.120183

Quan, H., Wang, B., Wu, L., Feng, H., Wu, L., Wu, L., Liu, D.L. & Siddique, K.H.M. 2024. Impact of plastic mulching and residue return on maize yield and soil organic carbon storage in irrigated dryland areas under climate change. *Agriculture, Ecosystems & Environment*, 362: 108838. https://doi.org/10.1016/j.agee.2023.108838

Ranneklev, S.B., Hurley, R., Bråte, I.L.N. & Vogelsang, C. 2019. *Plast i landbruket: kilder, massebalanse og spredning til lokale vannforekomster (Plastland).* Norsk insitutt for vannforskning. https://niva.brage.unit.no/niva-xmlui/handle/11250/2632595

Rehm, R., Zeyer, T., Schmidt, A. & Fiener, P. 2021. Soil erosion as transport pathway of microplastic from agriculture soils to aquatic ecosystems. *Science of The Total Environment*, 795: 148774. https://doi.org/10.1016/j.scitotenv.2021.148774

Ren, X., Tang, J., Wang, L. & Liu, Q. 2021b. Microplastics in soil-plant system: effects of nano/microplastics on plant photosynthesis, rhizosphere microbes and soil properties in soil with different residues. *Plant and Soil*, 462(1): 561–576. https://doi.org/10.1007/s11104-021-04869-1

Ren, Z., Gui, X., Wei, Y., Chen, X., Xu, X., Zhao, L., Qiu, H. & Cao, X. 2021a. Chemical and photo-initiated aging enhances transport risk of microplastics in saturated soils: Key factors, mechanisms, and modeling. *Water Research*, 202: 117407. https://doi.org/10.1016/j.watres.2021.117407

Rezaei, M., Riksen, M.J., Sirjani, E., Sameni, A. & Geissen, V. 2019. Wind erosion as a driver for transport of light density microplastics. *Science of The Total Environment.*

Rezaei, M., Abbasi, S., Pourmahmood, H., Oleszczuk, P., Ritsema, C. & Turner, A. 2022. Microplastics in agricultural soils from a semi-arid region and their transport by wind erosion. *Environmental Research*, 212: 113213. https://doi.org/10.1016/j.envres.2022.113213

Rillig, M.C., Ziersch, L. & Hempel, S. 2017. Microplastic transport in soil by earthworms. *Scientific Reports*, 7. https://doi.org/10.1038/s41598-017-01594-7

Rillig, M.C. 2012. Microplastic in Terrestrial Ecosystems and the Soil? *Environmental Science & Technology*, 46(12): 6453–6454. https://doi.org/10.1021/es302011r

Rong, L., Zhao, L., Zhao, L., Cheng, Z., Yao, Y., Yuan, C., Wang, L. & Sun, H. 2021. LDPE microplastics affect soil microbial communities and nitrogen cycling. *Science of The Total Environment*, 773: 145640. https://doi.org/10.1016/j.scitotenv.2021.145640

Rüthi, J., Rast, B.M., Qi, W., Perez-Mon, C., Pardi-Comensoli, L., Brunner, I. & Frey, B. 2023. The plastisphere microbiome in alpine soils alters the microbial genetic potential for plastic degradation and biogeochemical cycling. *Journal of Hazardous Materials*, 441: 129941. https://doi.org/10.1016/j.jhazmat.2022.129941

Scarascia-Mugnozza, G., Sica, C. & Russo, G. 2011. Plastic Materials in European Agriculture: Actual Use and Perspectives. *Journal of Agricultural Engineering*, 42(3): 15–28. https://doi.org/10.4081/jae.2011.3.15

Schell, T., Hurley, R., Buenaventura, N.T., Mauri, P.V., Nizzetto, L., Rico, A. & Vighi, M. 2022. Fate of microplastics in agricultural soils amended with sewage sludge: Is surface water runoff a relevant environmental pathway? *Environmental Pollution*, 293: 118520. https://doi.org/10.1016/j.envpol.2021.118520

Schöpfer, L., Möller, J.N., Steiner, T., Schnepf, U., Marhan, S., Resch, J., Bayha, A. *et al.* 2022. Microplastics persist in an arable soil but do not affect soil microbial biomass, enzyme activities, and crop yield. *Journal of Plant Nutrition and Soil Science*, 185(6): 836–849. https://doi.org/10.1002/jpln.202200062

The Scientists' Coalition for an Effective Plastic Treaty. 2024. Policy Brief: Impacts of plastics across the food system. DOI: 10.5281/zenodo.10653557

Sheng, D., Jing, S., He, X., Klein, A.M., Köhler, H.R. & Wanger, T.C. 2024. Plastic pollution in agricultural landscapes: an overlooked threat to pollination, biocontrol and food security. *Nature Communications*, 15(1): 8413. https://doi.org/10.1038/s41467-024-52734-3

Shi, M., Sun, Y., Wang, Z., He, G., Quan, H. & He, H. 2019. Plastic film mulching increased the accumulation and human health risks of phthalate esters in wheat grains. *Environmental Pollution*, 250: 1–7. https://doi.org/10.1016/j.envpol.2019.03.064

Sintim, H.Y., Bandopadhyay, S., English, M.E., Bary, A.I., DeBruyn, J.M., Schaeffer, S.M., Miles, C.A., Reganold, J.P. & Flury, M. 2019. Impacts of biodegradable plastic mulches on soil health. *Agriculture, Ecosystems & Environment*, 273: 36–49. https://doi.org/10.1016/j.agee.2018.12.002

Sintim, H.Y., Bary, A.I., Hayes, D.G., Wadsworth, L.C., Anunciado, M.B., English, M.E., Bandopadhyay, S. *et al.* 2020. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. *Science of The Total Environment*, 727: 138668. https://doi.org/10.1016/j.scitotenv.2020.138668

Steinmetz, Z. & Schröder, H. 2022. Plastic debris in plastic-mulched soil—a screening study from western Germany. *PeerJ*, 10: e13781. https://doi.org/10.7717/peerj.13781

Sun, H., Lei, C., Xu, J. & Li, R. 2021. Foliar uptake and leaf-to-root translocation of nanoplastics with different coating charge in maize plants. *Journal of Hazardous Materials*, 416: 125854. https://doi.org/10.1016/j.jhazmat.2021.125854

Sun, H., Shi, Y., Zhao, P., Long, G., Li, C., Wang, J., Qiu, D. *et al.* 2023a. Effects of polyethylene and biodegradable microplastics on photosynthesis, antioxidant defense systems, and arsenic accumulation in maize (Zea mays L.) seedlings grown in arsenic-contaminated soils. *The Science of the Total Environment*, 868: 161557. https://doi.org/10.1016/j.scitotenv.2023.161557

Sun, H., Shi, Y., Li, C., He, S., Bai, Y., Zhao, P., Qiu, D., Liu, J. & He, S. 2024. Factors controlling the heavy metal ion activity in soil contaminated by microplastics with different mulch durations: Partial least squares path model. *Journal of Hazardous Materials*, 464: 133027. https://doi.org/10.1016/j.jhazmat.2023.133027

Sun, Q., Zhang, X., Liu, C., A, N., Ying, S., Zhang, J., Zhao, Y. *et al.* 2023b. The content of PAEs in field soils caused by the residual film has a periodical peak. *The Science of the Total Environment*, 864: 161078. https://doi.org/10.1016/j.scitotenv.2022.161078

Sun, Y., Li, C., Zhang, X., Shi, M. & Wang, Z. 2021. Effects of film mulching on the distribution of phthalate esters in wheat grains from dryland. *Environmental Science and Pollution Research*, 28(22): 27844–27851. https://doi.org/10.1007/s11356-021-12406-x

Tan, C., Cao, X., Yuan, S., Wang, W., Feng, Y. & Qiao, B. 2015. Effects of Long-term Conservation Tillage on Soil Nutrients in Sloping Fields in Regions Characterized by Water and Wind Erosion. *Scientific Reports*, 5(1): 17592. https://doi.org/10.1038/srep17592

Tang, K.H.D. 2023. Microplastics in agricultural soils in China: Sources, impacts and solutions. *Environmental Pollution*, 322: 121235. https://doi.org/10.1016/j.envpol.2023.121235

Tang, X., Chen, M., Li, M., Liu, H., Tang, H. & Yang, Y. 2023. Do differentially charged nanoplastics affect imidacloprid uptake, translocation, and metabolism in Chinese flowering cabbage? *Science of The Total Environment*, 871: 161918. https://doi.org/10.1016/j.scitotenv.2023.161918

Tartiu, V., Hurley, R., Baann, C., Briassoulis, D., Schettini, E., Convertino, F., Le Moine, B. *et al.* 2024. Addressing the environmental sustainability of plastics used in agriculture: a multi-actor perspective. *Submitted to Cambridge Prisms Plastics.*

Tong, Y., Ding, J., Xiao, M., Shahbaz, M., Zhu, Z., Chen, M., Kuzyakov, Y. *et al.* 2022. Microplastics affect activity and spatial distribution of C, N, and P hydrolases in rice rhizosphere. *Soil Ecology Letters*, 5(3): 220138. https://doi.org/10.1007/s42832-022-0138-2

UNEP & GRID-Arendal. 2021. Plastics in Agriculture: Sources and Impacts - Working Paper. https://wedocs.unep.org/xmlui/handle/20.500.11822/37681

Uzamurera, A.G., Zhao, Z.-Y., Wang, P.-Y., Wei, Y.-X., Mo, F., Zhou, R., Wang, W.-L. *et al.* 2023. Thickness effects of polyethylene and biodegradable film residuals on soil properties and dryland maize productivity. *Chemosphere*, 329: 138602. https://doi.org/10.1016/j.chemosphere.2023.138602

van Loon, S., de Jeu, L., Hurley, R., Kernchen, S., Fenner, M. & van Gestel, C.A.M. 2024. Multigenerational toxicity of microplastics derived from two types of agricultural mulching films to *Folsomia candida. SCIENCE OF THE TOTAL ENVIRONMENT*, 949: 175097. https://doi.org/10.1016/j.scitotenv.2024.175097

van Schothorst, B., Beriot, N., Huerta Lwanga, E. & Geissen, V. 2021. Sources of Light Density Microplastic Related to Two Agricultural Practices: The Use of Compost and Plastic Mulch. *Environments*, 8(4): 36. https://doi.org/10.3390/environments8040036

Vert, M., Doi, Y., Hellwich, K.-H., Hess, M., Hodge, P., Kubisa, P., Rinaudo, M. & Schué, F. 2012. Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). *Pure and Applied Chemistry*, 84(2): 377–410. https://doi.org/10.1351/PAC-REC-10-12-04

Viljoen, S.J., Brailsford, F.L., Murphy, D.V., Hoyle, F.C., Chadwick, D.R. & Jones, D.L. 2023. Leaching of phthalate acid esters from plastic mulch films and their degradation in response to UV irradiation and contrasting soil conditions. *Journal of Hazardous Materials*, 443: 130256. https://doi.org/10.1016/j.jhazmat.2022.130256

Wagner, M., Monclús, L., Arp, H.P.H., Groh, K.J., Løseth, M.E., Muncke, J., Wang, Z., Wolf, R. & Zimmermann, L. 2024. *State of the science on plastic chemicals - Identifying and addressing chemicals and polymers of concern*. Zenodo. https://doi.org/10.5281/zenodo.10701706

Wan, Y., Wu, C., Xue, Q. & Hui, X. 2019. Effects of plastic contamination on water evaporation and desiccation cracking in soil. *Science of The Total Environment*, 654: 576–582. https://doi.org/10.1016/j.scitotenv.2018.11.123

Wang, D., Xi, Y., Shi, X.-Y., Zhong, Y.-J., Guo, C.-L., Han, Y.-N. & Li, F.-M. 2021a. Effect of plastic film mulching and film residues on phthalate esters concentrations in soil and plants, and its risk assessment. *Environmental Pollution*, 286: 117546. https://doi.org/10.1016/j.envpol.2021.117546

Wang, F., Zhang, X., Zhang, S., Zhang, S., Adams, C.A. & Sun, Y. 2020. Effects of Co-Contamination of Microplastics and Cd on Plant Growth and Cd Accumulation. *Toxics*, 8(2): 36. https://doi.org/10.3390/toxics8020036

Wang, J., Li, J., Liu, S., Li, H., Chen, X., Peng, C., Zhang, P. & Liu, X. 2021. Distinct microplastic distributions in soils of different land-use types: A case study of Chinese farmlands. *Environmental Pollution*, 269: 116199. https://doi.org/10.1016/j.envpol.2020.116199

Wang, J., Lv, S., Zhang, M., Chen, G., Zhu, T., Zhang, S., Teng, Y., Christie, P. & Luo, Y. 2016a. Effects of plastic film residues on occurrence of phthalates and microbial activity in soils. *Chemosphere*, 151: 171–177. https://doi.org/10.1016/j.chemosphere.2016.02.076

Wang, K., Chen, W., Tian, J., Niu, F., Xing, Y., Wu, Y., Zhang, R., Zheng, J. & Xu, L. 2022. Accumulation of microplastics in greenhouse soil after long-term plastic film mulching in Beijing, China. *Science of The Total Environment*, 828: 154544. https://doi.org/10.1016/j.scitotenv.2022.154544

Wang, S., Wang, Y., Luo, C., Li, J., Yin, H. & Zhang, G. 2016. Plant selective uptake of halogenated flame retardants at an e-waste recycling site in southern China. *Environmental Pollution*, 214: 705–712. https://doi.org/10.1016/j.envpol.2016.04.071

Wang, W., Xie, Y., Li, H., Dong, H., Li, B., Guo, Y., Wang, Y. *et al.* 2024c. Responses of lettuce (Lactuca sativa L.) growth and soil properties to conventional non-biodegradable and new biodegradable microplastics. *Environmental Pollution (Barking, Essex: 1987)*, 341: 122897. https://doi.org/10.1016/j.envpol.2023.122897

Wang, Y., Tang, L., Chen, J., Joseph, A., Wu, Y., Rene, E.R., Tang, J., Zhu, N. & Wang, P. 2024b. Susceptibility of Cd availability in microplastics contaminated paddy soil: Influence of ferric minerals and sulfate reduction. *Journal of Hazardous Materials*, 465: 133343. https://doi.org/10.1016/j.jhazmat.2023.133343

Wang, Y., Xv, X., Shao, T., He, Q., Guo, Z., Wang, Y., Guo, Q. & Xing, B. 2024a. A case on source to soil to solutions: Distribution characteristics of microplastics in farmland soil of the largest vegetable base in Northwest China. *Science of The Total Environment*, 907: 167910. https://doi.org/10.1016/j.scitotenv.2023.167910

Wen, X., Yin, L., Zhou, Z., Kang, Z., Sun, Q., Zhang, Y., Long, Y. et al. 2022. Microplastics can affect soil properties and chemical speciation of metals in yellow-brown soil. *Ecotoxicology and Environmental Safety*, 243: 113958. https://doi.org/10.1016/j.ecoenv.2022.113958

Wen, Y., Liu, J., Zhang, J., Li, W., Ayantobo, O.O. & Wang, Z. 2023. Effects of macro-plastics on soil hydrothermal environment, cotton yield, and fiber quality under mulched drip irrigation in the arid region of Northwest China. *Field Crops Research*, 302: 109060. https://doi.org/10.1016/j.fcr.2023.109060

Wu, X., Hou, H., Liu, Y., Yin, S., Bian, S., Liang, S., Wan, C. *et al.* 2022. Microplastics affect rice (*Oryza sativa* L.) quality by interfering metabolite accumulation and energy expenditure pathways: A field study. *Journal of Hazardous Materials*, 422: 126834. https://doi.org/10.1016/j.jhazmat.2021.126834

Wu, X., Lyu, X., Li, Z., Gao, B., Zeng, X., Wu, J. & Sun, Y. 2020. Transport of polystyrene nanoplastics in natural soils: Effect of soil properties, ionic strength and cation type. *Science of The Total Environment*, 707: 136065.

Wu, Z., Zheng, Y., Sui, X., Zhang, Z., Wang, E., Liu, Y., Yu, T., Yang, J. & Wu, Y. 2023. Comparative analysis of the effects of conventional and biodegradable plastic mulching films on soil-peanut ecology and soil pollution. *Chemosphere*, 334: 139044. https://doi.org/10.1016/j.chemosphere.2023.139044

Xiao, M., Ding, J., Luo, Y., Zhang, H., Yu, Y., Yao, H., Zhu, Z. *et al.* 2022. Microplastics shape microbial communities affecting soil organic matter decomposition in paddy soil. *Journal of Hazardous Materials*, 431: 128589. https://doi.org/10.1016/j.jhazmat.2022.128589

Xiang, P., Liao, W., Xiong, Z., Xiao, W., Luo, Y., Peng, L., Zou, L., Zhao, C. & Li, Q. 2024. Effects of polystyrene microplastics on the agronomic traits and rhizosphere soil microbial community of highland barley. *Science of The Total Environment*, 907: 167986. https://doi.org/10.1016/j.scitotenv.2023.167986

Xiong, Y., Zhang, Q., Chen, X., Bao, A., Zhang, J. & Wang, Y. 2019. Large Scale Agricultural Plastic Mulch Detecting and Monitoring with Multi-Source Remote Sensing Data: A Case Study in Xinjiang, China. *Remote Sensing*, 11(18): 2088. https://doi.org/10.3390/rs11182088

Xu, G., Liu, Y. & Yu, Y. 2021. Effects of polystyrene microplastics on uptake and toxicity of phenanthrene in soybean. *Science of The Total Environment*, 783: 147016. https://doi.org/10.1016/j.scitotenv.2021.147016

Xu, J., Bi, W., Hua, L., Cheng, Z., Wang, Y., Li, D., Liu, W., Wang, L. & Sun, H. 2022b. Wide occurrence of seven phthalate plasticizers and two typical microplastics in pig feed. *Chemosphere*, 307: 135847. https://doi.org/10.1016/j.chemosphere.2022.135847

Xu, L., Xu, X., Li, C., Li, J., Sun, M. & Zhang, L. 2022a. Is mulch film itself the primary source of meso- and microplastics in the mulching cultivated soil? A preliminary field study with econometric methods. *Environmental Pollution*, 299: 118915. https://doi.org/10.1016/j.envpol.2022.118915

Xu, L., Wang, Y., Wei, F., Dai, Z. & Zhang, M. 2024. Transport behavior of microplastics in soil-water environments and its dependence on soil components. *Environmental Pollution*, 346: 123542. https://doi.org/10.1016/j.envpol.2024.123542

Xu, M., Xu, Q., Wang, G., Du, W., Zhu, J., Yin, Y., Ji, R., Wang, X. & Guo, H. 2023. Elevated CO2 aggravated polystyrene microplastics effects on the rice-soil system under field conditions. *Environmental Pollution*, 316: 120603. https://doi.org/10.1016/j.envpol.2022.120603

Yan, P., Zhang, S., Wang, J., Xiao, Z., Yan, S., Wang, W. & Aurangzeib, M. 2022. Heterogeneity of plastic residue was determined by both mulch film and external plastic pollutants in the farmland of Northeast China. *Science of The Total Environment*, 853: 158681. https://doi.org/10.1016/j.scitotenv.2022.158681

Yang, H., Hu, Z., Wu, F., Guo, K., Gu, F. & Cao, M. 2023a. The Use and Recycling of Agricultural Plastic Mulch in China: A Review. *Sustainability*, 15(20): 15096. https://doi.org/10.3390/su152015096

Yang, L., Heng, T., He, X., Yang, G., Zhao, L., Li, Y. & Xu, Y. 2023b. Spatial-temporal distribution and accumulation characteristics of residual plastic film in cotton fields in arid oasis area and the effects on soil salt transport and crop growth. *SOIL & TILLAGE RESEARCH*, 231: 105737. https://doi.org/10.1016/j.still.2023.105737

Yang, M., Tian, X., Guo, Z., Chang, C., Li, J., Guo, Z., Li, H. *et al.* 2022b. Effect of Dry Soil Aggregate Size on Microplastic Distribution and Its Implications for Microplastic Emissions Induced by Wind Erosion. *Environmental Science & Technology Letters*, 9(7): 618–624. https://doi.org/10.1021/acs.estlett.2c00338

Yang, W., Cheng, P., Adams, C.A., Zhang, S., Sun, Y., Yu, H. & Wang, F. 2021. Effects of microplastics on plant growth and arbuscular mycorrhizal fungal communities in a soil spiked with ZnO nanoparticles. *Soil Biology and Biochemistry*, 155: 108179. https://doi.org/10.1016/j.soilbio.2021.108179

Yang, Y., Li, Z., Yan, C., Chadwick, D., Jones, D.L., Liu, E., Liu, Q., Bai, R. & He, W. 2022a. Kinetics of microplastic generation from different types of mulch films in agricultural soil. *Science of The Total Environment*, 814: 152572. https://doi.org/10.1016/j.scitotenv.2021.152572

Yu, L., Zhang, J., Liu, Y., Chen, L., Tao, S. & Liu, W. 2021. Distribution characteristics of microplastics in agricultural soils from the largest vegetable production base in China. *Science of The Total Environment*, 756: 143860. https://doi.org/10.1016/j.scitotenv.2020.143860

Yu, Y., Chen, Y., Wang, Y., Xue, S., Liu, M., Tang, D.W.S., Yang, X. & Geissen, V. 2023. Response of soybean and maize roots and soil enzyme activities to biodegradable microplastics contaminated soil. *Ecotoxicology and Environmental Safety*, 262: 115129. https://doi.org/10.1016/j.ecoenv.2023.115129

Zantis, L.J., Borchi, C., Vijver, M.G., Peijnenburg, W., Di Lonardo, S. & Bosker, T. 2023. Nano- and microplastics commonly cause adverse impacts on plants at environmentally relevant levels: A systematic review. *Science of the Total Environment*, 867: 161211. https://doi.org/10.1016/j.scitotenv.2022.161211

Zeng, L.-J., Huang, Y.-H., Lü, H., Geng, J., Zhao, H.-M., Xiang, L., Li, H. *et al.* 2022. Uptake pathways of phthalates (PAEs) into Chinese flowering cabbage grown in plastic greenhouses and lowering PAE accumulation by spraying PAE-degrading bacterial strain. *Science of The Total Environment*, 815: 152854. https://doi.org/10.1016/j.scitotenv.2021.152854

Zhang, K., Gao, N., Li, Y., Dou, S., Liu, Z., Chen, Y., Ma, C. & Zhang, H. 2023b. Responses of maize (*Zea mays* L.) seedlings growth and physiological traits triggered by polyvinyl chloride microplastics is dominated by soil available nitrogen. *Ecotoxicology and Environmental Safety*, 252: 114618. https://doi.org/10.1016/j.ecoenv.2023.114618

Zhang, L., Sintim, H.Y., Bary, A.I., Hayes, D.G., Wadsworth, L.C., Anunciado, M.B. & Flury, M. 2018. Interaction of *Lumbricus terrestris* with macroscopic polyethylene and biodegradable plastic mulch. *Science of the Total Environment*, 635: 1600–1608. https://doi.org/10.1016/j.scitotenv.2018.04.054

Zhang, L., Qin, R., Wei, H., Zhang, K., Yu, C., Li, F.-M. & Zhang, F. 2022c. Optimum plastic mulching application to reduce greenhouse gas emissions without compromising on crop yield and farmers' income. *Science of The Total Environment*, 809: 151998. https://doi.org/10.1016/j.scitotenv.2021.151998

Zhang, H., Huang, Y., An, S., Wang, P., Xie, C., Jia, P., Huang, Q. & Wang, B. 2024. Mulch-derived microplastic aging promotes phthalate esters and alters organic carbon fraction content in grassland and farmland soils. *Journal of Hazardous Materials*, 461: 132619. https://doi.org/10.1016/j.jhazmat.2023.132619

Zhang, S., Pei, L., Zhao, Y., Shan, J., Zheng, X., Xu, G., Sun, Y. & Wang, F. 2023b. Effects of microplastics and nitrogen deposition on soil multifunctionality, particularly C and N cycling. *Journal of Hazardous Materials*, 451: 131152. https://doi.org/10.1016/j.jhazmat.2023.131152

Zhang, S., Bao, A., Lin, X., Jia, G. & Zhang, Q. 2023a. Microplastic Accumulation in Agricultural Soils with Different Mulching Histories in Xinjiang, China. *Sustainability*, 15(6): 5438. https://doi.org/10.3390/su15065438

Zhang, W., Wang, Y., Li, C., Chang, S., Xue, Y., Dang, T. & Zeng, X. 2022e. Long-term ground cover affects soil bacterial community and carbon metabolism in the Loess Plateau, China. *Soil Science Society of America Journal*, 86(4): 918–931. https://doi.org/10.1002/saj2.20411

Zhang, W., Ma, J., Cui, Z., Xu, L., Liu, Q., Li, J., Wang, S. & Zeng, X. 2023c. Effects of Biodegradable Plastic Mulch Film on Cabbage Agronomic and Nutritional Quality Traits, Soil Physicochemical Properties and Microbial Communities. *Agronomy*, 13(5): 1220. https://doi.org/10.3390/agronomy13051220

Zhang, X., Chen, Y., Li, X., Zhang, Y., Gao, W., Jiang, J., Mo, A. & He, D. 2022d. Size/shape-dependent migration of microplastics in agricultural soil under simulative and natural rainfall. *Science of The Total Environment*, 815: 152507. https://doi.org/10.1016/j.scitotenv.2021.152507

Zhang, Y., Wang, K., Chen, W., Ba, Y., Khan, K., Chen, W., Tu, C., Chen, C. & Xu, L. 2022a. Effects of land use and landscape on the occurrence and distribution of microplastics in soil, China. *Science of The Total Environment*, 847: 157598. https://doi.org/10.1016/j.scitotenv.2022.157598

Zhang, Y., Yang, S., Zeng, Y., Chen, Y., Liu, H., Yan, X. & Pu, S. 2023c. A new quantitative insight: Interaction of polyethylene microplastics with soil - microbiome - crop. *Journal of Hazardous Materials*, 460: 132302. https://doi.org/10.1016/j.jhazmat.2023.132302

Zhang, Z., Wu, X., Zhang, J. & Huang, X. 2022b. Distribution and migration characteristics of microplastics in farmland soils, surface water and sediments in Caohai Lake, southwestern plateau of China. *Journal of Cleaner Production*, 366: 132912. https://doi.org/10.1016/j.jclepro.2022.132912

Zhao, Z.-Y., Wang, P.-Y., Wang, Y.-B., Zhou, R., Koskei, K., Munyasya, A.N., Liu, S.-T. ***et al.*** 2021. Fate of plastic film residues in agro-ecosystem and its effects on aggregate-associated soil carbon and nitrogen stocks. *Journal of Hazardous Materials*, 416: 125954. https://doi.org/10.1016/j.jhazmat.2021.125954

Zhou, B., Wang, J., Zhang, H., Shi, H., Fei, Y., Huang, S., Tong, Y. ***et al.*** 2020. Microplastics in agricultural soils on the coastal plain of Hangzhou Bay, east China: Multiple sources other than plastic mulching film. *Journal of Hazardous Materials*, 388: 121814. https://doi.org/10.1016/j.jhazmat.2019.121814

Zhou, J., Wen, Y., Marshall, M.R., Zhao, J., Gui, H., Yang, Y., Zeng, Z., Jones, D.L. & Zang, H. 2021. Microplastics as an emerging threat to plant and soil health in agroecosystems. *Science of the Total Environment*, 787: 147444. https://doi.org/10.1016/j.scitotenv.2021.147444

Zhou, W., Wang, Q., Wei, Z., Jiang, J. & Deng, J. 2023a. Effects of microplastic type on growth and physiology of soil crops: Implications for farmland yield and food quality. *Environmental Pollution*, 326: 121512. https://doi.org/10.1016/j.envpol.2023.121512

Zhou, Y., Jing, J., Yu, R., Zhao, Y., Gou, Y., Zhang, Z., Tang, H., Zhang, H. & Huang, Y. 2023. Microplastics in plateau agricultural areas: Spatial changes reveal their source and distribution characteristics. *Environmental Pollution*, 319: 121006. https://doi.org/10.1016/j.envpol.2023.121006

Zimmermann, L., Dombrowski, A., Völker, C. & Wagner, M. 2020. Are bioplastics and plant-based materials safer than conventional plastics? In vitro toxicity and chemical composition. *Environment International*, 145: 106066. https://doi.org/10.1016/j.envint.2020.106066

Appendix 1.
Report methodology

This report is based on a series of systematic literature reviews addressing several components of soil plastic pollution. The purpose of these literature reviews was to collate available published data and original scientific knowledge on the use of agricultural plastics, the occurrence of plastic pollution in soil derived from agricultural plastic use, and the effects of this plastic pollution on soil ecosystems. The outcomes of the reviews were used to evaluate available knowledge and identify and characterise persistent research gaps. This includes an evaluation of the current status of soil plastic pollution from agricultural plastic use and comparing this with relevant effects thresholds to establish the present and future risk and associated uncertainties.

Relevant literature was searched for and identified using the Web of Science online register, utilising a series of Boolean search strings (Table A1). Titles and abstracts of all search results were reviewed to determine whether they pass basic eligibility criteria related to the frame of each literature review. Only peer-reviewed scientific literature published in English was reviewed. Review articles were also excluded in favour of original results articles. Only articles published between 1 January 2014 and the date of the literature search were included. From this initial scoping, a subset of publications was further examined based on a deeper evaluation of the contents of each article and a more elaborate set of inclusion/exclusion criteria. These are described below in the context of each systematic literature review performed. This process was performed manually by a single analyst for each literature review. No automation tools were utilised to compile the lists of publications for review.

In total, the review encompassed 2 283 peer-reviewed papers, of which 505 were identified as eligible studies.

INVENTORIES OF AGRICULTURAL PLASTIC USE

General eligibility criteria

Studies addressing inventories of usage and waste generation of AP from any locations in the world, regardless of whether they were based on modelling, stakeholder surveys, aerial data, etc.

Inclusion/exclusion criteria

Reviews and perspective articles were not included in the systematic analysis, while a perspective article was consulted for quality assurance purposes.

OCCURRENCE IN SOILS

General eligibility criteria
Studies that investigate levels of plastic pollution in soils exposed to the use of AP.

Inclusion/exclusion criteria
All forms of plastic pollution were included in the review, from larger plastic residues to small particles, commonly referred to as microplastics. Only studies that sampled at least one field that was described in the text as having been currently or historically exposed to the use of AP were included. All plastic products utilised in agricultural production were included under the frame of AP. Only studies that reported written concentration data (in text or tables in the main document) were included. All publications passing the above criteria were included in an overview of occurrence data, regardless of the sampling or analytical methodology utilised, the quality of such methods, or the units in which reported data were assessed. A small number of studies were excluded from a quantitative review of levels of plastic pollution in soil based on insufficient detail provided in the summary of methods or results to allow for mass estimation (e.g. no details on particle size or shape) or the use of reporting units that are incompatible with establishing a sufficiently reliable mass estimate (e.g. items hectare^{-1}).

MICROPLASTIC GENERATION MECHANISMS IN SOIL

General eligibility
Studies that experimentally describe the fragmentation or degradation of agricultural plastic products.

Inclusion/exclusion criteria
Only studies that assessed fragmentation, degradation, and/or generation of microplastics from AP were included in this review; studies that describe degradation or breakdown of general polymer types in soil were excluded. (Studies on) Microplastic generation in field soils and simulated soil environments in laboratory conditions were both included. All sizes of plastic particles were included, from large pieces of agricultural plastic to smaller residues derived from AP.

FATE PROCESSES IN SOILS

General eligibility
Studies investigating the mobilisation or retention of plastics in soils, or the export of plastic from soil environments.

Inclusion/exclusion criteria

Only studies experimentally investigating or tracking fate processes were included. Studies describing inferred fate or transport processes from single timepoint occurrence data were excluded. Modelling studies, and other studies with a conceptual frame, were also excluded. Studies assessing particle fate in both real and simulated soil environments were included. However, studies that examine soils with lower relevance to agricultural environments were excluded, for example studies investigating non-agricultural floodplain or wetland soil dynamics. The full spectrum of plastic particle size was considered relevant for this review. All studies reporting fate processes in soil were compiled into an overview – including the study of plastic particles not derived from AP or agricultural plastic use.

EFFECTS ON SOIL PROPERTIES

General eligibility

Both experimental studies and field studies investigating the effects on soil properties, or investigating a possible relationship between concentrations of nano- or microplastics in soil and its properties, were included in this chapter. By soil properties we refer to heavy metal availability, physical and chemical properties (pH, bulk density, etc.), microbiota diversity and/or activity, among others.

Inclusion/exclusion criteria

Studies aiming only at quantifying and characterizing plastic in soils without assessing the effects were not included. Similarly, studies reporting effects on soil properties by other particles than plastic, such as biochar, wood, metal, etc. were excluded. Modelling and review studies were also excluded but were consulted for quality assurance purposes. All plastic sizes (from the nano-range to entire mulching films) were considered in this report.

EFFECTS ON PLANTS

General eligibility

Both experimental studies and field studies investigating the effects on plants, or investigating a possible relationship between concentrations of nano- or microplastics in soils and its effects on plants, were included in this review.

Inclusion/exclusion criteria

Modelling and review studies were excluded but were consulted for quality assurance purposes. The full spectrum of sizes (from the nano-range to entire mulching films) was considered in this review.

LONG-TERM EFFECTS OF THE USE OF AGRICULTURAL PLASTIC IN SOIL

General eligibility

Both experimental studies and field studies investigating the long-term effects (i.e. with a temporal scope longer than 3 years) on soil health or plant growth and quality, or investigating possible relationships between concentrations of nano- or microplastics in soils and their effects on plants, were included in this review.

Inclusion/exclusion criteria

Purely modelling and review studies were excluded but were consulted for quality assurance purposes. The full spectrum of sizes (from the nano-range to entire mulching films) was considered in this review as well as biodegradable and conventional materials.

PLANT UPTAKE AND TRANSFER

General eligibility

Studies investigating experimentally the uptake of nano- or microplastics, and the uptake of plastic related chemicals by plants from soil or from leaves (foliar uptake experiments).

Inclusion/exclusion criteria

Only studies explicitly mentioning the plastic composition of the tested particles were considered in this analysis. Studies investigating only the effects of nanoplastics, microplastics, or chemicals on the fitness, survival, etc. but not addressing uptake and translocation in the plant tissues were excluded from this review. Modelling studies, and other studies with a conceptual frame, and reviews without any additional experiments or data were also excluded.

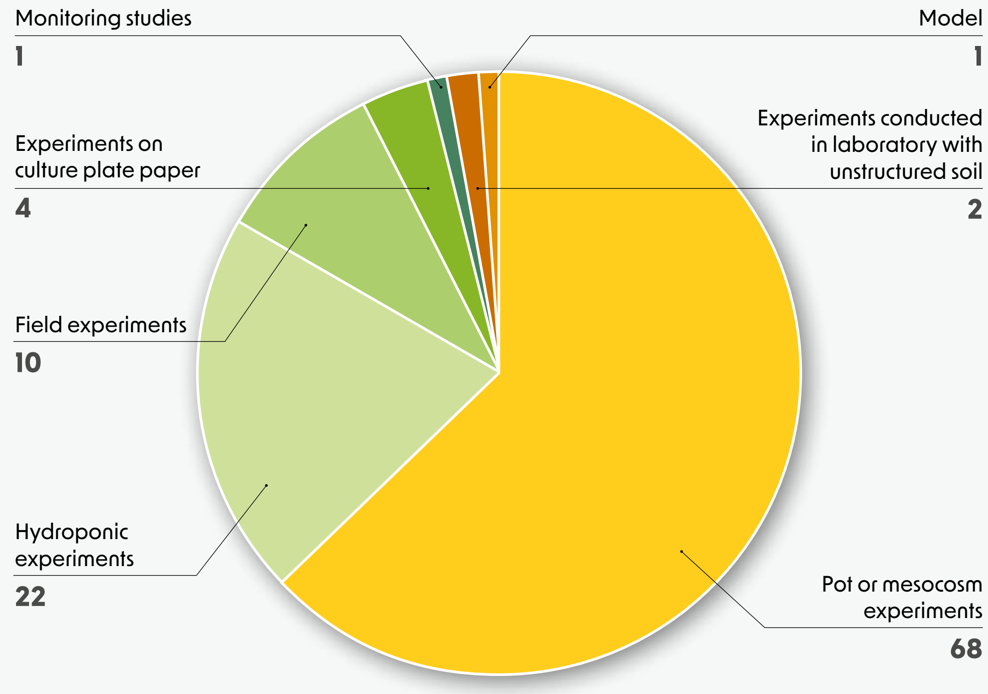
TABLE A1. Boolean search strings used in the systematic review

Systematic literature review	Boolean search strings	Date of search	Total number of search results	Number of eligible studies
Inventories of agricultural plastic use	Topic: "agricultural plastic*" OR Agriplastic* OR "agricultural plastic waste" AND inventor* OR generation OR Assessment OR survey OR map*	01.04.2024	73	22
Occurrence in soils	Title: soil; Topic: microplastic* OR "plastic residue" or "plastic litter" OR "plastic debris"; agricult* OR agriplastic* OR mulch OR mulching film* OR film* OR greenhouse OR encapsulated OR slow-release OR waste; monitor* OR occurrence OR source*	02.04.2024	529	67
Microplastic generation mechanisms in soils	Title: soil; Topic: microplastic* OR "plastic residue" or "plastic litter" OR "plastic debris"; agricult* OR agriplastic* OR mulch OR mulching film* OR film* OR greenhouse OR encapsulated OR slow-release OR waste; generation OR source* OR fragment*	04.04.2024	295	8
Fate processes in soils	Title: soil; Topic: microplastic* OR "plastic residue" or "plastic litter" OR "plastic debris"; fate OR transport* OR transfer* OR mobilis* OR retain* OR retention OR export OR runoff OR accumul*	08.04.2024	408	27
Effects on soil properties	Title: soil; Topic: microplastic* OR "plastic residue" or "plastic litter" OR "plastic debris"; agricult* OR agriplastic* OR mulch OR mulching film* OR film* OR greenhouse OR encapsulated OR slow-release OR waste; effect* AND soil properties OR microbio* OR bacteria	13.03.2024	619	231
Effects on plants	Topic: microplastic* OR "plastic residue" or "plastic litter" OR "plastic debris"; agricult* OR agriplastic* OR mulch OR mulching film* OR film* OR greenhouse OR encapsulated OR slow-release OR waste; effect* AND soil properties OR microbio* OR bacteria	13.03.2024	265	114
Long-term effect of AP use in soil	Topic: Mulch* AND plastic* AND effect AND crop AND yield AND "long-term"; Residue* OR microplastic* OR pollut*	28.04.2024	20	4
Plant uptake and transfer	Topic: microplast* uptake OR microplast* transfer OR nanoplast* uptake; vegetables OR maize OR corn OR pea* OR carrot OR soybean OR bean* OR wheat OR rice OR potato* OR fruit* OR peanut OR crop OR cabbage OR lettuce OR tomato; plastic related chemical OR additive* OR plasticizer OR flame retardant OR phthalate*	13.03.2024	74	32

Appendix 2. Supporting data and methodological details

Figure A2.1. details the number of studies addressing effects on plants of plastic in soil, organized by typology of experiment. The figure shows that most studies in the systematic review were conducted under conditions realistic for plant growth: 68 focused on pot or mesocosm experiments, 10 were field experiments, and only 22 involved hydroponic conditions. The remaining studies consisted of laboratory experiments, monitoring, or modeling studies.

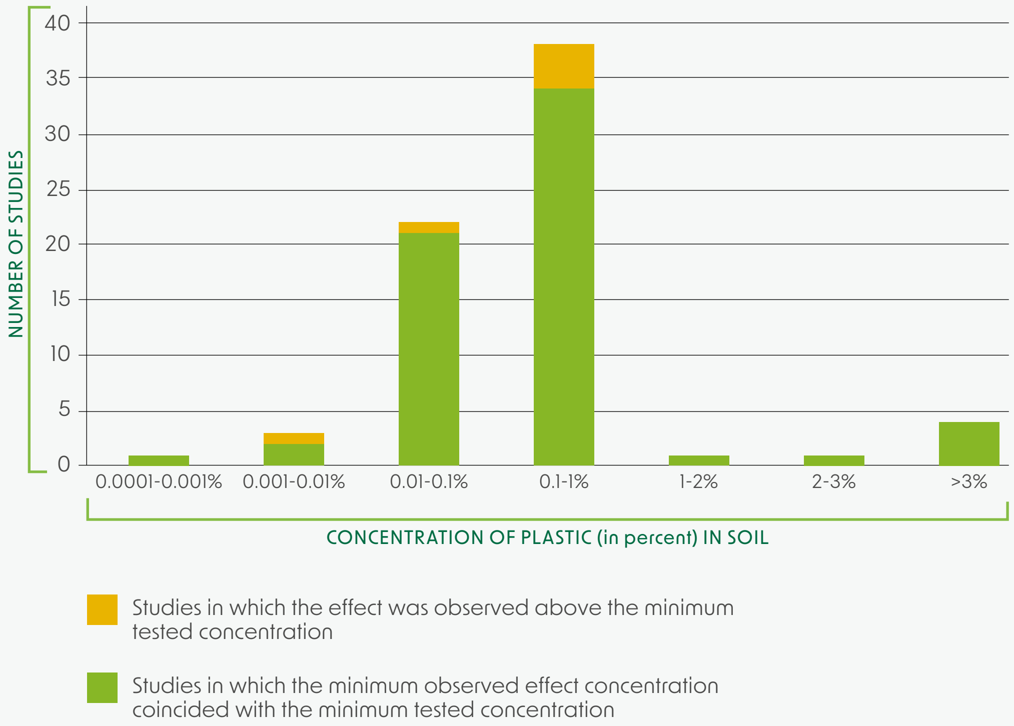
FIGURE A2.1. Number of studies addressing effects on plants of plastic in soil by typology of experiment



Source: Authors' own elaboration.

Figure A2.2 illustrates the frequency of observed effects on plants in relation to the tested concentrations. The figure depicts the large prevalence of studies in which significant effects were observed already at the minimum tested concentration. This indicates that the safety thresholds given by the non-observable-effect concentration of plastic in soil for effects on plants could not be identified in most of the studies, and that such a threshold is likely low.

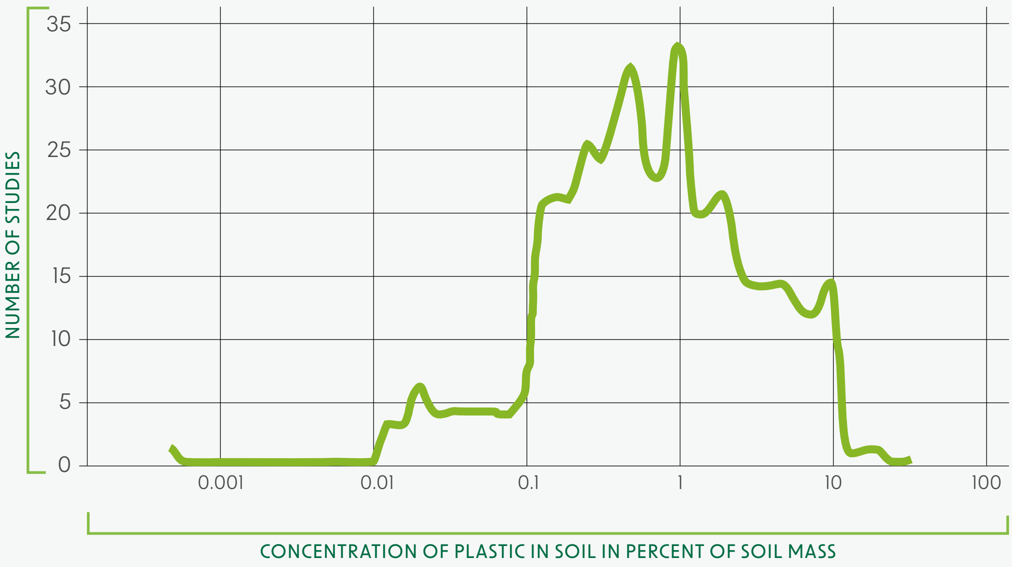
FIGURE A2.2. **Number of studies that observed an effect of plastic pollution on plant health along a concentration gradient**



Source: Authors' own elaboration.

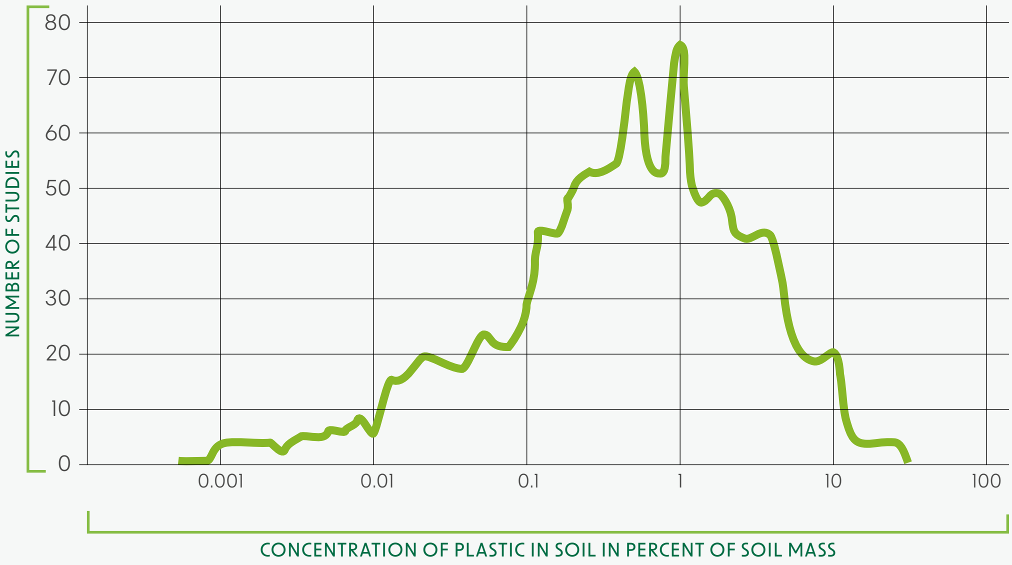
Figure A2.3 and Figure A2.4 provide an overview of the frequency at which various plastic concentration ranges have been included in studies addressing the effects of soil plastic pollution on plant health and on soil properties. These figures highlight the prevalence of studies conducted at higher plastic concentrations (e.g. above 0.05 percent of soil mass), while fewer studies have focused on lower, environmentally relevant exposure levels. The data presented in these figures offer insight into the experimental design trends observed in the systematic literature review and help contextualize the findings on plastic pollution's impact on soil ecosystems.

FIGURE A2.3. **Number of studies addressing effects on plant health at a given exposure level in soil**



Source: Authors' own elaboration.

FIGURE A2.4. **Number of studies addressing effects on soil properties at a given exposure level in soil**



Source: Authors' own elaboration.

Office of Climate Change, Biodiversity and Environment (OCB)

www.fao.org/in-action/sustainable-and-circular-bioeconomy

Bioeconomy@fao.org

Food and Agriculture Organization of the United Nations
Rome, Italy

ISBN 978-92-5-139996-5

9 789251 399965
CD6407EN/1/08.25