Food and Agriculture
Organization of the
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ASSESSMENT OF AGRICULTURAL PLASTICS AND THEIR SUSTAINABILITY

A CALL FOR ACTION

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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CONTENTS

FOREWORD ix

ACKNOWLEDGEMENTS x

ABBREVIATIONS AND ACRONYMS xi

EXECUTIVE SUMMARY xiii

1. Introduction 1
   - 1.1 The link between plastics and agriculture 1
   - 1.2 The problems associated with plastics 2
   - 1.3 Scope of this report 3
2. The use of plastics in agriculture 5
   - 2.1 Plastics and their properties 5
   - 2.2 Types of plastic products and their application 10
   - 2.3 The benefits of using plastic products in agriculture 10
   - 2.4 Estimated lifespans of selected plastic products 14
   - 2.5 Summary 15
3. The types and estimated quantities of agricultural plastic products in use 16
   - 3.1 Estimating the quantities of plastic products used in agriculture 16
   - 3.2 Global estimates 16
   - 3.3 Regional estimates 18
   - 3.4 Global product estimates 21
   - 3.5 Summary 28

4. The harm caused by plastics 31
4.1 Risk assessment model 31
4.2 Sources of agricultural plastics 31
4.3 Pathways and the 3D concept 32
4.4 Receptor environments 33
4.5 Consequences 36
4.6 Summmary 39

5. Assessment of agricultural plastic products 41
5.1 Selection of priority plastic products 42
5.2 Detailed analysis of selected products 45
5.3 Other products of potential concern 72
5.4 Summary 73

6. Current frameworks and mechanisms to facilitate good management practices 77
6.1 Transition towards sustainable agri-food systems 77
6.2 International policy and legal instruments 78
6.3 National and regional legislation 80
6.4 Key measures 82
6.5 Summary 96

7. Towards a circular economy for agricultural plastics
7.1 Need for new legal and policy measures 99
7.2 Elements for a proposed international voluntary code of conduct 101
7.3 Priority actions 105
7.4 Development of guidance documents 106
7.5 Gaps and further research 107
7.6 Summary 108

8. Conclusions 110

References 113

Glossary 124

ANNEX 1 Value chains

1. Horticulture 128

2. Livestock 129

2.1 Fodder and food 130

2.2 Animal production 131

2.3 Products from live animals 132

2.3.1 Wool 132

2.3.2 Milk 132

2.4 Products from slaughtered animals 133

2.3.3 Leather 133

2.3.3 Meat 133

3. Cotton 134

3.1 Seeds 134

3.2 Fibres 135

4. Forestry plantation 136

5. Marine capture fisheries 137

6. Aquaculture 138

7. Banana 139

8. Maize 140

TABLES, FIGURES AND BOXES

Tables

Table 1:	Agricultural plastic products and their typical polymers	8
Table 2:	Agricultural practices that use plastic products	11
Table 3:	Summary of the benefits of plastic products used in agriculture	12
Table 4:	Source of data for quantities of agricultural plastic products	22
Table 5:	RAG rating of identified agricultural plastic products	43
Table 6:	Priority and representative products selected for assessment	44
Table 7:	Identified alternatives and interventions for selected agricultural products	74
Table 8:	Summary of main international policy instruments relevant to agricultural plastics	78
Table 9:	Main types of regional and national level measures to address plastic pollution	80
Table 10:	Range of agricultural plastic products managed by selected collection and recycling schemes in different regions	83
Table 11:	Comparison of mulch film gauges in different countries and regions	87
Table 12:	Average rate of plastic mulch recovered from fields at different film gauges	88
Table 13:	Examples of biodegradable and compostable agricultural products and standards	90
Table 14:	Biodegradable products are potentially a suitable substitute in the following cases	92
Table 15:	Examples of alternatives to agricultural plastic products	93
Table 16:	Comparison of international policy options:	100
Table 17:	Elements of a new international code of conduct on agricultural plastics 1	102
Table 18:	Stakeholder roles in the voluntary code of conduct	104

Figures

Figure 1:	Classification of plastics by precursors and biodegradability	5
Figure 2:	Typical lifespan of agricultural plastic products	14
Figure 3:	Global plastic production and share of plastics used in agricultural production, 2018	14
Figure 4:	Plastic used annually in agricultural value chains	17
Figure 5:	Use of plastic film in agriculture in different regions	18
Figure 6:	Plastic use in agriculture in Europe for packaging and non-packaging purposes	18
Figure 7:	Plastic use in agriculture in Europe for livestock and crop production	19
Figure 8:	Relative amounts of different plastic products used in agriculture – Italy	19
Figure 9:	Different plastic products used in agriculture – China	20
Figure 10:	Estimated global annual quantities of agricultural plastics	21
Figure 11:	Estimated quantities of agricultural plastics used per hectare of land	22
Figure 12:	Global use of plastic films in agriculture in 2018	23
Figure 13:	Regional usage of plastic film on permanent cropland	24

Figure 14: Regional share of primary packaging used for pesticides 25
Figure 15: Regional collection rate of packaging used for pesticides, 2019 25
Figure 16: Estimated quantities of agricultural plastics used annually 26
Figure 17: The source-pathway-receptor-consequence model 28
Figure 18: The 3D concept 30
Figure 19: Schematic representation of the flow of plastics in terrestrial environments 32
Figure 20: Schematic representation of the flow of plastics in aquatic environments 34
Figure 21: Types of harm caused by plastics 35
Figure 22: Alternatives for polymer coated fertilizers 36
Figure 23: Alternatives for mulch films 48
Figure 24: Alternatives for irrigation drip tape 52
Figure 25: Alternatives for tree guards and shelters 54
Figure 26: Alternatives for ear tags 57
Figure 27: Alternatives for fishing gear 59
Figure 28: Alternatives for insulated fish boxes 61
Figure 29: Alternatives for greenhouse films 63
Figure 30: Alternatives for silage films 65
Figure 31: Alternatives for twines 67
Figure 32: Alternatives for pesticide containers 69
Figure 33: Alternatives for plastic sacks and bags for harvesting and distribution 70
Figure 34: Alternatives for fruit protection bags (banana cultivation) 72
Figure 35: Principles of good agricultural plastics management practices 78
Figure 36: Collection rates of agricultural plastics in selected European countries 84
Figure 37: Countries with dedicated used pesticide container management systems 85
Figure 38: Development of farm wastes managed by A.D.I.VALOR 86
Figure 39: The relationship between the terms bioplastic, biodegradable and bio-based 90
Figure 40: Plastic waste generation and amounts of waste collected for different regions in 2016. 95
Figure 41: Packaging for pesticides collection in different regions, 2019 96

Boxes

Box 1: Case study – How much plastic waste (films) per hectare under horticulture 24
Box 2: Plastic use and leakage in Norwegian fisheries and aquaculture operations 27
Box 3: The classification of plastic based on size 31
Box 4: Microplastic sources 32
Box 5: Global leakage of plastics into the environment 33
Box 6: The 6R approach 45
Box 7: Simulation of plastic accumulation into soil following different rates of mulch film retrieval at two scenarios of film use 88
Box 8: Defining biodegradable and compostable plastics 89

FOREWORD

Over the last 70 years, the use of plastics in agri-food systems and food value chains has become pervasive. Low-cost and adaptable plastic products have crept into every part of our food systems – from fishing gear and tree guards to greenhouses. While they can increase productivity and efficiency in all agricultural sectors and help minimize food loss and waste, plastics are a major source of contamination. And their widespread and long-term use, coupled with lack of systematic collection and sustainable management, leads to their accumulation in soils and aquatic environments.

Most agricultural plastic products are single use and can persist in the environment long after their intended use. Degrading into microplastics they can transfer and accumulate in food chains, threatening food security, food safety and potentially human health.

This new FAO report provides irrefutable evidence to support action towards the better management of plastics in agri-food systems before and after reaching their end-of-life. The global assessment fills a substantial gap in scientific research by improving the knowledge on the flows and fate of agricultural plastic products. It identifies the benefits and issues associated with major plastic products used in agriculture and assesses alternatives and interventions to reduce their adverse impacts while delivering similar advantages.

Soils are one of the main receptors of agricultural plastics and are known to contain larger quantities of microplastics than oceans. As the demand for agricultural plastics continues to grow, there is an urgent need to better monitor the quantities of plastic products used and that leak into the environment from agriculture. Promoting circular approaches is essential to reduce plastic waste generation through prevention, reduction, reuse and recycling.

Measures to both reduce the direct environmental harm caused by agricultural plastic pollution, and the indirect impacts of greenhouse gas emissions associated with the use of petroleum-derived plastics, need to be implemented as a matter of priority.

Tackling agricultural plastic pollution will be a vital measure in helping to deliver the objectives of the United Nations Decade on Ecosystem Restoration, launched by FAO and the UN Environment Programme in 2021. It also responds to FAO's new Strategic Framework 2022-2030 and its programme priority area on Bioeconomy for Sustainable Food and Agriculture, which has a particular emphasis on Sustainable Development Goal 12 – Responsible Consumption and Production, including waste disposal (SDG 12.4).

This report serves as a loud call to coordinated and decisive action to facilitate good management practices and curb the disastrous use of plastics across the agricultural sectors.

Ultimately, tackling agricultural plastic pollution is paramount to achieving more efficient, inclusive, resilient and sustainable agri-food systems for better production, better nutrition, a better environment, and a better life, leaving no one behind. As a specialized agency of the United Nations leading international efforts to achieve food security for all and ensuring that people have regular access to enough high-quality food to lead active and healthy lives, FAO will continue to play an important role in dealing with the issue of agricultural plastics holistically within the context of food security, nutrition, food safety, biodiversity and sustainable agriculture.

Maria Helena Semedo

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ABBREVIATIONS AND ACRONYMS

ABS	acrylonitrile butadiene styrene
ALDFG	abandoned, lost, or otherwise discarded fishing gear
APE	Agricultural Plastics Environment (association of producers of agricultural plastics)
ASTM	American Society for Testing and Materials
BRS	Basel, Rotterdam and Stockholm Conventions
CEN	European Committee for Standardization
CGIAR	Consultative Group on International Agricultural Research
CIPA	Comité International des Plastiques en Agriculture
CO_2-eq	Carbon dioxide equivalent (measure of global warming potential)
CSIR	Council for Scientific and Industrial Research, South Africa
EC	European Commission
EIP-AGRI	Agricultural European Innovation Partnership
EN	European Standard
EPR	extended producer responsibility
EPS	expanded polystyrene
EVA	ethylene-vinyl acetate copolymer
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO's database on agricultural statistics
FSC	Forest Stewardship Council
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	greenhouse gas
GPS	global positioning system
HDPE	high density polyethylene
IBC	intermediate bulk container
IFA	Integrated Farm Assurance standard of GLOBALG.A.P.
IMO	International Maritime Organization
ISO	International Organization for Standardization
ISWA	The International Solid Waste Association
LDPE	low density polyethylene
OECD	The Organization for Economic Co-operation and Development
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
MARPOL	International Convention for the Prevention of Pollution from Ships
PBS	polybutylene succinate

PCDD/F	polychlorinated dibenzodioxins and dibenzofurans
PCF	polymer coated fertilizer
PCL	polycaprolactone
PE	polyethylene
PET	polyethylene terephthalate
PHA	polyhydroxyalkanoate
PMMA	polymethylmethacrylate
POP	persistent organic pollutant (as defined under the Stockholm Convention)
PP	polypropylene
PRO	Producer Responsibility Organization
PVC	polyvinylchloride
RAG	"Red-Amber-Green" qualitative assessment
RFID	radio frequency identification device
SAICM	Strategic Approach to International Chemicals Management
SDG	Sustainable Development Goal
SPRC	source-pathway-receptor-consequence risk assessment model
TEQ	toxicity equivalence factor for polychlorinated dibenzodioxins and dibenzofurans
TPU	thermoplastic polyurethane
TÜV	technical standards certification body
UN	United Nations
UNEP	United Nations Environment Programme
UNICRI	United Nations Interregional Crime and Justice Research Institute
USD	United States dollar
UV	ultraviolet
WHO	World Health Organization
WWF	World Wildlife Fund

EXECUTIVE SUMMARY

PURPOSE

The purpose of this report is to present the results of a study investigating agricultural plastic products used globally in a range of different value chains. The investigation covered all sectors under FAO's mandate: crop production, livestock, aquaculture, fisheries and forestry, including subsequent processing and distribution. It assessed the types and quantities of plastic products, their benefits and trade-offs. Sustainable alternative products or practices were identified for products assessed as having high potential to cause harm to human and ecosystem health or having poor end-of-life management. The report is based on data derived from peer-reviewed scientific papers, governmental and non-governmental organization's research reports, as well as from industry experts, including relevant trade bodies. The report's recommendations were verified during extensive consultation and review with FAO and external experts. The authors hope that the study will provide an impetus for discussion about the use of agricultural plastics, their benefits and trade-offs, and ultimately stimulate action to reduce their potential for harm to human health and the environment.

This report provides information on the following:

- the use and benefits of plastics in agriculture;
- the types and estimated amounts of agricultural plastic products in use;
- the harm caused by plastics;
- priority agricultural plastic products;
- frameworks to facilitate good management practices;
- recommendations to move towards a circular economy for agricultural plastics; and
- a summary of the main findings and recommendations for policymakers.

CONTEXT

The use of plastic products in today's agriculture is becoming increasingly commonplace all around the world. The versatility and variety of plastic polymers, their ease of manufacture, physical properties and affordability make them the material of choice for many applications in agriculture. Most fishing gear is made of plastic. Plastic greenhouse and mulching films together with drip irrigation help fruit and vegetable growers to increase yields, reduce water and herbicide use, and control crop quality. Polymer coated controlled release fertilizer provide plants with the nutrients at the rate they need, avoiding emissions to water and air. Silage films help livestock farmers produce healthy, long-lasting and nutritious fodder, and avoid the need to construct barns and silage clamps. Plastic tree guards are used extensively in tree plantations. All these products provide a range of benefits that help farmers, foresters, and fishers to maintain livelihoods, enhance production, reduce losses, conserve water and reduce chemical inputs.

However, despite the many benefits listed above, agricultural plastics also pose a serious risk of pollution and harm to human and ecosystem health when they are damaged, degraded or discarded in the environment.

In 2019, agricultural value chains used **12.5 million tonnes** of plastic products in plant and animal production and **37.3 million tonnes** in food packaging. Data were not available for usage in storage, processing, and distribution. Furthermore, the agricultural plastic industry forecasts the global demand for greenhouse, mulching and silage films to increase by 50 percent from 6.1 million tonnes in 2018 to 9.5 million tonnes in 2030.

The crop production and livestock sectors are the largest users, accounting for 10 million tonnes per year collectively, followed by fisheries and aquaculture with 2.1 million tonnes, and forestry with 0.2 million tonnes.

Despite limitations in regional usage data, Asia was estimated to be the largest user of plastics in agricultural production; accounting for up to six million tonnes annually, almost half of global usage.

THE FATE OF AGRICULTURAL PLASTICS AT END-OF-LIFE IS NOT WELL DOCUMENTED.

Data suggest that only small fractions of agricultural plastics are collected and recycled, predominately in developed economies. There is evidence that elsewhere most plastics are burned, buried, or landfilled, although record keeping is generally non-existent.

RESEARCH ON THE HARM CAUSED BY PLASTICS TO TERRESTRIAL AND FRESHWATER ECOSYSTEMS CURRENTLY FALLS FAR BEHIND THAT OF THE MARINE ENVIRONMENT.

The accumulation in surface soils of residues of mulching film – a major category of agricultural plastic by mass – has been shown to reduce agricultural yields. Of increasing concern is the formation and fate of microplastics derived from agricultural plastic products, which have potential to transfer along trophic levels, with the possibility of adversely affecting human health. Larger plastic residues in both aquatic and terrestrial environments have the potential to harm wildlife through entanglement and ingestion. Some plastic resins contain toxic additives such as phthalates and bisphenols that have known endocrine disrupting properties. Furthermore, the evidence is increasing that plastic fragments and microplastics are vectors for the long-range dispersal of pathogens and toxic chemicals in oceans, although the evidence base in terrestrial environments is currently limited. Inappropriate disposal of agricultural plastic at dumpsites prone to fires, or open burning on farms, are sources of toxic emissions including polychlorinated dibenzo-p-dioxins and furans, both persistent organic pollutants. The majority of plastics are derived from fossil-based sources and contribute to global greenhouse gas emissions.

ENVIRONMENTAL ISSUES OF AGRICULTURAL PLASTICS ARE BOTH GLOBAL AND TRANSBOUNDARY IN NATURE.

They have both positive and negative impacts on food security, food safety and nutrition, as well as social and economic dimensions of sustainability. It recommends that they be addressed urgently in a holistic manner using life cycle approaches and the principles of circularity.

A CALL FOR ACTION

The report identifies alternatives and interventions to improve the circularity and sound management of agricultural plastics based on the 6R model (Refuse, Redesign, Reduce, Reuse, Recycle, and Recover). Depending on the application, these could include: adopting agricultural practices that avoid the use of plastic; eliminating the most polluting plastic products; substituting plastic products with natural or biodegradable alternatives; promoting reusable plastic products; improving waste management practices; adopting new business models; establishing and enforcing mandatory extended producer responsibility schemes for collection and sound environmental management of agricultural plastic; and establishing fiscal measures and incentives to drive behavioural change within the supply chain, and among users and consumers.

Based on a review of the existing global legal, policy and management frameworks, the study concludes that there is no overarching international policy or legislative instrument that addresses all aspects of the use of plastics in agri-food value chains and throughout their lifecycle.

Furthermore, the review of frameworks did not identify any one single measure that could be applied in isolation in order to facilitate good management practices.

At the international level, the report recommends a two-pronged approach:

1. **Developing a comprehensive voluntary code of conduct to cover all aspects of plastics throughout agri-food value chains.** The code of conduct should pay attention to the full life cycle of a plastic product from its design, regulatory approval, manufacture, distribution, sale, use, and management at end-of-life. It should also aim to support the transformation towards sustainable agri-food systems considering all the benefits and trade-offs in relation to all dimensions of sustainability. The code of conduct should be science-based and developed in an inclusive, participatory and transparent way involving governments and regional bodies, plastic producers and users, the waste management sector, standards setting and certification bodies, academia and civil society.

2. **Where appropriate, existing international conventions could consider mainstreaming specific aspects of the life cycle of agricultural plastics,** such as: the Basel Convention, beyond just wastes; and the MARPOL Convention for the management of plastics used in fisheries and aquaculture.

This study also recommends mainstreaming the sustainability of agricultural plastics throughout FAO's instruments and guidance related to good agricultural practice, food security, food safety and nutrition.

In this way, the overarching principles of good management practices can be established relatively quickly through a voluntary code of conduct. At the same time, the slower process of taking into account and integrating, where feasible, agricultural plastics issues into the legally binding multilateral agreements and "soft law" instruments can still be pursued.

The study also identified existing knowledge gaps and suggested areas for further research, including:

1. **The global flows and fates of agricultural plastics**; their quantities, composition, where and how they are used, their environmental fate throughout the supply chain, during use and at end-of-life.
2. **Life cycle assessments of fossil-based and bio-based agricultural plastics** (both biodegradable and non-biodegradable) and the alternative products and practices to determine and compare their risks and benefits for specific applications in agri-food value chains.
3. **The pathways and impacts of plastics, micro- and nanoplastics on agroecosystems, food safety and human health,** including their potential for transference and accumulation along the food chain and in agri-food systems.
4. **The behaviour and rate of degradation of biodegradable products** in different environments and conditions of temperature and humidity. This includes: aquatic environments and soils in various climatic zones; products not in direct contact with soils; and synergistic effects with other chemicals. Impacts of agricultural plastic pollution on microbiomes, soil and water quality, and on long-term soil productivity should also be studied.

The urgency for coordinated and decisive action cannot be understated.

1. Introduction

1.1 The link between plastics and agriculture

Plastics have become ubiquitous since their widespread introduction in the 1950s. Their properties, functionality, and relatively low cost have made them the polymers of choice for the creation of an extensive range of products, thereby helping transform food value chains, as well as massively increasing consumer choice. At present, it would be difficult to envisage living without plastics in some form or another.

Agriculture broadly covers the growth and production of plants and animals for human use, either as food to feed a growing global population, or for fibres, fuels, or medicines. It includes crop and livestock production, forestry, fisheries and aquaculture.

Modern agricultural practices employ a wide range of plastic products to help improve productivity, such as:

- **mulch films** – to reduce weed growth, evaporative water losses, the need for pesticides, fertilizer and irrigation, whilst also enhancing plant growth;
- **tunnel and greenhouse films and nets** – to protect and enhance plant growth, extend cropping seasons, and increase yields;
- **irrigation tubes and driplines** – to optimize water use;
- **bags and sacks** – to transport seeds and fertilizers to nurseries and fields;
- **silage films** – to aid fermentation of biomass for animal fodder and avoid the need for storage buildings;
- **bottles** – to transport liquid pesticides and fertilizers to nurseries and fields;
- **coatings on fertilizers, pesticides and seeds** – to control the rate of release of chemicals or improve germination;
- **non-woven protective textiles or "fleece"** – to protect crops from extreme cold and/or sunlight;
- **fruit protectors** – bags, sheaths, and nets, sometimes impregnated with pesticides to cover and protect fruit from insect and weather damage;
- **plant protectors** – to protect young seedlings/saplings against damage by animals and provide a microclimate that enhances growth (e.g. tree guards in forestry); and
- **nets, ropes, lines, traps and enclosures** – to catch and farm fish and other aquatic species.

Plastic products also help reduce food losses and waste, and maintain its nutritional qualities throughout a myriad of value chains, thereby improving food security (FAO, 2020c) and reducing greenhouse gas (GHG) emissions (FAO, 2015). Hygienic plastic packaging also improves food safety by reducing contamination and premature decay (Han *et al.*, 2018). However, despite these benefits, plastics can also be problematic, impairing agricultural productivity in both terrestrial and aquatic environments.

Overall, there are two main routes by which plastic contaminants can enter agricultural systems, namely:

- **leakage from non-agricultural sources**, such as windblown litter, air-borne pollutants, such as microplastics from tyre wear, unplanned dumpsites, and contaminated flood/drainage waters; and
- **leakage from agricultural activities**, through agricultural plastic products becoming damaged, degraded, or discarded (the so-called 3Ds – see Figure 18) and the application of microplastic contaminated organic amendments and irrigation water.

The former has been reasonably well characterized (Lau *et al.*, 2020; Ryberg, Hauschild, Michael and Laurent, 2018), whilst there are relatively few reports summarizing the extent of plastic use in agriculture and how they may leak into the environment.

1.2 The problems associated with plastics

The properties that make plastics so useful, concomitantly create problems when they reach the end of their intended lives. The diversity of polymers and additives blended into plastics to reach optimal properties make their sorting and recycling more difficult. Being man-made polymers, there are few microorganisms capable of degrading conventional plastics in a timely manner (Roager and Sonnenschein, 2019); meaning that once in the environment, they may fragment and remain there for many decades. Of the estimated 6.3 billion tonnes of plastics produced up to 2015, just under 80 percent is thought to have been disposed of either in the natural environment or in landfill sites (Geyer, Jambeck and Law, 2017).

As the world's demand for plastics increases, leakage into the environment also increases, hindering efforts to mitigate environmental contamination (Borrelle *et al.*, 2020; Lau *et al.*, 2020; Ryberg, Hauschild, Michael and Laurent, 2018; The Pew Charitable Trusts and SYSTEMIQ, 2020). This is due to the affordability, availability and versatility of plastics compared to more environmentally sustainable alternatives, coupled with inadequate and/or inappropriate recycling and disposal infrastructure, and a near absence of extended producer responsibility (EPR) obligations in most parts of the world.

Once in the natural environment, plastics can cause harm in several different ways. The effects of large plastic items on marine fauna have been well documented in the popular press and in scientific journals (Gall and Thompson, 2015; McHardy, 2019; Woods, Rødder and Verones, 2019). However, as these larger plastics begin to disintegrate and degrade, their impacts begin to be exerted at the cellular level, affecting not only individual organisms but also, potentially, entire ecosystems (GESAMP, 2015a; Shen *et al.*, 2020).

Microplastics (plastics less than 5 mm in size – see Box 3 on page 31) are thought to present specific risks to animal health. Ingestion and biomagnification up some food chains has been shown to occur (Beriot *et al.*, 2021; Huerta Lwanga *et al.*, 2017), with a recent study detecting microplastic particles in human faeces (Schwabl *et al.*, 2019) and placentas (Ragusa *et al.*, 2021), and evidence of mother-to-foetus transmission of nanoplastics (plastics less than 1 µm in size) documented in rats (Fournier *et al.*, 2020). As microplastics have been shown to both adsorb and concentrate persistent organic pollutants (Andrady, 2011; GESAMP, 2015a; Harding, 2016; Horton *et al.*, 2017), and harbour colonies of pathogenic microorganisms (Bowley *et al.*, 2021), it is likely that they present, as yet unquantified, risks to human health.

To date, most scientific research on plastics pollution has been directed at aquatic ecosystems, especially oceanic environments. Although it is commonly reported that 80 percent of marine plastic litter is thought to be derived from land-based sources (Li, Tse and Fok, 2016), the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) could not trace it to a published scientific paper and is investigating its history (GESAMP Working Group 43, 2020). Agricultural soils, in particular,

are thought to receive greater quantities of microplastics than oceans (Nizzetto, Futter and Langaas, 2016), a proportion of which will result from the use of agricultural plastics.
As the majority (93 percent) of global agricultural activities take place on land,[1] this warrants further investigation.

1.3 Scope of this report

This report presents the results of a study investigating the types and quantities of agricultural plastic products used globally in a range of different value chains. The value chains investigated included: crop production – horticulture, bananas, maize and cotton; fodder and livestock production; plantation forestry; and marine fisheries and aquaculture. The primary focus of the report is the use of plastics within the production phases of the agri-food value chains, while references are provided to other steps (storage, transportation, processing, consumption). Data were derived from scientific papers and research reports, as well as extensive consultation with FAO and industry experts.

This report provides information on the following:

- The use of plastics in agriculture (Chapter 2).
- The types and estimated amounts of agricultural plastic products in use (Chapter 3).
- The harm caused by plastics (Chapter 4).
- Priority agricultural plastic products and an analysis of potential more sustainable alternatives and practices (Chapter 5).
- Frameworks to facilitate good management practices (Chapter 6).
- Recommendations to move towards a circular economy for agricultural plastics (Chapter 7).
- A summary of the main findings and recommendations for policymakers (Chapter 8).

The intent is to stimulate discussion about the use of agricultural plastics, their benefits and trade-offs, and ultimately to reduce their potential for harm to human health and the environment. Overall, the objective is to contribute towards the transformation of agri-food systems and achieving sustainable food security without compromising terrestrial and aquatic ecosystem functions (Webb *et al.*, 2021). This study also aims to provide guidance on improvements that will assist in the achievement of the United Nations' 2030 Sustainable Development Goals (SDGs), and in particular:

- SDG 1 – No poverty;
- SDG 2 – Zero hunger;
- SDG 3 – Good health and well-being;
- SDG 6 – Clean water and sanitation;
- SDG 11 – Sustainable cities and communities;
- SDG 12 – Sustainable consumption and production;
- SDG 13 – Climate action;
- SDG 14 – Life below water;
- SDG 15 – Life on land; and
- SDG 17 – Partnerships for the goals.

[1] See Chapter 4.4.1 for further details.

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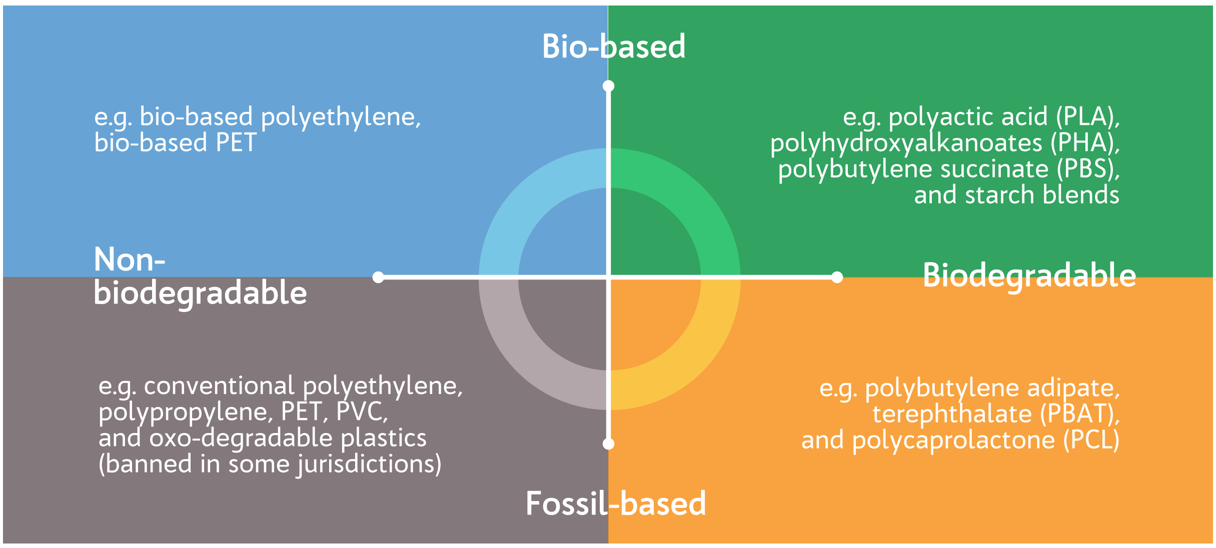
2. The use of plastics in agriculture

2.1 Plastics and their properties

Plastics are synthetic or semi-synthetic polymers of organic molecules that have been designed to create a wide range of products with different structural and chemical properties. They can be derived from either single monomer molecules (e.g. polyethylene, which is a long chain polymer of ethylene) and are termed homopolymers, or they can be composed of two or more polymers (e.g. starch and polycaprolactone) and are termed copolymers. Additionally, most plastics contain additives introduced during the compounding process to bestow the polymer with specific properties depending upon its intended application. These additives include stabilizers, fillers and plasticizers (Andrady, 2015). Polymers can be derived from both fossil-based (petroleum) and bio-based precursors. The bio-based precursors can be intentionally produced biomass (from plants or microorganisms) or from biomass waste. Some plastic polymers originating from fossil- and bio-based precursors are biodegradable.

These are represented in Figure 1 below:

Figure 1: Classification of plastics by precursors and biodegradability



Source: Based on European Bioplastics fact sheet, European Bioplastics, 2019.

The classification of a final product, which is often a mixture of polymers, may not fit neatly in one of the quadrants. For example, European Bioplastics has confirmed that in a final biodegradable product, fossil-based polybutylene adipate terephthalate (PBAT) is always mixed with bio-based PLA or starch blends (European Bioplastics, personal communication, 2021).

Plastic polymers can be moulded, extruded, or pressed into rigid, semi-rigid, or flexible products. Being light weight, waterproof, and durable means that they can be used in a wide variety of applications, including agriculture. Numerous product types can be found in agricultural settings, helping famers and fisheries increase productivity and reduce food losses throughout their value chains.

Agriculture uses a wide range of plastic polymers, each tailored in both the additives they contain and the physical properties (i.e. strength, transparency, insulation, water resistance, etc.) to their intended products.

The main polymers are:

- **Polyethylene (PE)** – a polymer of ethylene, that can be either:
  - **Low density PE (LDPE)** – blown into films,

  or

  - **High density PE (HDPE)** – extruded into rigid and semi-rigid products, and thick films, and protective and bale nets.

- **Polypropylene (PP)** – a polymer of propylene often used in films and bags (woven and non-woven) and rigid crates.

- **Expanded polystyrene (EPS)** – a lightweight rigid foam material with a closed cellular construction consisting of small hollow spherical balls produced from solid beads of polystyrene. It is produced in a wide range of densities providing a varying range of physical properties. It is primarily used for insulation e.g. packaging for produce where temperature needs to be controlled.

- **Ethylene-vinyl acetate copolymer (EVA)** – the copolymer of ethylene and vinyl acetate. It is an elastomeric polymer that produces materials which are "rubber-like" in softness and flexibility. The material has good clarity and gloss, low-temperature toughness, stress-crack resistance, hot-melt adhesive waterproof properties, and resistance to ultraviolet (UV) radiation.

- **Polyvinylchloride (PVC)** – a polymer that comes in two basic forms: rigid and flexible; the rigid form of PVC is used in construction of pipe and in profile applications. Flexible PVC is claimed to be the second most common polymer used in mulching films (Sarkar *et al.*, 2019). It is also reported to be used in some irrigation drip tape and greenhouse films (Zhou *et al.*, 2018).

- **Polyethylene terephthalate (PET)** – a polyester thermoplastic polymer used for fibres and containers for liquids and foods.

and less frequently:

- **Polycarbonate (PC)** – a group of thermoplastic polymers containing carbonate groups in their chemical structures and which are easily worked, moulded, and thermoformed.

- **Polymethylmethacrylate (PMMA)** – also known as acrylic – is a transparent thermoplastic often used in sheet form as a lightweight or shatter-resistant alternative to glass.

- **Thermoplastic polyurethane (TPU)** – a block copolymer resulting from the reaction of diisocyanates with diols. With its thermoplastic properties and toughness when cool, TPU is often used to make uniquely marked traceability ear tags for livestock.

- **Polyamide (Nylon)** – used for making monofilament fishing lines and gill nets (Global Ghost Gear Initiative, 2021) and coextruded with HDPE for some pesticide containers.

- **Acrylonitrile butadiene styrene (ABS)** – an opaque thermoplastic and amorphous polymer used for making rigid products such as fishing net floats.

and biodegradable polymers:

- **Polylactic acid (PLA)** – a thermoplastic polyester, often manufactured from bio based lactic acid precursors, and is used as a component in mulching films, twines, nets and monofilament fishing lines.

- **Polyhydroxyalkanoates (PHA)** – a class of biodegradable plastic naturally produced by various microorganisms starting from sugars, starches, glycerine, triglycerides, or methane; the physical properties of PHAs make it a potential substitute for polyethylene and polypropylene. A seminal report by the Ellen MacArthur Foundation titled The New Plastics Economy: Rethinking the Future of Plastics (2016) lists PHAs as potential substitutes for polyolefins as well as polyethylene terephthalate, polystyrene, and polyvinylchloride (Ellen MacArthur Foundation, World Economic Forum, and McKinsey & Company, 2016; Tullo, 2019).

- **Polybutylene succinate (PBS)** – a thermoplastic polymer resin of the polyester family. It is a biodegradable aliphatic polyester with properties that are comparable to polypropylene, including high heat resistance.

- **Starch blends** – a blend of starches (polysaccharides) with other biodegradable polymers and additives (with low molecular mass plasticizers) that improve mechanical integrity, thermal stability, and humidity absorption of the starch (Encalada *et al.*, 2018).

- **Polybutylene adipate terephthalate (PBAT)** – an aliphatic-aromatic co polyester with mechanical properties similar to LDPE (Jian, Xiangbin and Xianbo, 2020).

- **Polycaprolactone (PCL)** – a linear, semi-crystalline, aliphatic polyester, hydrophobic polymer, often added as a blend to starch-based biodegradable plastics (Encalada *et al.*, 2018).

Examples of the different types of polymers used in agricultural plastic products are shown in **Table 1**. In quantitative terms, the three main polymers used in agriculture are PE (both low and high density), PP and PVC (Circular Plastics Alliance - Agriculture Working Group, 2020; PlasticsEurope e.V., 2020; Sarkar *et al.*, 2019).

Table 1: Agricultural plastic products and their typical polymers

Crop production		
		
Polymer coated fertilizer PE, EVA, LDPE, cellulose	Fertilizer sacks PP	Flexible intermediate bulk containers, PP
		
Seedling plug trays PP, PE, EPS	Nursery pot trays PP, PE	Mulching films LDPE, PVC, PLA/PHA
		
Non-woven textile protection PP, Polyester	Greenhouses and low tunnels Multilayer LDPE/EVA films, PC rigid	Shade and protective nets HDPE
		
Irrigation drip tapes HDPE, LDPE, PVC	Irrigation pipes PE, PVC	Support ties and clips, HDPE, PVC, synthetic rubber and biodegradables
		
Hermetic storage bags LDPE	Pesticide containers, HDPE, PET, co-extruded mixed polymers	Reusable crates HDPE

Table 1 *(continued)*

Forestry

Tree guards
PP

Chainsaw fuel container
HDPE, PP

Tree labels and support ties
PVC and synthetic rubber

Livestock production

Ear tags
thermoplastic polyurethane

Bunker covers
HDPE

Bale nets and twines
HDPE, PP

Silage tubes
LDPE

Used bale twines
PP

Film wrapped silage bales
LDPE

Fisheries and aquaculture

Insulating crates
EPS, Expanded PE and PP

Ropes
PE, PP

Fishing nets
PE, nylon

2.2 Types of plastic products and their application

Plastic products are used extensively in all aspects of plant production, livestock production (feed and animal care), and fisheries and aquaculture. They are also used systematically in distribution and retail to protect and maintain the quality of agricultural products.

Plastic products are used globally, although the types of products and the extent to which they are used, varies by region and by country, depending on the level of mechanization, the length of the supply chain, and the dependence on export. Films generally represent the largest quantities of non-packaging plastics used in agriculture (see Chapter 3).

Table 2 summarizes the main types of agriculture, the activities in which plastic products are generally used, and the types of products. A comprehensive list of plastic products that were identified during this study is included in the value chains described in Annex 1.

2.3 The benefits of using plastic products in agriculture

The lightweight, water resistant and durable properties of plastics mean that they are now widely used in plant and livestock production on a global scale, both on land and in water; a practice that has largely developed over the past 70 years. When used to grow plants, the use of plastic products is often referred to as 'plasticulture' (Orzolek, 2017).

The benefits of using plastics in agriculture are wide ranging and include (see also Table 3):

Reducing water demand – through the use of mulch films to reduce evaporative losses from soil, and irrigation systems (tubes and driplines to direct water in precise amounts to plant root systems

Optimizing germination from seeds and for planting – through the use of seedling trays and pots; coatings on seeds improve germination and survival of seedlings.

Reducing herbicide use – by using mulch films to prevent weed growth.

Extending the growing season or protect crops from extreme cold and/or sunlight – through the use of greenhouses/polytunnels and insulating non-woven textile "fleeces".

Increasing crop yield – by combining the benefits of reducing moisture loss of soils, reducing weed growth, stabilizing the temperature, extending the growing season, using coatings on controlled release fertilizers – to facilitate the release of plant nutrients.

Reducing damage by animals – by using semi-rigid guards around seedlings, for example, around tree seedlings in forestry.

Aiding fermentation of grasses for animal fodder – through the use of silage films.

Relying on nets, ropes and floats – to constrain and catch aquatic species, such as fish and crustaceans.

Reducing food losses – avoiding damage by using purposely designed products, such as stackable and insulated crates, along the (temperature controlled) supply chain from farm to processing up to distribution and consumption.

Maintaining the quality of fresh products – by using insulated boxes or packaging, for example in fish transport, from the capture site to processing plants up to local markets and retail.

Optimizing the cost and fuel needed to transport products – by using lightweight packaging for final products to be distributed or sold to consumers.

Delivering description and notice to consumers – by using labels and liners that keep the user/consumer information or description intact.

Table 2: Agricultural practices that use plastic products

TYPE OF AGRICULTURE	ACTIVITY	EXAMPLE PRODUCTS
Plant production	Seeding	Seed containers/bags, polymer coated seeds, plant pots, seed trays
	Cultivation	Mulch film, greenhouse films, non-woven textile protection "fleece", protection nets, plant support twine and clips, pesticide containers, fertilizer containers, polymer coated fertilizer, hydroponic bags and slab wraps, supports/posts, spray tanks, personal protective equipment
	Irrigation	Drip tape, pipes, drippers, pond and canal liners
	Harvesting and transportation	Boxes, crates, pallets, insulated crates
	Ornamental plants	Pots, clips, supports, labels, trays, supports/posts, twine, plastic covered wires, soft plastic grow bags, mulch films or ground cover liners (e.g. in container nurseries), pesticide containers and personal protective equipment
	Storage	Hermetic sealed bags
Livestock	Feed and fodder production	Fertilizer containers, polymer coated fertilizer, seed containers, silage films, bale wrap, twine and net, feed sacks, personal protective equipment
	Animal care	Crates, ear tags, bottles, and containers for medicines and hygiene products, personal protective equipment
Forestry	Plantation management	Controlled release fertilizers and their containers, plant protectors, tree guards, mulch films, pesticide containers, chainsaw fuel and lubricant containers
Fisheries	Marine fishing	Nets, ropes, floats, traps, insulated crates, fish aggregating devices, buoys, bait bags and containers plus general garbage
	Aquaculture	Floats, ropes, cages, nets, insulated crates
Agroprocessing	Processing of agricultural produce	Bags, crates, boxes, films and trays
Distribution and consumption	Distribution	Crates, liners, boxes, films and trays
	Retail	Crates, liners, boxes, films and trays
	Consumption	Crates, liners, boxes, films and trays

Source: FAO, 2021.

Table 3: Summary of the benefits of plastic products used in agriculture

TYPE OF PLASTIC PRODUCT	BENEFIT	SCALE OF BENEFIT/REFERENCES
CROP PRODUCTION		
Mulch films in horticulture and fruit production	• Increased crop yields	Average yield of four field crops over different regions in China increased by 24.3% compared to un-mulched controls (Gao *et al.*, 2019) Tropical tree fruit crop yields increased by between 12% and 64% (Bhattacharya, Das and Saha, 2018)
	• Improved water use efficiency	Average water use efficiency in four crops over a number regions in China was 27.6% higher than in un-mulched control (Gao *et al.*, 2019)
	• Earlier harvests • Control of soil temperature and moisture • Reduction in soil nutrient loss • Weed control and reduced herbicide use • Prevention of soil erosion in heavy rain	(Bhattacharya, Das and Saha, 2018) (Kader *et al.*, 2019)
Polymer coatings for fertilizers	• Improved efficiency of nutrient take-up by plants • Reduced risk of emissions and nutrient runoff	(Gil-Ortiz *et al.*, 2020)
Polymer coatings for seeds	• Improved germination and growth promotion	(Amec Foster Wheeler Environment & Infrastructure UK Limited, 2017; Su *et al.*, 2017)
	• Pesticides in the coatings can assist the survival of seedlings	(Accinelli *et al.*,2019) (Rayns *et al.*, 2021)
Greenhouses, screenhouses	• Extending growing season and plant growth Controlled growing environment Reduced pesticide use	(Bartok, 2015) (Sangpradit, 2014)
Weather protection products (shade and hail nets) Non-woven frost protection	• Extending growing season and plant growth • Increased yields and nutritional value • Protects from extreme weather variations • Improved water use efficiency • Protection from harmful solar radiation	(López Marín, Josefa, 2018)
Insect-proof fruit protection net bags Pesticide impregnated banana sheathes	• Reduction in pesticide spray • Increased yields and plant growth • Higher quality and value fruits	Protect from insects and prevent disease by 80%; protect from physical damage e.g. weather events (Sharma, Reddy and Jhalegar, 2014) (ProMusa, 2020)
Drip irrigation	• Direct and precision irrigation • Water use efficiency	Increase water use efficiency by 30%–40% (Nikolaou *et al.*, 2020)

Source: FAO, 2021.

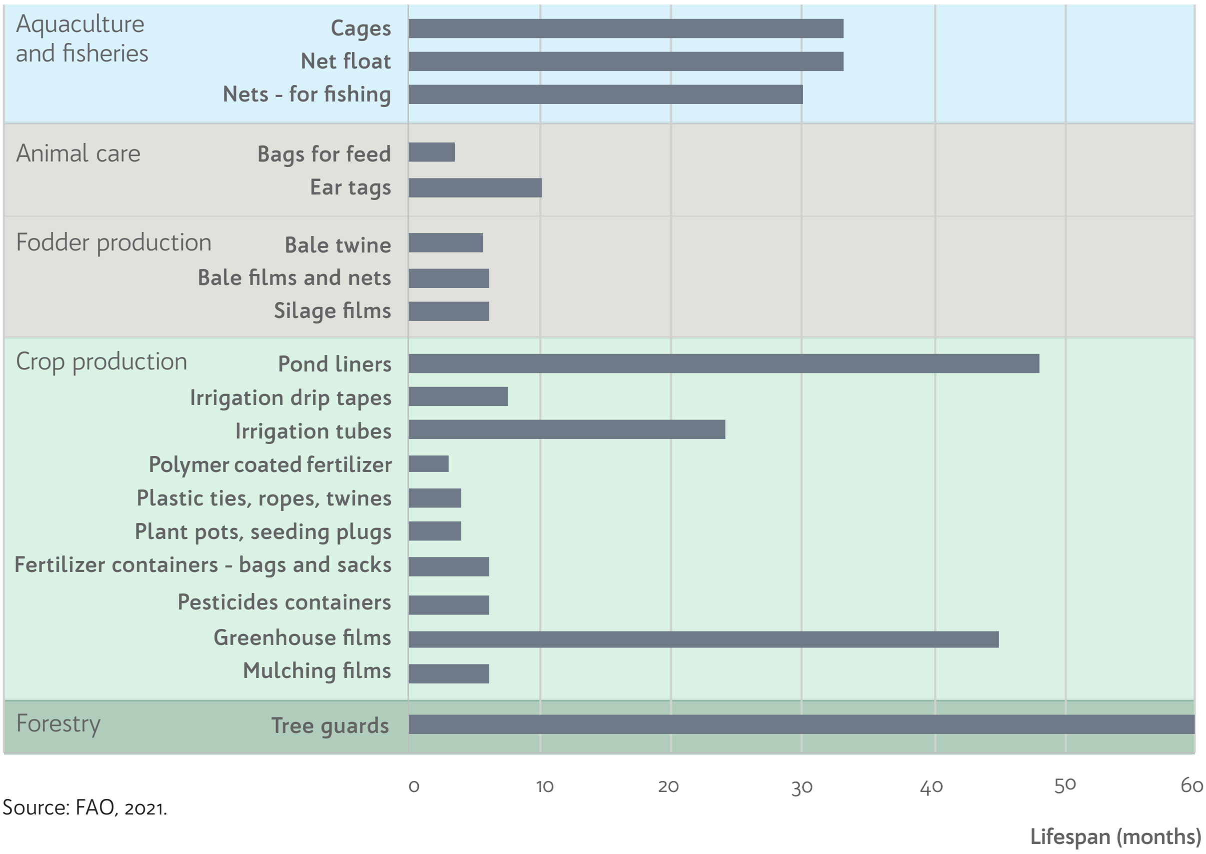
Table 3 *(continued)*

TYPE OF PLASTIC PRODUCT	BENEFIT	SCALE OF BENEFIT/REFERENCES
Pesticide containers Fertilizer sacks	• Safe containment of inputs during transport, storage and use, minimizes risks of exposure • Safety instructions for use are printed on the container	(CropLife International, 2015) (FAO and WHO, 2008)
Rigid pipes and semi-rigid tubes for irrigation	• Durable and economic tubing for direct and precision irrigation	(Fattah and Mortula, 2020)
Reusable nestable/stackable plastic crates	• Reduction of food loss during post harvest transportation and storage	Losses of fruit and vegetables reduced by between 43% and 87% using crates rather than sacks (FAO, 2019b)
Hermetic bags, plastic grain storage silos	• Reduced losses during storage • Retains product quality for longer	In Uganda maize and beans could be stored an extra 1.5 months, improving food security and increasing farmer incomes through access to higher market prices off season (Baributsa and Ignacio, 2020; FAO, 2019b).
LIVESTOCK		
Ear tags	• Traceability, tracking and monitoring of livestock throughout their life	(Bowling *et al.*, 2008)
Silage film and tubes	• Improved fermentation of silage • Avoids need to build silage clamp	(Bisaglia, Tabacco and Borreani, 2011)
Insulated plastic crates and boxes	• Conserving quality of meat in the distribution channel • Reducing food loss and waste • Maintaining food safety	
FORESTRY		
Tree protectors	• Microclimate for faster growing • Protection from grazing animals	Higher variability in the survival rates of trees grown without protection (2% to 90%) than trees planted with protection (67% to 100%) (Chau *et al.*, 2021) (Forestry Commission, 2020)
FISHERIES		
Aquaculture enclosures	• Durable enclosures	(Global Ghost Gear Initiative, 2021)
Fishing nets & lines	• Light, low visibility, and durable in water	(Strietman, 2021)
Insulated plastic crates and boxes	• Conserving quality of fish in the distribution channel • Reducing food loss and waste • Maintaining food safety	(Global Ghost Gear Initiative, 2021)
DISTRIBUTION AND RETAIL		
Consumer packs (trays and food contact films)	• Conserving quality and safety of food during retail • Reducing food loss and waste	(European Union, 2020)

2.4 Estimated lifespans of selected plastic products

The majority of agricultural plastics are single-use products, although their useful lifespan varies depending on the application and region of the world in which they are used. The vast majority, however, become waste within a twelve-month period. Figure 2 shows the lifespans of selected plastic items in different agricultural sectors. The duration of the items has been estimated based on a review of agricultural practices and interviews with agricultural experts.

Figure 2: Typical lifespan of agricultural plastic products



Source: FAO, 2021.

2.5 Summary

A wide range of plastic products are used in almost all agricultural settings, providing benefits that improve crop productivity, animal nutrition, water use efficiency, and reduce food loss. The types of plastic polymers used, and the ways in which they are manufactured, are tailored to confer each product with specific functional characteristics according to their intended use. This means that there is a high degree of variability between different plastic products, both within, and between different agricultural sectors.

Moreover, the rate at which these plastic products reach the end of their useful lives again depends on their application. With the exception of durable structures, the majority of products are single-use with lifespans of less than 12 months; a factor that will influence the ways in which they are managed at their end-of-life.

3. The types and estimated quantities of agricultural plastic products in use

3.1 Estimating the quantities of plastic products used in agriculture

As data summarizing the quantities of plastics used globally in different agricultural sectors are generally not captured through national and international surveys, they needed to be derived from a range of different sources. Where possible, data were obtained from published sources in peer reviewed scientific papers, international organizations, trade bodies, and discussion with sectoral experts and FAO specialists. Consequently, estimated totals from different sources were not always consistent, the range of data sometimes overlapped, and the datasets did not always include the same variety of products, although the authors have endeavoured to explain extrapolated data as fully as possible.

Most data sources defined agricultural plastics as those used in the production phases of value chains. Data on plastic products used in the middle and later phases of agricultural value chains were difficult to disaggregate from total packaging waste. It proved impossible to attribute quantities of such products to specific agricultural value chains.

Additionally, as some plastic products have lifespans greater than one year, annual estimates may not fully represent the overall turnover of these materials. In these circumstances, it was assumed that supply equalled demand and that overall there was no sizeable growth or contraction in the sectors. Notwithstanding, as the majority of plastic products are replaced at the end of their life, annual production and use estimates can provide an indication of the annual quantity of used plastics that need to be managed as waste.

3.2 Global estimates

There are very limited, poorly defined and often old data on the quantities of plastics used in agri-food value chains across the regions of the globe.

3.2.1 Plastic used in agricultural production

According to Sintim and Flury (2017), the annual global use of plastics films in terrestrial agricultural production is estimated at 7.4 million tonnes or two percent of the most recent estimation of the global plastic production of 359 million tonnes (PlasticsEurope e.V., 2019). In the EU, plastic films account for 75 percent of all plastics used in crop and livestock production (APE Europe, 2019). In the absence of similar data from other regions, the European ratio for the proportion of films to all agricultural plastics has been used to estimate the global level of other types of agricultural plastic products, such as irrigation tape and pipes, twines and nets, at 2.5 million tonnes per year. The data sources did not always specify the agricultural value chains that had been included in their assessments, so the quantities of plastics in agricultural production may be underestimated.

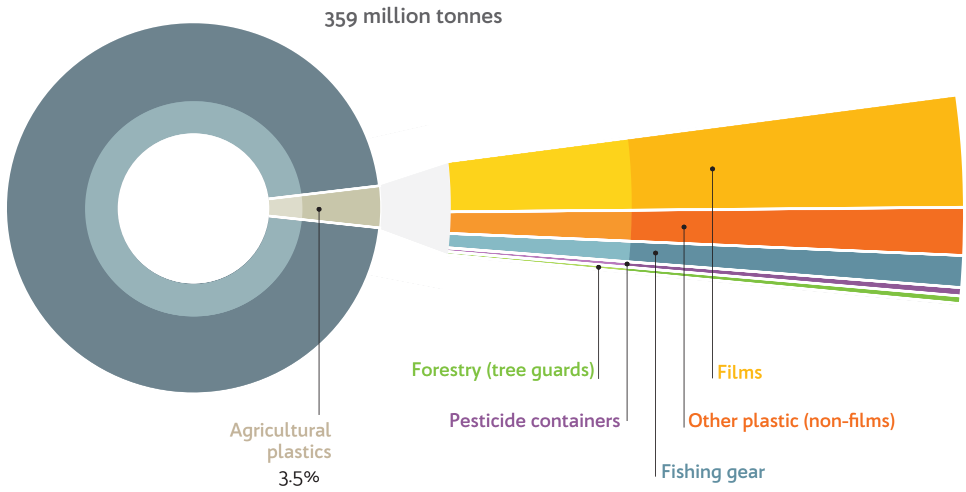
Hence, for the purpose of this report, we have used the figure of approximately ten million tonnes to represent the quantity of plastics used in terrestrial crop and livestock production.

In addition, plastics used in fisheries and aquaculture production contribute at least 2.1 million tonnes per year, an estimation derived from the quantities of plastics that enter the world's oceans from this sector (see Section 3.4.5). There are no data on waste fishing gear disposed of on land, so this number is likely to be an underestimation. In forestry, it is estimated that 0.23 million tonnes of plastic are used as tree guards (see Section 3.4.4), while the annual use of plastics in polymer coated fertilizers contributes approximately a further 0.1 million tonnes, according to our calculations (see Section 3.4.3).

Hence, throughout the rest of this report our estimates account for at least **12.5 million tonnes** of plastics used globally in agricultural production annually, an amount equivalent to almost 3.5 percent of the global plastic production of 359 million tonnes in 2018 (PlasticsEurope e.V., 2019). These quantities are shown in Figure 3.

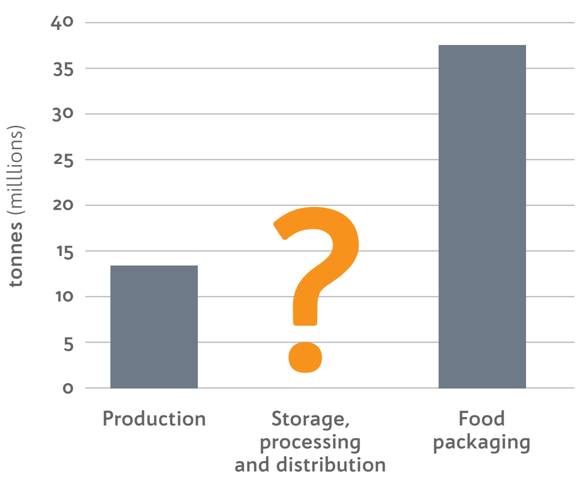
The global total quantities of plastic used annually in agricultural value chains is shown in Figure 4.

Figure 3: Global plastic production and share of plastics used in agricultural production, 2018.



Source: Global plastic production from PlasticsEurope e.V., 2019 – 12.5 million tonnes are derived in this study based on the sources and assumptions quoted in the text.

Figure 4: Plastic used annually in agricultural value chains



Source: Authors' estimates based on APE Europe, 2019; Ellen MacArthur Foundation, World Economic Forum, and McKinsey & Company, 2016; Geijer, 2019; PlasticsEurope e.V., 2019; Sintim and Flury, 2017.

3.2.2 Plastics used downstream in value chains

There are no specific data available for plastics used in the agri-food value chains between production and consumption i.e. storage, processing, transportation and distribution.

However, there are data available to allow an estimation of global plastic usage in the consumption of agricultural produce. The Ellen MacArthur Foundation has estimated that 26 percent of global plastic production in 2016 was used in packaging (Ellen MacArthur Foundation, World Economic Forum, and McKinsey & Company, 2016). Unfortunately, this is not broken down further to identify the proportion used for agricultural product packaging. The only region for which such data exist is Europe, where 40 percent of consumer packaging relates to food packaging (Geijer, 2019).

Although it is unlikely that this packaging practice models that of other regions, in the absence of better data, the European proportion together with the Ellen MacArthur Foundation data would indicate that food packaging comprises approximately 10.4 percent of global plastic production. On this basis and using the 2019 global production data described in Section 3.2.1 above, it can be estimated that 37.3 million tonnes of plastic were used globally in food packaging.

3.3 Regional estimates

Regional estimates have been derived from various sources hence the data cannot be standardized and may not be fully comparable across different regions. These aspects need further investigation in order to obtain a more detailed understanding of the issues and priorities relating to agricultural plastics in different regional contexts.

According to various authors, Asia is the largest user of agricultural plastic products, accounting for almost 70 percent of the global use of films (Jansen, Henskens and Hiemstra, 2019; Le Moine, 2018; PlasticsEurope e.V., 2019). Regional variations in the scale of use of agricultural plastic is illustrated in Figure 5 using films as an example product.

The forecast for usage in 2030 shows a 54 percent increase, driven by the anticipated increased amounts to be used in Asia, partly due to the increased minimum thickness for mulching films.

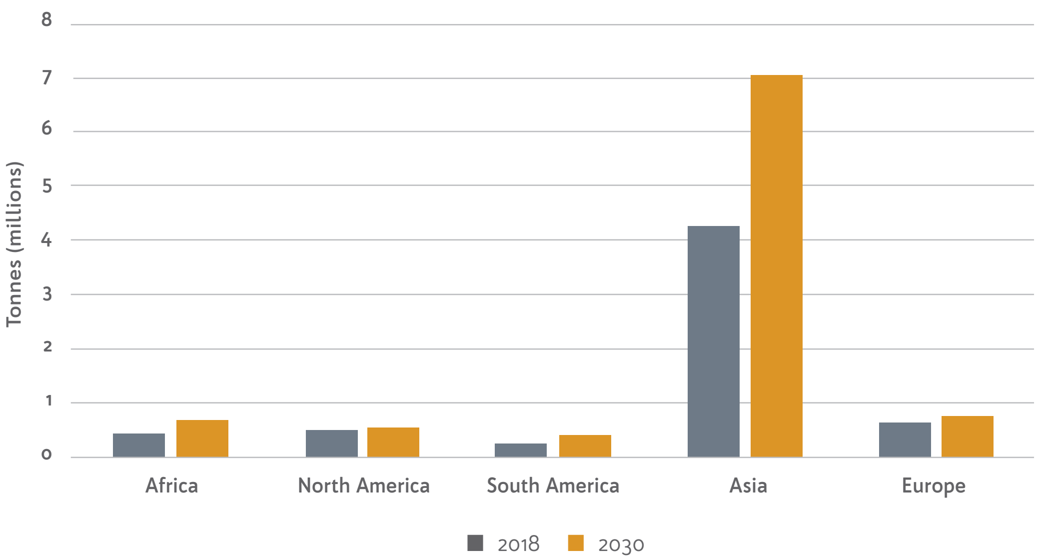
3.3.1 Europe

In the European Union 28+2 countries,[2] approximately 1.74 million tonnes of plastics were used in 2018 for the agricultural sector, that is between 3 percent and 4 percent of the total European plastic converter demand of 51.2 million tonnes (PlasticsEurope e.V., 2019). The main polymer types are PP and PE, followed by PVC. These amounts also include plastic packaging used for harvesting and transport.

According to APE Europe (2019), about 0.71 million tonnes were used in agriculture for non-packaging purposes, with 44 percent of those plastics used for crop production and 56 percent for livestock.

Focusing on the types of plastic products used in European agriculture, data suggests that 63 percent of the non-packaging quantities were films used for silage and mulch (i.e. 0.45 million tonnes), 16 percent were used for greenhouses, 11 percent for twines, 6 percent for irrigation quipment, and 1 percent for nets (Figure 7) (APE Europe, 2019).

Figure 5: Use of plastic film in agriculture in different regions

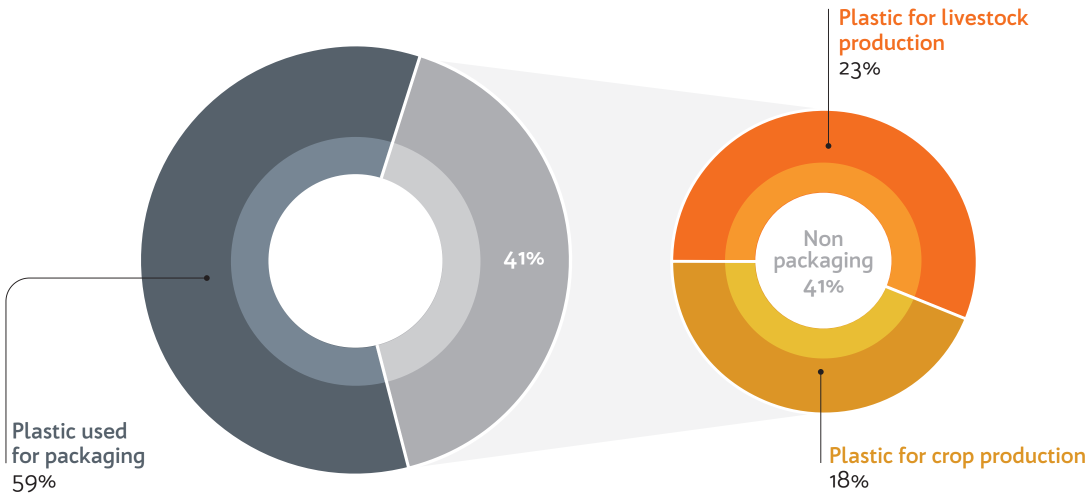


Source: Based on data from Le Moine, 2018.

[2] The 28 members of the European Union up to 31 January 2020, plus Norway and Switzerland.

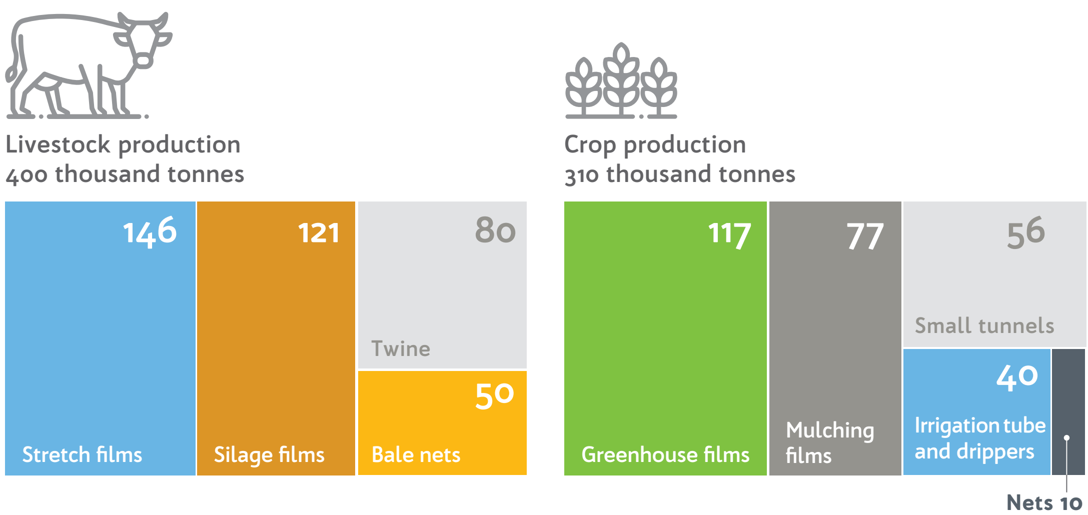
Looking at the statistics of single countries, Italy's terrestrial agricultural production, for example, uses almost 372 000 tonnes of plastic products annually (Figure 8). The distribution of products reflects the predominance of horticulture in Italy and the limited use of silage in its livestock production.

Figure 6: Plastic use in agriculture in Europe for packaging and non-packaging purposes



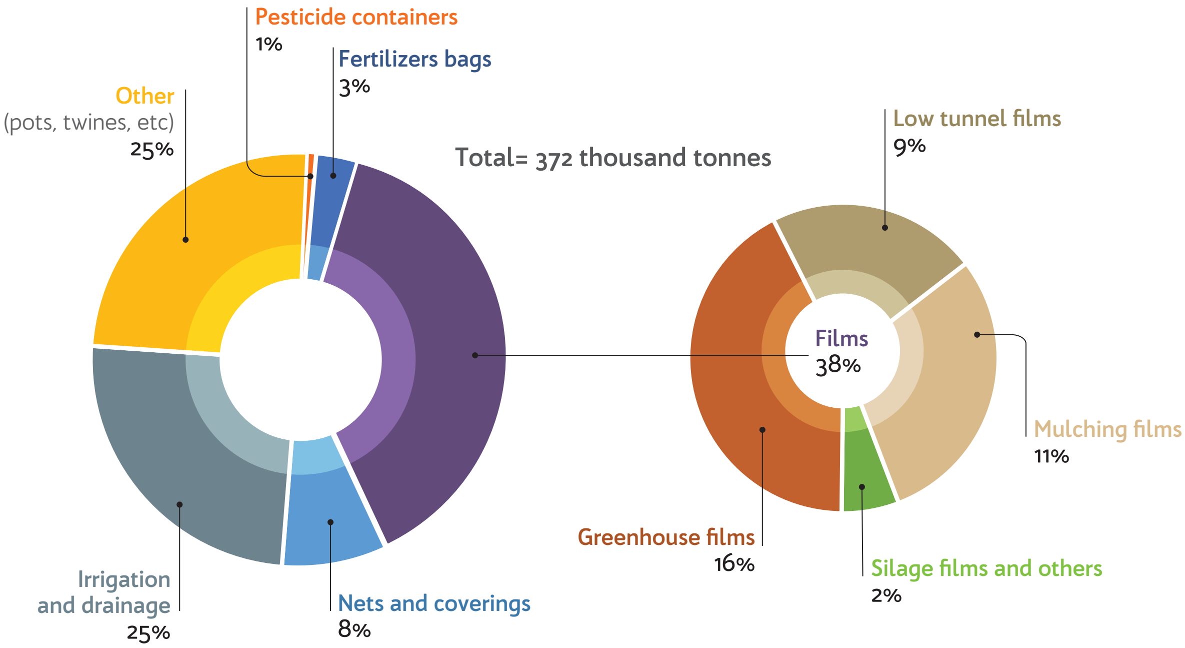
Source: APE Europe, 2019; PlasticsEurope e.V., 2019.

Figure 7: Plastic use in agriculture in Europe for livestock and crop production



Source: Data readapted from APE Europe, 2019.

Figure 8: Relative amounts of different plastic products used in agriculture – Italy



Source: Adapted data from Scarascia-Mugnozza, Sica and Russo, 2011.

3.3.2 Africa

A specific assessment regarding the use of different types of agricultural plastics for the African continent was not available, but data were available for a few specific countries. For example, in 2019, the agricultural sector in **South Africa** used 152 000 tonnes or ten percent of the total plastics consumption in the country. Of all polymers, PE represented 52 percent of plastic products in agriculture, followed by PP (34 percent). Overall, the agricultural sector used 11 percent of all plastic recyclate – mainly HDPE and PVC – for making irrigation equipment and fencing poles (Pretorius, 2020).

3.3.3 Asia

In Asia, the largest user (and producer) of agricultural plastics is **China**, with an annual consumption of at least 5.2 million tonnes; this figure includes three million tonnes of film (Chinese Academy of Agricultural Sciences and Ministry of Agriculture and Rural Affairs, 2020) and two million tonnes for irrigation equipment (Zen, 2018). CropLife International has estimated that up to 150 000 tonnes of empty pesticide containers are produced annually (Ward, 2020).

According to Government researchers, less than ten percent of used plastic films are currently recycled (Reuters, 2019).

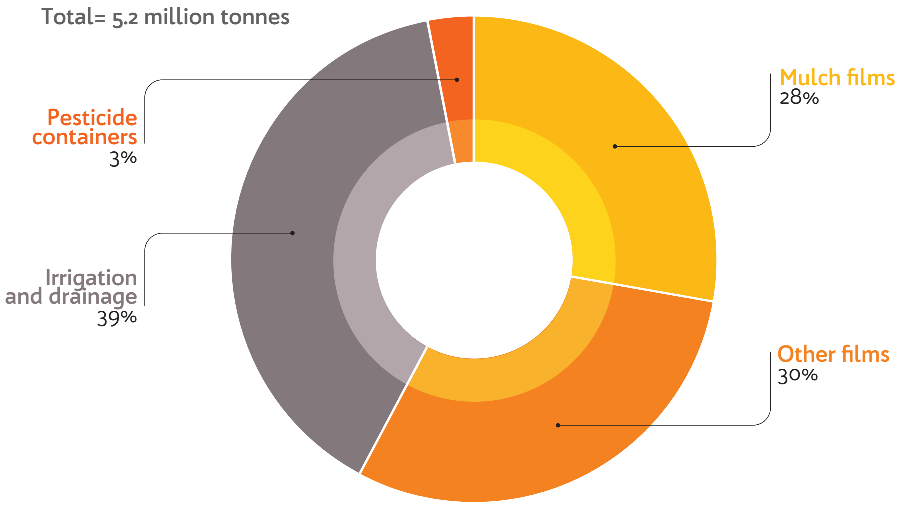
Quantities of agricultural plastics are expected to increase in China due to the introduction of new greenhouses, new standards that specify thicker mulch films, and an increasing reliance on mulching practices. Controlled release fertilizers are expected to increase, especially in China, as it has become the major market for both the commodity agriculture and agricultural crop markets (IHS Markit, 2020).

In 2017, the agricultural sector of the **Republic of Korea** used at least 320 000 tonnes of plastics (including LDPE films, HDPE, PVC and other plastics), with PE representing almost 97 percent of the total amount (Ghatge *et al.*, 2020).

3.3.4 Latin America

In Latin America, agriculture annually uses 240 000 tonnes of plastic films (Le Moine, 2018). The majority is used for mulching or tunnels, covering almost 200 000 hectares, with **Brazil** having the largest quota of covered areas. Silage film, at 60 000 tonnes make up the bulk of the rest (CIDAPA, 2018).

Figure 9: Different plastic products used annually in agriculture – China



Source: Figure based on data of Zen, 2018, CropLife International Personal communication, 2020 and of the Chinese Academy of Agricultural Sciences and Ministry of Agriculture and Rural Affairs, 2020.

3.3.5 North America

There are few and inconsistent data on the quantities of agricultural plastics used in North America. Le Moine (2018) indicates that 490 000 tonnes of plastic films (greenhouse, mulching, silage and storage) are used. Jones (2014) cites market research data for 2012 that estimated a total of 280 000 tonnes of agricultural plastic films were used in the **United States of America**.

In **Canada,** agricultural plastic waste is estimated to be in the range of 40 000 tonnes/year (Friesen, 2017). Silage films are a significant proportion of this. An innovation project organized with Laval University students identified that the province of Quebec used 11 000 tonnes of agricultural plastics annually, 69 percent of which were silage films. The recycling rate of used silage films was estimated to be between 20 to 40 percent (Matériaux Renouvelables Québec, 2021). Friesen (2014) identified that in the province of Saskatchewan, 79 percent of used silage wrap and 85 percent of used twines were burned on farms.

3.3.6 Australia

In **Australia,** the agricultural sector uses almost 82 800 tonnes of plastic products, equivalent to 2.3 percent of national consumption. Of this quantity, 7.1 percent of the plastic is recovered.

The main agricultural plastics are flexible films, twines, ropes, and irrigation pipes. Polyethylene (both high and low density) account for 81 percent of all agricultural plastics followed by PP at eight percent (O'Farrell, 2020).

3.4 Global product estimates

For many agricultural sectors and supply chains, there is a lack of data or publications that quantify the specific plastic products that they use. Likewise, information on the leakage of plastic into the environment due to unintended releases or inappropriate disposal is lacking.

Given the inconsistency and lack of data, it is difficult to make quantitative comparisons of the use of plastic products in value chains in different regions of the world. The need for further investigation and data mining has been summarized in Table 4.

A rough estimation of the main plastic products used in agriculture (see Section 3.2) divides the global amounts into three groups: films for mulch, silage, and greenhouses representing up to 60 percent of the total quantities, and fishing gear constituting 16 percent (Figure 10). These specific plastics products are analysed in greater depth in the following chapters.

Based on the literature review and the estimations included in this report, it is possible to compare the quantity of plastic used per hectare for different terrestrial agricultural applications, as shown in Figure 11. For durable plastic products such as greenhouse films, this considers the total installed quantity of plastics, while for short cycle products it considers the total quantity used within a year. In particular, the quantities for greenhouse and mulch films are taken from Sanchez (2020), while the amounts of plastic bags used in banana plantation are derived from personal communications with FAO experts. The quantities of irrigation tape, polymer coated fertilizers, tree shelters for forest plantation and bale nets are based on the authors' estimations. Plastic ear tags were assessed based on a rate of accidental loss by grazing animals.

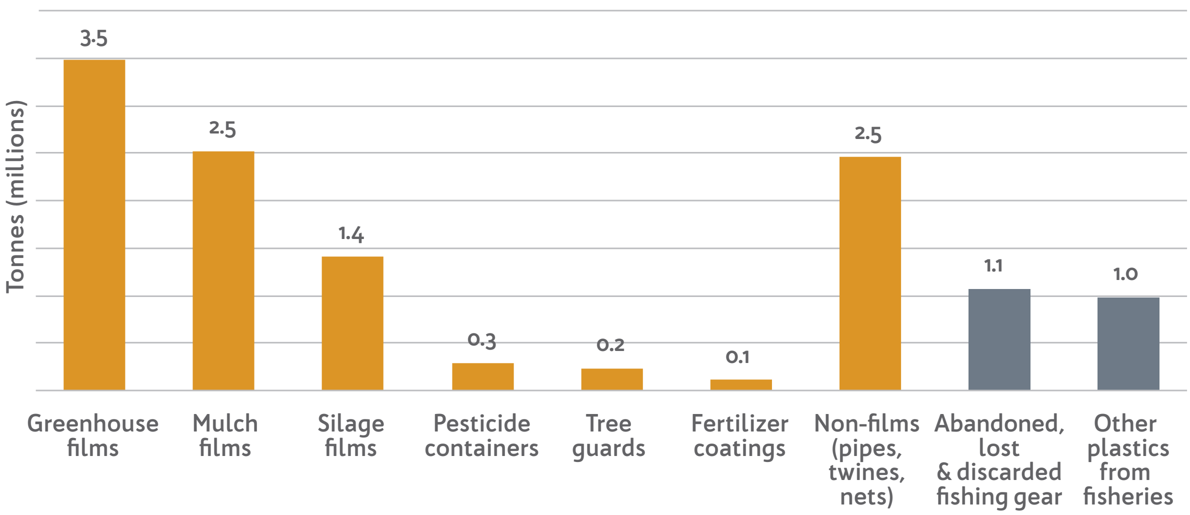
Table 4: Source of data for quantities of agricultural plastic products*

SECTOR	TYPE OF ITEM	QUANTITIES OR USE	LEAKAGE
Crop production	Films	Available at national and regional level	Limited, for specific national cases only
Fodder	Bale wrap or silage	No specific data available	No specific data available
Tropical agriculture (bananas)	Plastic bags	Data available for specific situations	No specific data available
Livestock	Ear tags, etc.	No specific data available at national or regional level	No specific data available
Forestry	Tree shelters	Estimated in this report (see Section 3.4.4)	No specific data available
Fisheries and aquaculture	Fishing gear	Very limited for production or use	Limited data available for some sectors (Richardson *et al.*, 2021; Richardson, Hardesty and Wilcox, 2019)
Various	Pesticide containers	Available at national level	Can be derived from collection and recycling data at the national level

*Colour coding: green= data available; amber= limited data available; red= no specific data available.

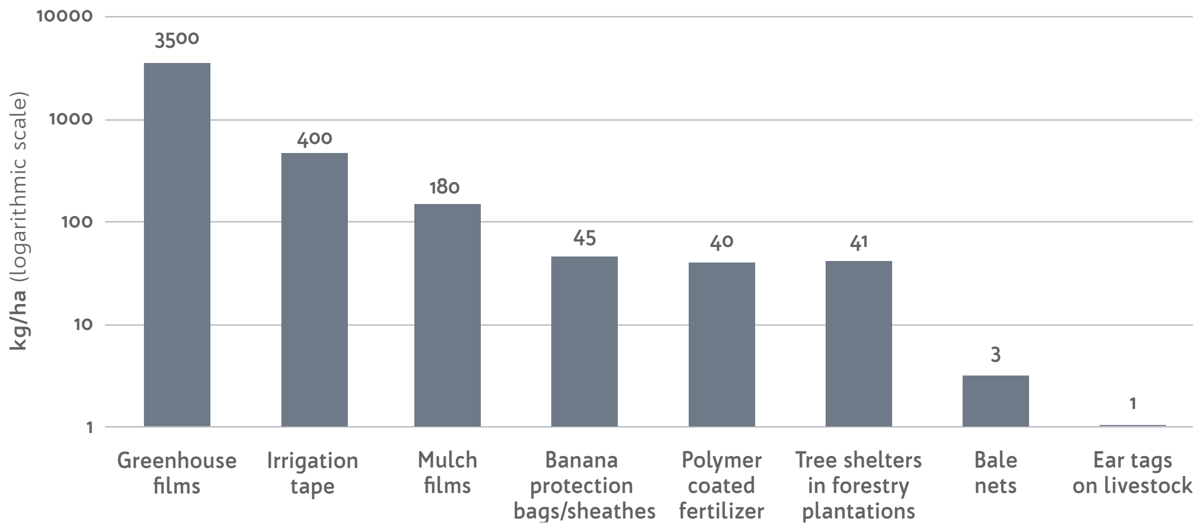
Source: FAO, 2021.

Figure 10: Estimated global annual quantities of agricultural plastics



Source: Based on data of APE Europe, 2019; Le Moine, 2018; Sintim and Flury, 2017 and our estimation as commented in Section 3.2.

Figure 11: Estimated quantities of agricultural plastics used per hectare of land



Source: Adapted from Sanchez (2020) and FAO (2021).

3.4.1 Plastic films and mulch

The extensive use of plastic products in plant production on land, so-called plasticulture, leads to significant benefits that include an increase in crop yield, saving of agricultural inputs such as agrochemicals and fertilizers, and improved irrigation efficiency. The concomitant trade-offs in terms of environmental pollution, GHG emissions, soil contamination are discussed in Chapters 4 and 5.

Most authors identify films (including mulching, greenhouse, shading nets and others) as the largest "family" of agricultural plastics used in land-based systems, with mulch films representing almost 40 percent of the total according to Sintim and Flury (2017). The global agricultural film market is expected to increase by 50 percent from 6.1 million tonnes in 2018 to 9.5 million tonnes in 2030 (Figure 12) (Le Moine, 2018).

Focusing on plastic films, it is estimated that 47 percent of agricultural film demand is for greenhouses, 34 percent for plastic mulch film, and 19 percent for silage, thus at least 50 percent of the film used in agriculture lasts for only one cropping cycle and then becomes waste (Le Moine, 2018).

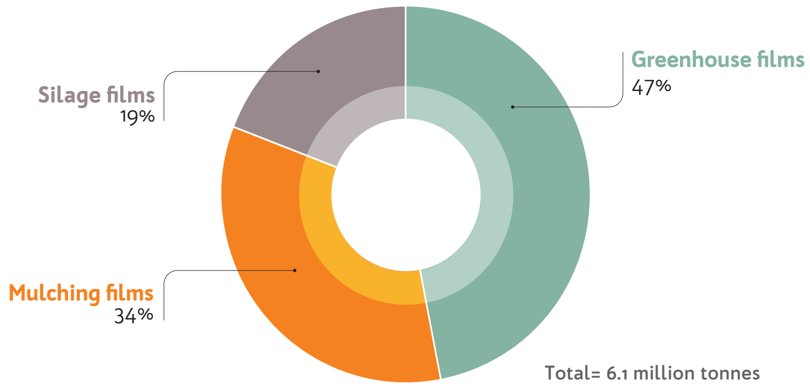
Greenhouses represent the largest quantity of plastic films used in plant production with almost three million tonnes/year (Le Moine, 2018).

Greenhouses, walk-in high tunnels and low tunnels are used to extend the growing season in the temperate regions of the world, while in tropical regions they enable crop production during the rainy or monsoon seasons. The use of plastic greenhouses and high tunnels is concentrated in Asia (China, Japan and the Republic of Korea) with almost 80 percent of the world's greenhouse covered area, and in the Mediterranean Basin with 15 percent.

Mulch films represent the second largest use of plastic films in agriculture by volume, exceeding 2 million tonnes globally (Le Moine, 2018). Low density polyethylene is the dominant plastic in mulch film applications (Sarkar *et al.*, 2019). In response to environmental and disposal issues associated with non-biodegradable plastics, mulching films made from degradable plastics have been introduced. These include biodegradable and oxo-degradable plastics, the latter of which have subsequently been banned in some regions due to the risk of microplastic pollution. The performance and standards for biodegradable plastics are discussed in Section 6.4.3.

Protection nets represent another type of plastic product used in plant production to protect crops – particularly fruit – from hail, wind, snow or strong rainfall, or as shading against strong sunlight. The most widely used raw material for protection nets is high density polyethylene (HDPE). These quantities do not include fishing gear.

Figure 12: Global use of plastic films in agriculture in 2018



Source: Adapted from Le Moine, 2018.

BOX 1: CASE STUDY – PLASTIC FILM WASTE FROM SPANISH HORTICULTURE

In Almeria, the southern agricultural province of Spain, intensive horticulture makes use of large amounts of plastic film for greenhouses and mulching covering 31 000 ha. About 15 percent of the plastic films are not collected for proper recycling or disposal (Sanchez, 2020) and are illegally dumped into the soil or burned. The sector employs 50 000 people and registers export for USD 2 880 million per year.

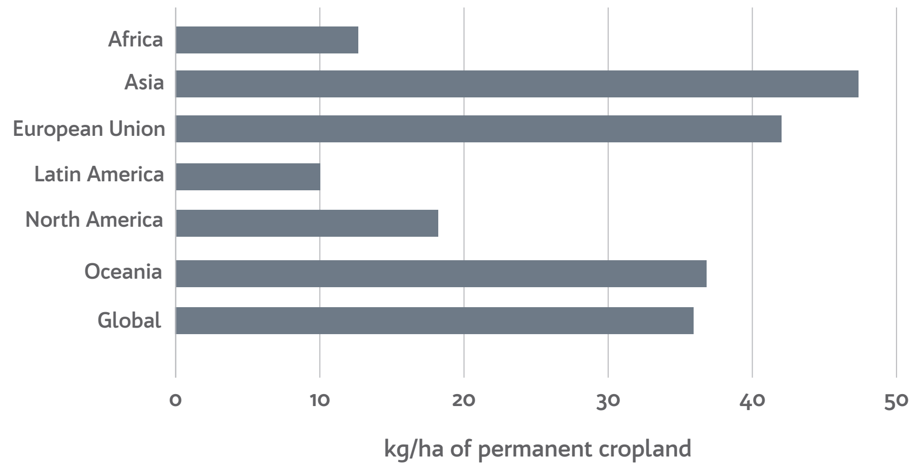
A group of local municipalities chaired by the city of Adra launched the initiative "compromiso blanco" aiming to recycle 100 percent of all plastic waste generated by greenhouses.

Comparison of greenhouse and mulch films	Greenhouses	Mulch films
weight of plastic per hectare (kg)	3,000	250
lifetime	3–5 years	3–5 years
waste characteristics	high density and clean	low density, with high levels of soil and plant residues
annual quantities of waste (kg/ha)	600	250-500
income from recycling/cost of disposal: USD per hectare	100	40-80
destination of plastic waste:	unknown (previously exported to China for recycling)	sorting and limited recycling, disposal*

*The data predate the ban on importing plastics by the Government of the People's Republic of China.

Knowing the absolute amounts of agricultural plastic films used and the extent of permanent cropland in each region, it has been possible to derive estimates of the intensity of their use in different regions (see Figure 13) (FAO, 2020b). The lowest use is in South and North America, probably due to extensive commodity cultures, whilst in the case of Africa, it may relate to lower infrastructure and purchase capacity of farmers. The highest demand for plastics is in Europe, Australia, and Asia.

Figure 13: Regional annual usage of plastic film on permanent cropland



Source: 2018 data for plastic films are from Le Moine, 2018 and data on cropland from FAOSTAT.

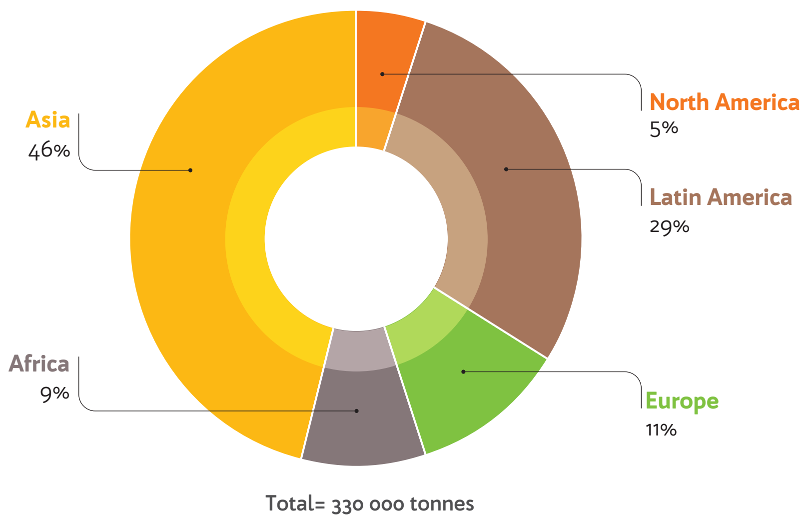
3.4.2 Containers for pesticides

Pesticides are defined in the International Code of Conduct on Pesticide Management (the Code) as "any substance, or mixture of substances of chemical or biological ingredients intended for repelling, destroying or controlling any pest, or regulating plant growth" (FAO and WHO, 2014). The Code sets voluntary standards for all actors engaged in the management of pesticides that aim to ensure that any benefit derived from their necessary and appropriate use are achieved without significant adverse effects on human and animal health and/or the environment.

Amongst other things, the Code and its supporting technical guidance documents sets voluntary standards for the design and management of pesticide containers (FAO and WHO, 2008) that aim to protect users, the public and the environment from unnecessary exposure.

According to CropLife International (2021) at least 330 000 tonnes of primary packaging for pesticides were put onto the market in 2019. Figure 14 shows the distribution of pesticide containers by weight of plastic across the regions, the largest being Asia (46 percent) and Latin America (29 percent).

Figure 14: Regional share of primary packaging used for pesticides



Source: Based on data from CropLife International, 2021b; quantities include also non-plastic packaging.

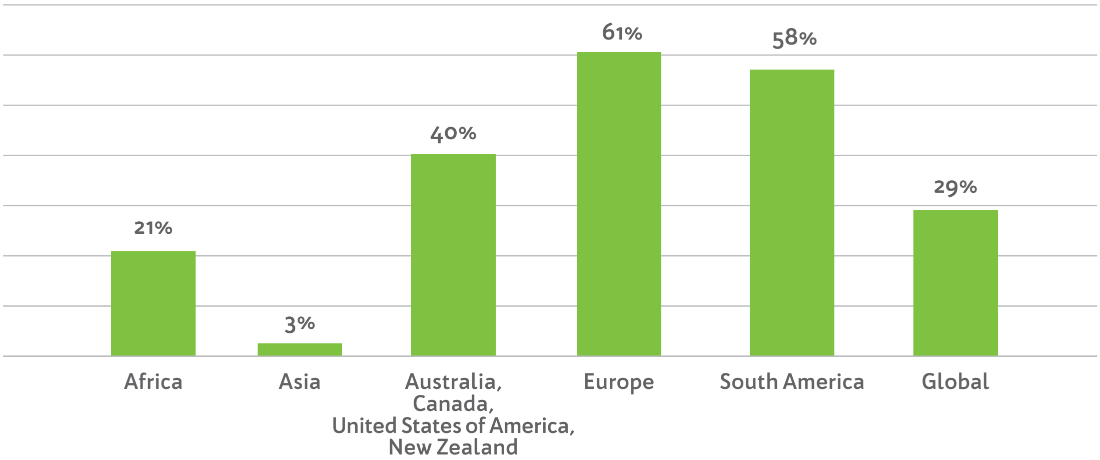
CropLife International monitors data on container management schemes in almost 60 countries (see Figure 37 in Section 6.4.1). Together these schemes collect 30 percent of the global quantity of empty pesticide containers.

Figure 15 shows the regional collection rates of empty pesticide containers as a proportion of the quantity of new containers put onto the market.

The data for Asia are underestimated due to a limited availability of information about the quantities collected and recycled.

Almost 83 percent of the quantities collected are recycled, indicating that, where container management schemes are in place, the circularity of plastics is improved.

Figure 15: Regional collection rate of packaging used for pesticides, 2019
Source: Based on data from CropLife International, 2021b; quantities include also non-plastic packaging.



3.4.3 Polymers for controlled release fertilizers

Mineral fertilizers are an integral part of global food security, facilitating the level of food production required to meet the needs of about half the global population (Fertilizers Europe, 2020b).

Polymer coated controlled release fertilizers (PCF) are used to release nutrients to soil at a rate optimized for plant uptake, and to avoid losses through leaching and runoff. As an example, using controlled release fertilizers for rice cultivation led to a yield increase by 24 percent compared to the use of traditional fertilizers (Gil-Ortiz *et al.*, 2020).

In the European Union, it is estimated that approximately 8 000 tonnes of polymers are used annually in PCF. From this data we can estimate[3] that 67 000 tonnes of polymers are used for coating the 440 000 tonnes of PCFs used globally each year (Amec Foster Wheeler Environment & Infrastructure UK Limited, 2017).

Polymers are also used to coat seeds and some pesticide formulations (Dubey, Jhelum and Patanjali, 2011).

3.4.4 Forestry and plantations

Tree guards and shelters are semi-rigid tubes that are wrapped around the base of newly planted tree saplings to help them become established. They are generally manufactured out of polypropylene, either as non-perforated or perforated mesh structures, although alternative materials are available. They are used in forest plantations, vineyards and orchards, although use varies across tree species and climatic zones. There are no definitive data for tree guard/shield use, therefore a derived estimate was made based on FAO data for plantations (FAO, 2020a), typical planting densities and time to maturity in different climatic zones. Overall, an estimated 23 000 tonnes of plastic are used every year in plantations as tree guards/shelters.

[3] Assuming that the rate of PCF to the total fertilizer market in Europe (Amec Foster Wheeler Environment & Infrastructure UK Limited, 2017) can be extended to the global fertilizer market of 251 million tonnes (Fertilizers Europe, 2020b).

3.4.5 Plastic used in fisheries and aquaculture

Plastic is widely used in fisheries and aquaculture in a variety of applications and polymers. There are no specific data sources available that provide estimates of the global quantities of the various types of plastics used in these two sectors. Instead, a derived estimate of 2.1 million tonnes/year has been made based on the amounts that are littered into the world's oceans from fisheries according to a comparison by Sherrington *et al.*, (2016) of various investigations (range 300 000 to 3.8 million tonnes/year). These quantities include abandoned, lost, or otherwise discarded fishing gear (ALDFG). Richardson, Hardesty and Wilcox (2019) undertook a literature review and meta-analysis of 68 publications (1975 to 2017) on ALDFG and estimated that 5.7 percent of all fishing nets, 8.6 percent of all traps and 29 percent of all lines are lost to the world's oceans annually.

In a separate study, they highlight the complexities in estimating ALDFG, questioning some of the frequently quoted quantities and make recommendations for improved methodologies for reporting ALDFG (Richardson *et al.,* 2021). Given these uncertainties, it is estimated that ALDFG ranges between 640 000 to 1.5 million tonnes per year (FAO, 2018) and so contributes approximately 50 percent of the total plastic pollution from the fisheries sector.

According to Sundt and Syversen (2014), as of 2011, Norway generated approximately 15 500 tonnes of plastic waste annually from fisheries and aquaculture, of which only 23 percent was recycled. The exact fate of the remainder was uncertain, but the authors commented that the leakage as litter *"seems to be quite high"*, potentially up to 65 percent of all the waste. The main components of the annual plastic waste arisings were 7 000 tonnes of PE fish farming rings (45 percent) and 4 500 tonnes of fishing and aquaculture nets (26 percent).

BOX 2: PLASTIC USE AND LEAKAGE IN NORWEGIAN FISHERIES AND AQUACULTURE

The aquaculture sector industry in Norway relies significantly on various plastic equipment and inputs, using almost 190 000 tonnes of plastic in fish farms, equivalent to approximately 1.3 kg of plastic for every tonne of fish harvested in 2015 (Sundt, 2020).

Of the plastic equipment used in aquaculture, 25 000 tonnes is discarded annually. This mainly consists of float collars and plastic pipes, but also fishing nets, feed hoses and ropes. This is equivalent to approximately 0.18 kg of discarded plastic per tonne of harvested fish.

According to Sundt (2020), Norway is considering the establishment of an extended producer responsibility scheme that specifically addresses used fishing gear and other equipment used in capture fisheries, aquaculture, and recreational fishing.

3.5 Summary

An estimated, 12.5 million tonnes of plastic products are used in agricultural production annually, with films accounting for approximately 60 percent of this total. Overall, it is estimated that the vegetable, fruit, crop, and livestock sectors are the largest users, accounting for ten million tonnes a year collectively, followed by fisheries and aquaculture, then forestry (Figure 16). This therefore suggests that soil is the predominant receptor for agricultural plastic products, both during their intended use and at the end of their useful lives.

Despite limitations in the data derived for different regions, Asia is thought, by far, to be the largest user of agricultural plastics; with China alone accounting for at least six million tonnes annually. Overall, demand for agricultural plastics in Asia is anticipated to increase as a result of the increasing use of greenhouse and mulching practices to meet the growing demand for food. Climate change adaptation and an increasing global population are also likely to drive an increase in the use of agricultural plastics.

In terms of the types of plastic products used globally in agricultural production, films for mulching, silage production and greenhouses account for up to 50 percent of the total annual quantities, with fishing gear accounting for around 17 percent. Looking at specific rates of use on land, greenhouse films are used at an estimated 3 500 kg/ha, irrigation tape at 400 kg/ha and mulch films at 180 kg/ha, with all other product categories falling below 45 kg per hectare.

These estimates provide a useful indication of the agricultural sectors and product types to investigate in greater detail and for which mechanisms to minimize their environmental impact should be prioritized.

Figure 16: Estimated annual quantities of agricultural plastics used globally

Source: Data summarized from Figure 10.

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5. The harm caused by plastics

Irrespective of their intended use, plastics cause harm when they leak to the environment (WWF, Ellen MacArthur Foundation, and Boston Consulting Group, 2020). This arises during their manufacture, use, and at the end of their intended life. Ecosystem harm may be indirect (for example, through diffuse emissions of GHGs during manufacture and transportation) or direct (such as localized impacts on soil function and the health of grazing animals, for example).

As most plastics are made from petroleum-derived precursors, they are associated with significant GHG emissions. Recent estimates suggest that global GHG emissions in 2019 attributed to plastics were in the region of 86 gigatonnes of carbon dioxide equivalents (CO_2-eq) (equivalent to emissions from 189 five-hundred-megawatt coal fired power stations); a figure that is expected to rise to 1.34 Gt CO_2 eq by 2030 and 2.8 Gt CO_2 eq by 2050 should plastics consumption and use continue to increase at current rates (Hamilton *et al.*, 2019). Assuming that plastics used in agricultural production represent 3.5 percent of global plastic production (see Section 3.2.1), it can be estimated that annual GHG generation will be 47 Mt CO_2 eq by 2030 and 98 Mt CO_2 eq by 2050.

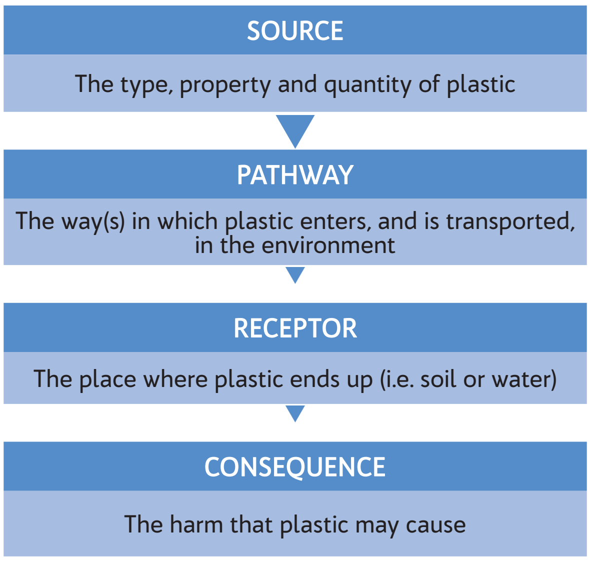
Thus, policy options to reduce plastic's environmental impact should ideally target multiple steps in the value chain through a combination of interventions based on the 6Rs; this is discussed in further detail in Chapter 7 (Gu *et al.*, 2017; Zheng and Suh, 2019).

4.1 Risk assessment model

Environmental risk assessments rely upon a number of different techniques, of which the source-pathway-receptor-consequence (SPRC) model has been developed for chemical pollutants and physical hazards, such as flood water. The model is outlined in Figure 17 and shows that by breaking any one link in the chain, harm associated with a hazard can be prevented. This model is used in the assessments of specific agricultural plastic products discussed in Chapter 5.

The SPRC model has been used in this study, with each step being discussed separately.

Figure 17: The source-pathway-receptor-consequence model



Source: FAO, 2021.

4.2 Sources of agricultural plastics

The main types of agricultural plastics include surface mulching films, containers, polymer coated controlled release fertilizers, and nets/lines used in fisheries and aquacultural operations (see Section 3.4).

Being highly resistant materials, end-of-life plastics left in both terrestrial and aquatic environments tend to persist, causing environmental harm. This is a function of both the amount of plastic released, and its chemical and physical properties.

In general, agricultural plastics can be grouped into three main categories, based on their physical properties:

- **flexible products** – such as mulch films, tunnel and greenhouse films/nets, bags/sacks, silage films, non-woven textile protective "fleeces" and fishing netting and lines;
- **semi-flexible products** – such as tubes and driplines, tree guards/shelters; ropes; and
- **rigid products** – such as bottles, baskets, cages and fishing floats.

The nature of these different types of plastic categories influences the ways in which they may enter terrestrial and aquatic ecosystems, and how they subsequently behave. Most plastics can be considered to be **point sources**, although subsequent disintegration of large pieces into smaller and smaller fragments can result in **diffuse pollution.**

Of the approximate 12.5 million tonnes of agricultural plastics generated annually (see Section 3.1), the amounts that leak into the environment are largely unknown, and will vary depending upon the specific type of plastic product, its use, local collection and recycling/disposal infrastructure, legislation, and compliance/certification schemes.

Data from five European countries with established national collection and recycling schemes indicates collection of between 50 percent and 84 percent of end-of-life agricultural plastics (see Section 6.4.1); which means the balance remains either uncollected, disposed of on farms or sent directly for disposal elsewhere. Areas that are not served by a formal collection and recycling/disposal service are therefore likely to employ informal reuse, recycling, and disposal activities; all of which have potential to leak plastics into the environment.

BOX 3: THE CLASSIFICATION OF PLASTIC BASED ON SIZE

At present there is no commonly agreed definition of plastic size categories, as different researchers have used different size ranges depending upon their chosen analytical methods and field of study. In an attempt to standardize this, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) has suggested the following classification system:

FIELD DESCRIPTOR	RELATIVE SIZE	COMMON SIZE DIVISIONS
Mega	Very large	> 1 m
Macro	Large	25 – 1000 mm
Meso	Medium	5 – 25 mm
Micro	Small	< 5 mm
Nano	Extremely small	< 1 µm

GESAMP has assumed that these plastics would have a near-spherical form, although most items of agricultural plastics are non-spherical: for example, mulch films, and fishing nets and lines. This means they have potential to exert effects typical of a range of plastic sizes, which may broaden the potential harm they may cause.

Source: GESAMP, 2019.

BOX 4: MICROPLASTIC SOURCES

Microplastics can be intentionally manufactured (e.g. in personal care products), where they leak into the environment during use; or unintentionally created as a result of wear, tear and disintegration of macroplastics (Juergen Bertling, Hamann and Bertling, 2018).

Overall, it is thought that about 3.2 million tonnes of microplastics are released into the environment annually, of which 1.5 million tonnes (48 percent) enters the world's oceans (Boucher and Friot, 2017). Of the latter, the majority (98 percent) is thought to be derived from land-based sources, such as vehicle tyres (Tumlin, 2017).

There is strong evidence that agricultural plastics used on land cause microplastic pollution that can then disperse to other environments. A temporal study of soil cores from seagrass meadows in the Mediterranean Sea identified that elevated microplastic pollution near Almeria, Spain was associated with changes in agricultural practices to intensive greenhouse production. Levels were an order of magnitude greater than in historic soils from the same location and from recent sedimentation on undeveloped coasts (Dahl *et al.*, 2021).

4.3 Pathways and the 3D concept

Agricultural plastics that are not collected for separate recycling or formal disposal may enter terrestrial and aquatic ecosystems through any one of three main mechanisms: namely, through being **damaged, degraded,** or **discarded**. This has been termed the '3D concept' and is defined in Figure 18.

Plastics that are damaged, degraded or discarded in the environment are sometimes referred to as 'leaked plastics' (Boucher and Billard, 2019) and "mismanaged plastic" (Jambeck *et al.*, 2015) and this has been the focus of much research in recent years (Richardson, Hardesty and Wilcox, 2019; The Pew Charitable Trusts and SYSTEMIQ, 2020).

Figure 18: The 3D concept

DAMAGED

DEFINITION: This is where agricultural plastics are damaged in situ which results in their unintended and erratic release into the environment.

CAUSE(S): Through inappropriate selection, management practices and machinery (e.g. mulch film retrieval machines/entrapment of nets in motors); animals (e.g. chewing by wild animals/livestock), abrasion of fishing gear etc.

EFFECT(S): Erratic release of agricultural plastic fragments into the environment (aquatic and terrestrial) where they may then be dispersed.

DEGRADED

DEFINITION: This is the abiotic or biotic degradation of agricultural plastics in the environment.

CAUSE(S): Through the inapproporiate or excessively extended use of agricultural plastics, they can be subject to conditions, e.g. weathering, that weaken their structure.

EFFECT(S): They become more susceptible to wear, disintegration and fragmentation, and ultimately more readily dispersed by wind and runoff.

DISCARDED

DEFINITION: This covers both the erratic disposal of agricultural plastics in the environment in an unplanned, diffuse manner as in littering and its inappropriate disposal at a site that has very limited, if any, measures to control the operation and protect the surrounding environment. It can include surface and below ground disposal, and burning.

CAUSE(S): Through the intentional or unintentional release of agricultural plastics (both intact and fragments) into the environment (e.g unwanted fishing nets jettisoned at sea or tree shelters left attached to the tree beyond the product's useful life) or through disposal at a site that does not have appropriate environmental control measures in place (e.g a logging camp's waste dumpsite or used bale-nets dumped at the borders of a farmer's field).

EFFECT(S): Burning causes the release of hazardous substances into the air, where they may pollute water and land, and harm human, animal and plant health. Disposal on land may result in the subsequent disintegration of agricultural plastics and their dispersal into the environment (aquatic and terrestrial).

Source: FAO, 2021.

Most agricultural plastics leaking into the environment have potential to accumulate for long periods of time. Items manufactured out of conventional plastic polymers have biodegradation times of several decades (Ghatge *et al.,* 2020). This means that whenever environmental inputs exceed biodegradation and output rates, accumulation will occur.

BOX 5: GLOBAL LEAKAGE OF PLASTICS INTO THE ENVIRONMENT

Mismanaged plastic waste from all sources accounted for around 91 million tonnes in 2016, of which, 31 million tonnes leaked into the terrestrial environment and 11 million tonnes into oceanic environments (The Pew Charitable Trusts and SYSTEMIQ, 2020). Estimates of marine inputs do, however, vary, with Borrelle *et al.,* (2020) suggesting between 19 to 23 million tonnes in 2016, and Eunomia Research & Consulting Ltd (2016) estimating 12.2 million tonnes/year. Overall, it is thought that approximately 80 percent of marine plastics are derived from land-based sources (Li, Tse and Fok, 2016).

The extent to which plastics are mismanaged and leak into the environment is dependent upon the extent of urbanization and the income profile of individual countries/areas, with lower-middle and upper-middle income countries contributing the most (The Pew Charitable Trusts and SYSTEMIQ, 2020). This is therefore a function of both consumer behaviour and the provision of recycling/waste management infrastructure and legislation.

Although these estimates imply that there is currently a significant environmental burden associated with plastic leakage, a combination of population growth and changing consumer preferences for purchasing plastic products, means that plastic waste is expected to double by 2040, with a corresponding tripling of leakage into oceans (The Pew Charitable Trusts and SYSTEMIQ, 2020). It is likely leakage of agricultural plastics will follow a similar trend unless measures are put in place to improve their management.

4.4 Receptor environments

4.4.1. Terrestrial environments

As the majority (93 percent) of global agricultural activities take place on land,[4] agricultural soils are likely to be the principal receptors for damaged, degraded, or discarded agricultural plastics. Scientific knowledge about the dispersal and ultimate fate of plastic in these terrestrial environments and ecosystems is, however, limited compared with other pollutants and oceanic environments (Horton *et al.,* 2017). Moreover, it is estimated that agricultural soils may receive greater quantities of microplastics than oceans (Nizzetto, Futter and Langaas, 2016).

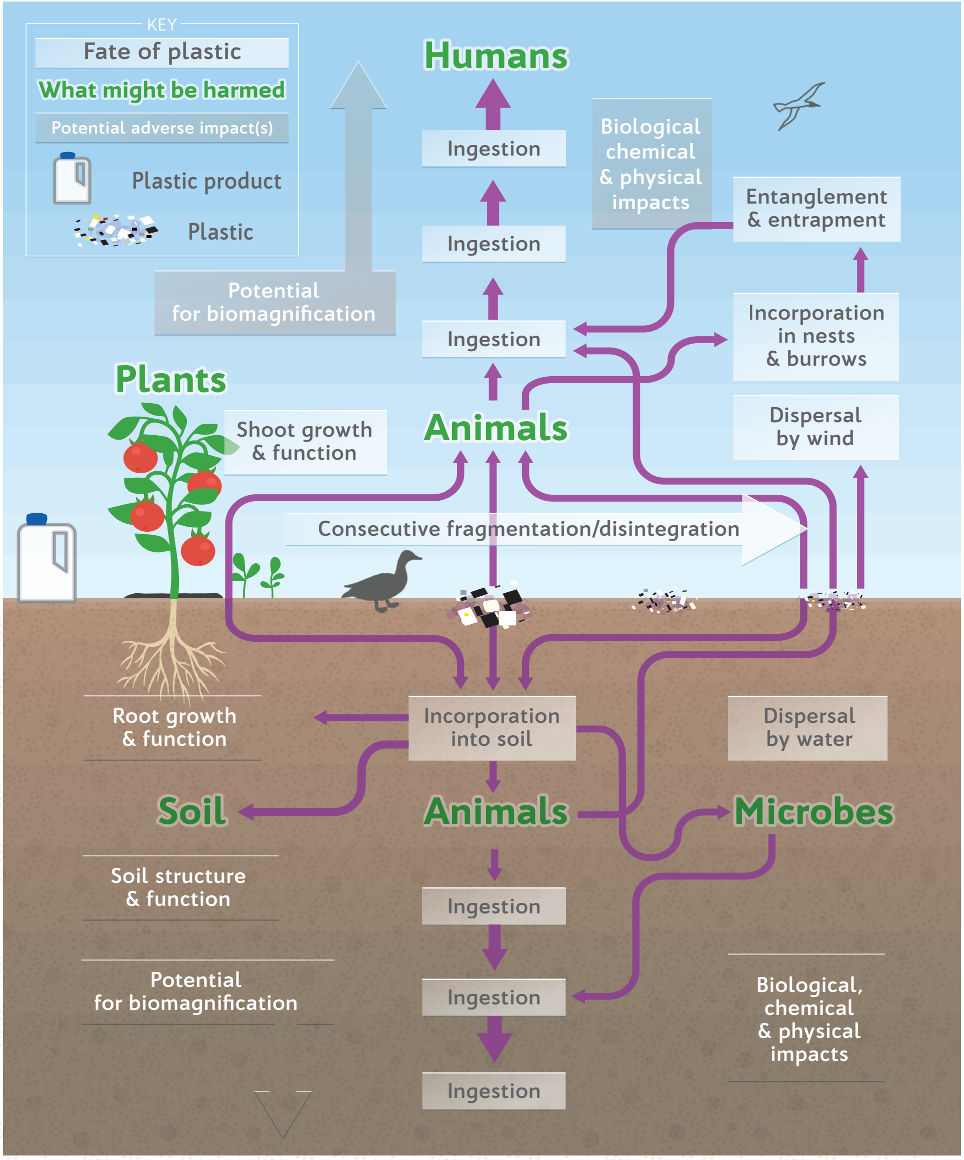
What is known, however, is that plastics can be dispersed from the site of deposition and enter new ecosystems or food chains through a variety of mechanisms. These include, *inter alia*:

- dispersal of films and flexible products in the air by wind;
- dispersal in surface and ground waters, either as macroplastic fragments following heavy rainfall events, or as micro or nanoplastics following *in situ* disintegration;
- incorporation into soil, then subsequent ingestion by soil invertebrates and vertebrates; both of which, may, in turn, be consumed by animals living above ground; and
- dispersal through ingestion, entanglement and use of plastics in nests/burrows by animals, including birds.

The main flows of plastics in terrestrial environments are summarized in Figure 19.

[4] Based on the global employment in agriculture of 866 million people (source: ILOSTAT, updated on Dec-2018) and almost 60 million fishers and fish farmers (source: https://www.statista.com/, data for 2018)

Figure 19: Schematic representation of the flow of plastics in terrestrial environments



Source: FAO, 2021.

4.4.2 Atmospheric environments

The open burning of plastics releases a range of contaminants into the atmosphere that have potential for harm to human health and the environment. These contaminants include polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs) (Weber *et al.*, 2018), both of which are listed as persistent organic pollutants under the Stockholm Convention (Stockholm Convention Secretariat, 2001). In their studies on open burning of eight different types of wastes including electrical cables and tyres, Ikeguchi and Tanaka (1999) identified that PVC-based agricultural plastic waste had the highest releases of PCDD/Fs, at 6 554.1 ng (TEQ) per kilogram of waste.

Fires on dumpsites are also a source of atmospheric contaminants including PCDD/Fs (Rim-Rukeh, 2014; Weber *et al.*, 2018). Where agricultural plastics are disposed of at dumpsites, they provide a ready energy source to exacerbate fires.

There are no specific global data on the proportion of agricultural plastic waste that is openly burned or dumped. However in their global review of solid waste management, Kaza *et al.*, (2018) assessed national disposal practices by income level. Open dumping was widely practised, at a rate of 93 percent of solid waste from low-income countries, 66 percent for lower-middle income countries and 30 percent for upper-middle income countries.

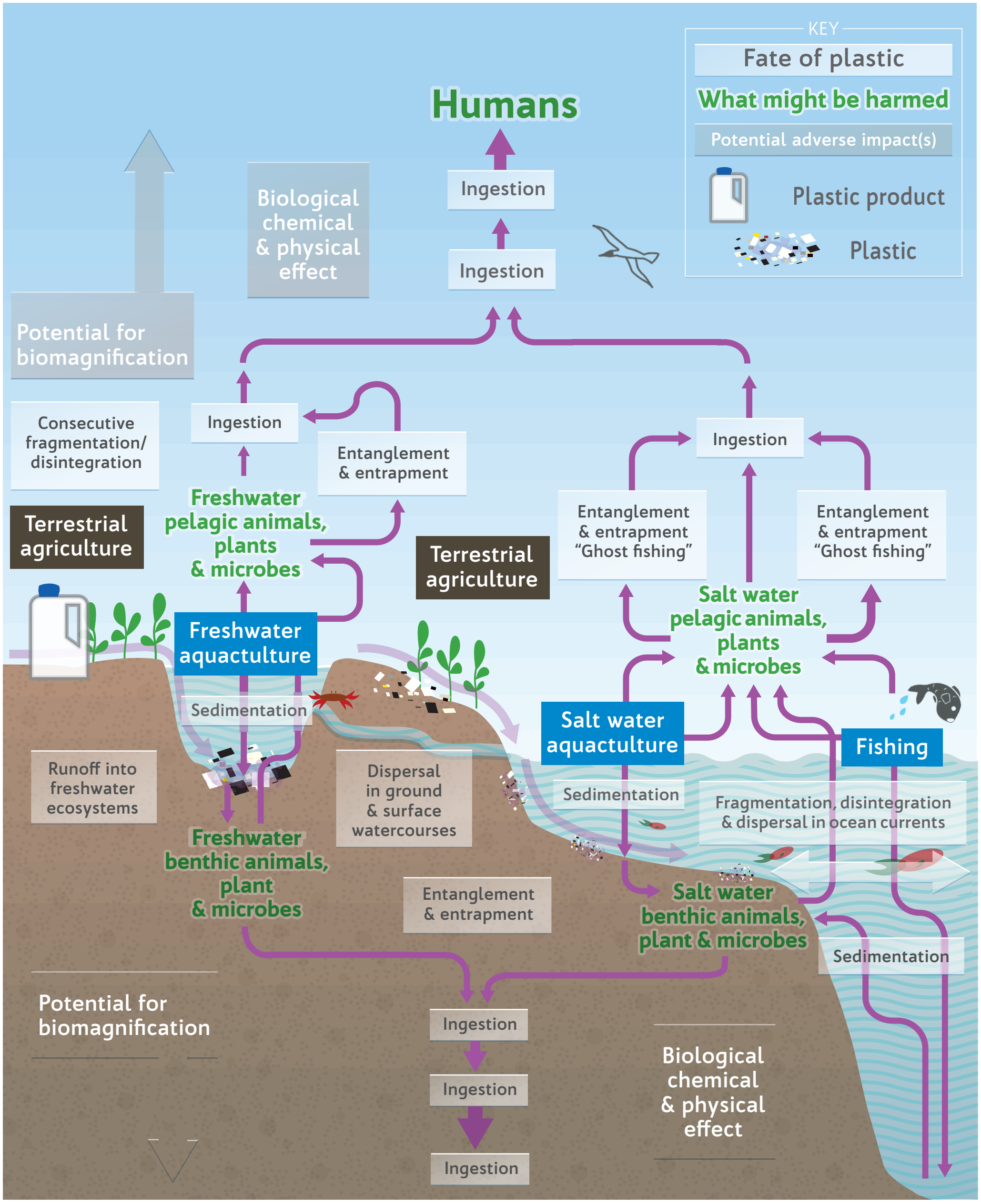
Data were available for the province of Saskatchewan in Canada, where Friesen (2014) identified that 79 percent of used silage wrap and 85 percent of used twines were burned on farms.

Microplastics are also dispersed through atmospheric pathways, mostly from secondary re-emission sources. A recent study estimated that of all microplastics released into the atmosphere, five percent originated from agricultural soils (Brahney *et al.*, 2021).

4.4.3 Aquatic environments

The dispersal of plastics in aquatic environments is complex due to the connectivity of fresh and saltwater courses, the flow of ocean currents, and their interface with land-based sources (Figure 20). Microplastics have been detected in all aquatic environments, from surface waters to oceanic sediments at depths of up to 3 km (Barrett *et al.*, 2020).

Figure 20: Schematic representation of the flow of plastics in aquatic environments



Source: FAO, 2021.

The primary source of agricultural plastics in these environments stems from discarded nets, floats and lines from aquaculture structures and fishing vessels; however, significant input from land-based sources is known to occur, primarily as a result of inadequate waste containment and disposal (Li, Tse and Fok, 2016). The proximity of land-based agricultural activities using plastics to aquatic environments is also a factor, as demonstrated by elevated levels of microplastics in the seas around Almeria, Spain (Dahl *et al.*, 2021).

Notably, ingestion of microplastics by zooplankton is thought to affect the density of excreted faeces, which reduces its rate of sedimentation, hence affecting cycling of nutrients and carbon in deep oceans (Shen *et al.*, 2020).

Overall, it is estimated that, annually, between 300 000 and 3.8 million tonnes enter the world's oceans from fisheries according to a comparison by Eunomia between various investigations (Sherrington *et al.*, 2016). There are between 640 000 and 1.5 million tonnes of ALDFG (FAO, 2018), accounting for up to 50 percent of the total plastic load from fisheries.

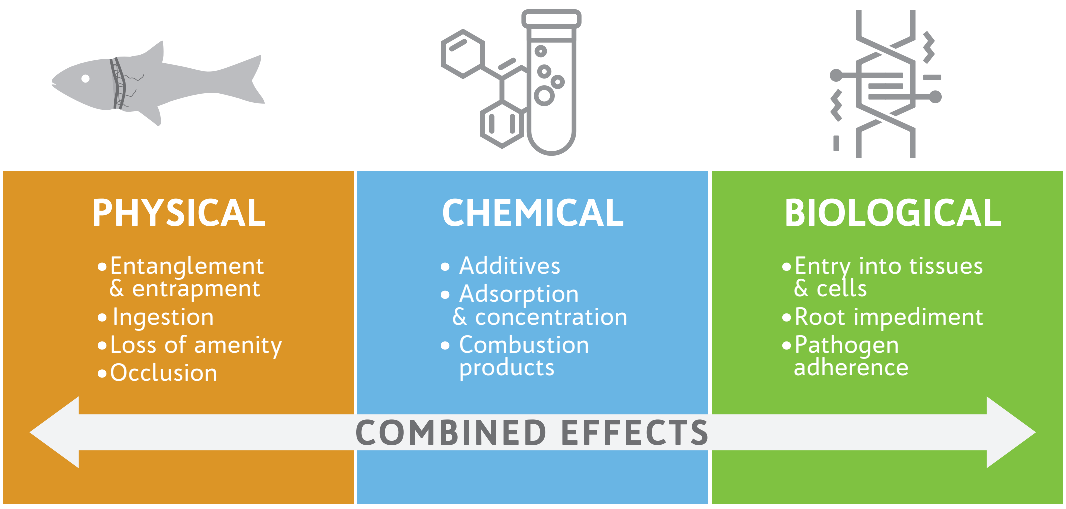
4.5 Consequences

The harm plastic may cause to both biota and ecosystems is often a function of its size, due to the way it specifically interacts with different organisms. For example, larger items of plastic may cause physical harm through ingestion or entanglement, whilst smaller fragments may enter tissues and cells where they exert their effects at the cellular level. Although there is no formal classification scheme for plastic fragments of different sizes, commonly used size ranges are shown in Box 3.

Plastics can cause harm in three main ways: through physical, chemical, and/or biological effects, as summarized in Figure 21, although there is overlap between the different categories.

Most scientific research to date has centred on the marine environment, as this is where the adverse impacts of plastic pollution have been most keenly observed. It is currently the focus of intensive investigation, although there are comparatively fewer published research papers of their effects in terrestrial ecosystems (de Souza Machado *et al.*, 2018). The main impacts plastics have been shown to exert on biota and ecosystems are summarized below; although they necessarily draw principally on research conducted in aquatic environments due to this current research bias.

Figure 21: Types of harm caused by plastics



Source: FAO, 2021.

4.5.1 Physical impacts

Plastics have been shown to harm animals, plants and soil in the following ways:

Entanglement and entrapment

Plastic nets, ropes, bags and cages have all been shown to ensnare or impede the movement of animals in aquatic (Ryberg, Hauschild, Michael and Laurent, 2018) and terrestrial (Kolenda *et al.*, 2021) environments; an effect that not only harms the individual but may also have wider ecosystem impacts (McHardy, 2019; Woods, Rødder and Verones, 2019). In water, the drifting of discarded nets, pots, and traps has been termed 'ghost fishing' due to the ability of these items to continue to trap animals, leading to their unintended death (Lively and Good, 2019)

Ingestion and inhalation

Most animals are potentially exposed to plastics through ingestion, either directly (e.g. through grazing or filter feeding), or indirectly by consuming contaminated animals; thus transferring and accumulating ingested plastics up the food chain (Huerta Lwanga *et al.*, 2017). The evidence base for exposure through inhalation is not as well documented; however, it is still thought that inhaled micro- and nanoplastics may cause respiratory and cardiovascular diseases (Prata, 2018).

The harm caused by ingested plastics is generally a function of their size which means they exert their effects in different ways:

Macro and meso plastics

These have potential to be co-ingested when attached to an animal's food, ingested by mistake when the plastic resembles a predator's prey (Machovsky-Capuska *et al.*, 2019), or through scavenging (Andrades *et al.*, 2019). In oceanic ecosystems, evidence suggests that different taxa of mega fauna ingest different types and colours of plastic that look and behave in a similar way to their normal prey (López Martínez *et al.*, 2021). Overall, it is thought that the size of the animal is directly proportional to the size of ingested plastic, in an approximate 20:1 ratio (Jâms *et al.*, 2020).

Ingested meso and macroplastics may accumulate in an animal's gastrointestinal tract, where they can result in blockage or perforation leading to starvation and death; or cause sublethal effects, such as altered growth or reduced body condition (Puskic, Lavers and Bond, 2020).

Microplastics

Plastics less than 5 mm in size are generally referred to as microplastics (see Box 3). Their small size makes them highly mobile within the environment in general, and aquatic environments in particular.

The uptake of microplastic particles has been observed in a wide range of aquatic and terrestrial animals (GESAMP, 2015; Truong and beiPing, 2019), in plants, including vegetables (Oliveri Conti *et al.*, 2020) and in drinking water (Koelmans *et al.*, 2019). Ingestion of microplastics by earthworms has been shown to increase movement of these fragments within soil (Rillig, Ziersch and Hempel, 2017).

With regard to humans, a study of diets in the United States of America has estimated that an adult ingests between 40 000 to 50 000 microplastic particles a year due to consuming contaminated food (Cox *et al.*, 2019). Small fish, such as sardines that are eaten whole, and shellfish are considered to be a major route of human exposure to marine microplastics (Landrigan *et al.*, 2020).

Although the physical harm microplastics may cause individual organisms is currently uncertain, it has been suggested that they are able to elicit inflammatory responses, and damage cells and tissues (Landrigan *et al.*, 2020). The recent detection of microplastic particles in human placentas (Ragusa *et al.*, 2021) and evidence of mother-to-foetus transmission of nano-polystyrene particles in rats following acute lung exposure during late-stage pregnancy (Fournier *et al.*, 2020) is therefore a major concern.

Occlusion

Mega and macroplastics, and films in particular, have the ability to block out sunlight and also impede the flow of fluids. In terrestrial environments, it has been suggested that plastics may impede the movement of essential elements in soil such as air, moisture, and nutrients and the mobility of soil organisms including earthworms (Liu, He and Yan, 2014). Additionally, microplastics have been shown to affect soil properties, including density, aggregation and water availability (de Souza Machado *et al.*, 2019).

In aquatic environments, it is thought that they may prevent the transmission of light into the water column thereby affecting photosynthesis by free floating phytoplankton and those in corals (Landrigan *et al.,* 2020; Shen *et al.,*, 2020).

Loss of amenity

Despite a great deal of talk in the popular press about the visual impacts of marine plastics on coastal communities, there is relatively little published research aimed at quantifying this (Corraini *et al.,* 2018). In addition, it is also not reflected in economic impact assessments, especially in developing countries. Notwithstanding, a study in southern California suggested that a 25 percent reduction in marine debris at selected beaches resulted in a seasonal benefit of USD 12.91 per capita (Leggett *et al.,* 2018). Overall, it has been estimated that marine plastic pollution could cost the global economy in the region of USD 2.5 trillion annually (WWF, Ellen MacArthur Foundation, and Boston Consulting Group, 2020).

4.5.2 Chemical impacts

Chemicals associated with plastic waste stem from two main sources: those adsorbed from the environment (in particular, aquatic environments), and those introduced into plastic products during their manufacture. The former include POPs and some metals, whilst the latter include a range of compounds, such as phthalates and brominated flame retardants (Andrady, 2011; GESAMP, 2015a; Harding, 2016; Horton *et al.,* 2017). Most, if not all, are deemed to be toxic to varying degrees in humans and animals (Ashraf, 2017; Okunola A *et al.,* 2019; Wiesinger, Wang and Hellweg, 2021).

Due to their high surface area to volume ratios and hydrophobic nature, microplastics have the ability to adsorb these chemicals and concentrate them (Andrady, 2011), especially if they have become enveloped in a biofilm.[5] When ingested, there is potential for biomagnification up trophic levels; although the extent to which these substances become bioavailable and are released systemically within individual organisms, and the harm they may cause, is likely to depend upon a range of factors (GESAMP, 2015a). The sorption of chemicals onto plastic debris potentially affect their transport to other environments and may reduce chemical degradation (Beriot *et al.,* 2020).
The chemical effects of plastics in soil is less well documented; however, Liu, He and Yan (2014) have suggested that agricultural mulch film residues left in soil may increase topsoil salt concentrations.

4.5.3 Biological impacts

Plastics, particularly micro- and nanoplastics, can harm organisms across the spectrum of animal, plant and microbial kingdoms, through a combination of chemical and physical effects; both of which have potential to elicit biological responses in organisms.

Harm to animals

Unlike mega and macroplastics, which are likely to kill animals relatively quickly through entanglement and engulfment, microplastics are more likely to exert chronic, sublethal effects on animals. This affects not only individual organisms, but may also affect shoals in aquatic environments, and groups/flocks on land.

There is evidence that nanoplastics may cross cell membranes, where there is potential to accumulate and impair cellular physiology and evoke inflammatory responses (GESAMP, 2015a; Landrigan *et al.,* 2020).

Harm to plants

Both higher and lower plants may be adversely affected by plastics. As higher plants include almost all of the commercially important crops used as food by humans, this has potentially significant implications for agricultural productivity and global food security.

Higher plants

There is evidence that residues of agricultural mulch films can reduce seed germination and impair root growth. In China, Liu, He and Yan (2014) cited research in which cotton production was reduced by 15 percent when mulch fragments of around 200 kg ha-1 were present in the top 20 cm of soil. Similarly, high levels of plastics (>240 kg ha-1) were shown to impair yields of a range of crops between 11 percent to 25 percent (Gao *et al.,* 2019).

[5] In this context, the term biofilm refers to a collection of microorganisms and associated extracellular polymer(s) on the surface of an object. It does not refer to a bio-based plastic film, or any other plastic product.

In a series of experiments assessing the effects of a range of different microplastics on the growth of spring onions, de Souza Machado *et al.*, (2019) noted that both the roots and leaves were adversely affected, as well as soil properties and soil microbial activity.

Lower plants

Most research has been carried out on phytoplankton in seas and oceans. In a review article, Shen *et al.*, (2020) summarized research suggesting that phytoplankton may be susceptible to the toxic effects of microplastics, with toxicity increasing as particle size decreases. Notably, they also cited research suggesting that photosynthetic activity could be impaired by microplastics (either by reducing sunlight penetration in the water column, or by affecting phytoplankton metabolism). This has potential to not only affect carbon cycling in the oceans, but also the basis of almost all oceanic food chains.

Effect on microorganims

The effect of plastics on microbial communities is better researched in soil rather than aquatic environments, whilst their impact appears to be dependent upon the type of plastic and its size (de Souza Machado *et al.,* 2019).

Overall, experimental data suggest that microplastics can affect both the composition, biomass, and metabolism of soil microbes (Awet *et al.,* 2018; de Souza Machado *et al.,* 2019; Wang *et al.,* 2019) and potentially affect the evolution of soil microbes by placing new selective pressures on communities (Rillig *et al.,* 2019).

The implications of this are somewhat uncertain, although as soil microbes are principally involved in nutrient recycling and organic matter degradation and sequestration, it has potential to affect soil productivity.

Vectors for pathogenic microorganisms

There is evidence that oceanic plastics, especially microplastics, may harbour colonies of pathogenic microorganisms on their surface, including those that confer antimicrobial resistance. This not only has implications for animals that may ingest them, but also has ecological implications due to potential transport across wide areas on oceanic currents (Bowley *et al.,* 2021).

4.6 Summary

Agricultural plastics can enter the environment through either being damaged, degraded, or discarded. These plastics comprise a mixture of flexible, semi-flexible, and rigid products, each having the potential to cause different types of environmental harm.

The amount of plastic from agricultural sources that leak into the environment is largely unknown; however, what is becoming clear is the extent to which plastics, in general, can exert adverse effects on both ecosystems and individuals. As conventional plastics are generally resistant to biodegradation, they can persist in the environment for long periods of time and continue to cause harm long after they have reached the end of their useful lives.

Terrestrial environments, and in particular soils, are the main initial receptors for plastics used in agricultural production, whilst aquatic environments are impacted by ALDFG and other plastic waste from fishing activities. The extent to which terrestrial agricultural plastics enter aquatic environments is currently unclear.

Once in the environment, plastics can cause harm through physical effects (such as entanglement or entrapment); chemical effects (such as the release of additives or combustion products); and biological effects (such as root impediment or tissue/cellular damage). The type and severity of harm caused by plastics is generally a function of their size, with particles smaller than 5 mm – so-called microplastics – currently receiving considerable attention.

6. Assessment of agricultural plastic products

This chapter describes eight representative agricultural value chains and the range of plastic products associated with each of them. They are as follows:

- **Greenhouse horticulture** – this was chosen as it provides food for a large proportion of the human population. It includes an analysis of greenhouses, mulching films and drip irrigation, and subsequent distribution of vegetables to consumers.

- **Livestock production** of food and non-food products from both live and slaughtered animals – this was chosen as it also covers both livestock and fodder production. It includes using hay and silage bales as animal fodder, the various stages in animal husbandry and subsequent processing and distribution of their products.

- **Maize cultivation** – this was chosen as it is a global crop used for human consumption, animal feed, and as a source of renewable of energy. It includes production, distribution, processing, retail, and consumption.

- **Banana cultivation** – this was chosen as an example of a large tropical commodity that uses significant amounts of plastics, especially during growth and harvest. It includes production, processing, and transport.

- **Cotton and wood production** – these were chosen as examples of non-food products. They include production, processing, and transport.

- **Capture fisheries and aquaculture** – this includes fishing gear and aquaculture structures, in the marine and freshwater environments and the subsequent processing, distribution, retail, and consumption of fish and seafood.

The detailed representations of the phases of each value chain, the plastic products that are used, and the wastes they generate can be found in Annex 1.

The variety of plastic products used in the different value chains were identified through a combination of Internet searches, review of scientific papers and reports, plus a series of stakeholder dialogues with FAO and industry sector experts. Due to the complexity and size of many of the value chains, it was not possible to identify all plastic products involved, especially after the products had left the farm/fishery/forest. Therefore, the majority of the analyses have been restricted to products used during the production and distribution phases of the value chains.

The selection of products for assessment was made on the basis of either the level of potential risks that they posed, or to provide representative examples of single-use and durable products from across the value chains.

5.1 Selection of priority plastic products

The range of different plastic products identified for each of the eight value chains was subjected to a qualitative risk assessment using a Red-Amber-Green (RAG) rating approach. Each product was assessed in terms of the following criteria using the SPRC model described in Section 4.1:

- how much of the product is used annually;
- the potential for leakage into the environment at the site of use by applying the 3D concept defined in Section 4.3;
- the ecosystem(s) into which the plastic may leak, such as soil or water courses; and
- the potential harm it may cause to plants, animals (livestock, domestic and wild) and to humans. This also included an assessment of the product's ability to form microplastics.

Each step was RAG-rated assuming that there would be inappropriate collection and treatment/recycling/disposal at the end of its useful life. This was carried out to identify products associated with a 'worst-case scenario' and to select priority products for further evaluation.

For each step, the following rating was used:

- **red** = high risk/amount and was assigned a number 3;
- **amber** = medium risk/amount and was assigned a number 2; and
- **green** = low risk/amount and was assigned a number 1.

For each SPRC category, the numbers were summed and normalized for each plastic product. Finally, an overall score was obtained and normalized, allowing a relative risk rating to be derived for comparative purposes. The results are shown in Table 5 and the calculated relative risk associated with each of the main products are shown in the last row of the table.

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Table 5: RAG rating of identified agricultural plastic products

Agricultural activity or phase	Propagation		Cultivation											Feed production			Animal care		Fisheries and aquaculture			
DECISION-MAKING CRITERIA	Greenhouse films	Pesticide containers	Mulching films	Fertilizer containers – bags and rigid	Plant pots, seedling plugs	Tree guards	Plastic bags (bananas)	Plastic ties, ropes, twines	Polymer coated slow release fertilizer	Crates for harvesting	Irrigation tubes and drips (semi-permanent)	Irrigation drip tape (single-use, on-soil applications)	Pond liners	Silage films	Bale films and nets	Bale twine	Ear tags	Bags for feed	Fishing nets and ropes	Net float	Cages	EPS boxes
SOURCE (what are the products and how they are used)																						
Extent of usage - how much is used	3	3	3	3	3	1	3	1	3	1	2	3	1	2	3	1	2	2	3	3	3	2
Turnover factor (number of applications/year)	0,3	5,0	2,0	2,0	3,0	0,3	1,3	3,0	4	1	0,5	2	0,3	0,5	2	2,2	1,2	3,4	0,4	0,4	0,4	6
Normalized SUM	1,65	4,00	2,50	2,50	3,00	0,65	2,15	2,00	3,50	1,00	1,25	2,50	0,65	1,25	2,50	1,60	1,60	2,70	1,70	1,70	1,70	4,00
PATHWAY (how it enters the environment – 3Ds)																						
Potential for leakage into the environment at site of use:																						
Damaged	2	1	3	1	2	3	3	3	3	1	2	3	2	2	3	3	2	1	3	3	3	2
Degraded	1	2	3	2	2	2	3	3	3	1	1	3	1	2	3	3	2	2	3	3	3	2
Discarded	1	2	3	2	2	1	2	2	3	1	2	3	3	2	3	3	1	2	3	3	3	1
Potential for leakage from site of use/application (diffusion into wider environment)	3	1	2	1	1	2	2	1	3	1	1	2	1	1	2	1	1	1	3	3	3	2
Normalized SUM	1,75	1,50	2,75	1,50	1,75	2,00	2,50	2,25	3,00	1,00	1,50	2,75	1,75	1,75	2,75	2,50	1,50	1,50	3,00	3,00	3,00	1,75
RECEPTOR (primarily where it ends up)																						
Extent of direct contact with terrestrial environments	1	2	3	2	2	3	2	2	3	1	3	3	3	2	2	2	1	2	1	1	1	1
Extent of direct contact with aquatic environments	1	2	1	2	1	1	1	1	2	1	1	1	3	1	1	1	1	1	3	3	3	2
Normalized SUM	1,00	2,00	2,00	2,00	1,50	2,00	1,50	1,50	2,50	1,00	2,00	2,00	3,00	1,50	1,50	1,50	1,00	1,50	2,00	2,00	2,00	1,50
CONSEQUENCE (harm it causes once it has reached the receptor)																						
Potential to harm plants (crops & loss of productivity)	3	1	3	2	1	1	3	1	1	1	1	1	1	3	3	1	1	2	1	1	1	1
Potential to harm animals (livestock, domestic & wild)	3	3	3	2	2	2	3	3	1	1	1	2	1	3	3	3	1	2	3	2	3	2
Potential to harm humans	1	3	1	1	1	1	2	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1
Potential to form microplastics	2	1	3	2	2	3	2	2	3	1	1	1	1	2	3	2	1	2	3	3	3	3
Normalized SUM	2,25	2,00	2,50	1,75	1,50	1,75	2,50	1,75	1,50	1,00	1,00	1,50	1,00	2,25	2,50	1,75	1,00	1,75	2,00	1,75	2,00	1,75
RISK TOTAL – Normalized	6,7	9,5	9,8	7,8	7,8	6,4	8,7	7,5	10,5	4,0	5,8	8,8	6,4	6,8	9,3	7,4	5,1	7,5	8,7	8,5	8,7	9,0

Source: FAO, 2021.

The selected higher risk products and representative examples are shown in Table 6 below:

Table 6: Priority and representative products selected for assessment

Product	Priority/ Representative	Relative risk score	Value chain	Durability
Polymer coated slow release fertilizer	Priority	10,5	Food crop Non-food crop	Single-use
Mulching films	Priority	9,8	Food crops Non-food crops	Single-use
Pesticide containers	Priority	9,5	Food crops; Non-food crops Livestock; Fisheries; Forestry	Single-use
Bale films and nets	Priority	9,3	Non-food crops	Single-use
EPS boxes	Priority	9,0	Fisheries	Single-use
Irrigation drip tape (single-use, on-soil applications)	Priority	8,8	Food crops Non-food crops	Single-use
Fishing nets and ropes	Priority	8,7	Fisheries	Durable
Cages	Priority	8,7	Fisheries	Durable
Plastic bags (bananas)	Priority	8,7	Food crop	Single-use
Net float	Priority	8,5	Fisheries	Durable
Fertilizer containers – bags and rigid	Representative	7,8	Food crops Non-food crops	Single-use
Plant pots, seedling plugs	Representative	7,8	Food crops Non-food crops	Single-use
Plastic ties, ropes, twines	Representative	7,5	Livestock, fisheries	Single-use
Bags for feed	Representative	7,5	Food crops Non-food crops; Forestry	Single-use
Bale twine	Representative	7,4	Food crops Non-food crops	Single-use
Silage clamp films	Representative	6,8	Food crops Non-food crops	Durable
Greenhouse films	Representative	6,7	Food crops Non-food crops	Durable
Tree guards	Representative	6,4	Food crops; Non-food crops Forestry	Durable
Pond liners	Representative	6,4	Food crops Non-food crops	Durable
Irrigation tubes and drips (semi-permanent)	Representative	5,8	Food crops Non-food crops	Durable
Ear tags	Representative	5,1	Livestock	Durable
Crates for harvesting	Representative	4,0	Food crops Non-food crops	Durable

Source: FAO, 2021.

5.2 Detailed analysis of selected products

The selected products were reviewed in detail with regard to the following criteria:

- their anticipated agricultural benefits and disbenefits;
- factors that contribute to their leakage into the environment; and
- their potential for circularity.

The latter aimed to identify potential interventions that could drive innovation and adoption of alternative practices or products that would provide the benefits of the original plastic products but with improved sustainability and reduced environmental impact. The 6R (refuse, redesign, reduce, reuse, recycle and recover) framework, which is detailed in Box 6, was used to help identify alternatives. As many of the products have interventions or alternatives in common, these are addressed in detail in Chapters 6 and 7.

BOX 6: THE 6R APPROACH

The 6R criteria are hierarchical options that can be applied to the design, manufacture, supply, mode of use, and end-of-life management of products in order to move from a linear to a circular economy. The definitions of the 6Rs are based on definitions of the European Union related to waste management (European Parliament and the Council, 2008) on the strategies embedded into the circular economy concept of the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2021) and on the so-called Zero Waste approach towards waste production and recycling (ZeroWasteEurope, 2019). In cases where the 6R concept cannot be applied, then disposal in a sanitary, engineered landfill site should be considered as the next most sustainable option. Open burning should be avoided due to its potential for generation of GHGs, POPs and other harmful emissions.

REFUSE	**DEFINITION:** Intentionally avoiding use of the product. **EXAMPLE:** Not using labels and stickers on single fruit items that are packaged in a larger retail box.
REDESIGN	**DEFINITION:** Modifying a product in order to enhance its retrieval and waste management options; the redesign is intended to maintain/enhance the current agricultural benefit and/or health and safety performance the product. **EXAMPLE:** Using thicker gauge mulch films to enhance retrieval from the field following use.
REDUCE	**DEFINITION:** Minimising the quantity of plastic products used to deliver the same benefit, resulting in reduced need for raw materials, less plastic waste produced per batch of product and fewer amounts of plastic waste that need to be collected for recycling or disposal. **EXAMPLE:** Adopting a stronger polymer for twines, allows a thinner cross-section.
REUSE	**DEFINITION:** Intentionally switching from using single-use plastics to more durable items that can be reused a number of times along the value chain, thus reducing the quantities of plastics used. **EXAMPLE:** Adopting reusable, reconditionable insulated boxes for transporting fish.
RECYCLE	**DEFINITION:** Reprocessing plastic waste into new materials or products of the same or lower quality. **EXAMPLE:** Recycling broken plastic crates or used containers into secondary materials such as plastic pellets.
RECOVER	**DEFINITION:** Extracting energy from plastics; it should only be carried out if the previous 5Rs cannot be applied for technical or economic constraints and life assessments indicate it is more sustainable than landfilling. **EXAMPLE:** For mixed plastic residues, such as thin films contaminated with organic residues, soil and chemical products.

5.2.1 Polymer coated fertilizers

Polymer coated fertilizers are produced as tablets or granules and coated with a polymer that results in the slow or controlled release of their plant nutrients. The coating may be a conventional plastic polymer (PE, EVA and LDPE), a natural material (e.g. cellulose) or a biodegradable plastic (polylactic acid, starch–polyvinyl alcohol and others) (Sarkar *et al.*, 2019).

Benefits and issues

Polymer coated fertilizers provide significant benefits for crop production, including controlling the rate of release of nutrients to optimize their availability for plant uptake, thereby lowering the risk of nutrient runoff to soil and water courses.

The fragmentation of conventional plastic polymers may lead to the production of microplastics that accumulate in soil and runoff by rain and irrigation. The kinetics of degradation of microplastic coating fragments in soil was found to be highly variable (Accinelli *et al.*, 2019).

The intentional releases of microplastics from polymer coated fertilizers and fertilizer additives was estimated at 22 500 tonnes/year, equivalent to 62 percent of all intentionally released microplastics in the European environment (European Chemicals Agency, 2019). Intentionally released microplastics from coated seeds and coated pesticide formulations were each estimated at 500 tonnes/year.

Alternatives and Interventions

One intervention and one alternative have been identified below and in Figure 23 and assessed in terms of delivering similar benefits to crops, whilst also reducing the adverse impacts of fertilizers covered with conventional plastic polymers:

- Banning the use of conventional (non-biodegradable) polymers in coatings would avoid the leakage of microplastics into soil; and
- Substituting with biodegradable coatings, which are designed to fully degrade in soil according to specific technical standards, would avoid the accumulation of plastic fragments in soil.

The 6Rs approach was used to identify and categorize these options.

Figure 22: Alternatives for polymer coated fertilizers

Alternatives and interventions		Biodegradable coatings	Ban
6R options	Refuse		●
	Redesign	●	
	Reduce		
	Reuse		
	Recycle		
	Recover		
3D consequence	Damaged		
	Degraded	Reduces harm (intentional microplastics) in soil	Reduces harm (intentional microplastics) in soil
	Discarded		

Source: FAO, 2021.

Legislative measures to drive sustainability

In order to restrict the release of microplastics from polymer coated fertilizers, some countries have started to implement additional legislative measures. For example, the European Union's Fertilising Products Regulation 2019/1009 (European Union, 2019c) includes a restriction on the marketing for PCF to only those with polymers that comply with the European Union's biodegradability criteria (Fertilizers Europe, 2020a). These restrictions should enter into force in 2026 in all European Union Member States.

5.2.2 Mulch films

Conventional, non-biodegradable plastic mulching films are produced with LDPE or other flexible polymers. Increasingly, agriculture has relied on synthetic mulching films rather than the traditional organic based materials such as crop residues.

Benefits and issues

The benefits of mulching films in crop production have been widely cited and include suppression of weed growth, increased soil temperatures, reduced evaporation from soil, and reduced runoff of nutrients due to excessive rainfall. These factors increase crop yields, lengthen the growing season, and reduce the requirement for irrigation, and fertilizer and herbicide applications.

However, mulching films – if incorrectly specified, applied, managed, and removed from fields – can leave large quantities of plastics in the soil.

The main factors that influence the leakage of plastics to the soil are: the capacity and motivation of farmers and the specification of the film, primarily its thickness. The latter determines its structural integrity throughout its use and its retrievability after harvest. Damage during use and/or incorrect retrieval contribute to fragmentation of the film or contamination of the plastic with high amounts of soil and plant residues, making logistics and recycling processes difficult and uneconomic. In Europe, the typical ratio of contaminants (moisture, soil and plant residues) to plastic in used mulching films is 2:1 (Le Moine *et al.*, 2021). At such levels of soilage, recycling is uneconomic and as such used mulching films are usually disposed of at a sanitary landfill.

Plastic mulch is also used on some permanent planting such as orchards and vineyards. In such cases it is often difficult to retrieve mulch that has been in place over many seasons, due to physical damage and photodegradation.

Sarkar *et al.*, (2019) report that, after polyethylene, PVC is the second most common material used for the manufacture of mulch films. Its use, however, is not reported in Europe (Hann *et al.*, 2021). In the event that used PVC films are burned on farms or at dump sites, they would be a significant source of polychlorinated dibenzo para dioxins and polychlorinated dibenzofurans (PCDD/Fs), both of which are listed under the Stockholm Convention as persistent organic pollutants. In their studies on the open burning of eight types of wastes, Ikeguchi and Tanaka (1999) found that the highest dioxin emissions were from agricultural plastics (PVC) at 6 554.1 ng TEQ/kg of waste.

Alternatives and interventions

A number of interventions and alternatives have been identified and assessed in terms of delivering similar benefits but reducing the adverse impacts of non-biodegradable mulching films:

- Adopting mulching practices using organic materials or cover crops avoids the use of plastics. Although these practices may seem to be more costly, savings in inputs, the long-term improvement of the soil, maintenance of yields and access to premium markets could drive change in farming practices. In addition to the avoidance of GHGs associated with plastics, there is an additional climate benefit in the incorporation of biomass in the soil that captures carbon. Examples and guidance on cover crops and conservation agriculture are available at the Consultative Group on International Agricultural Research (CGIAR) and the Rodale Institute websites.

- Redesigning products by changing to a biodegradable film – for using paper based materials or biodegradable polymers – would avoid the need for retrieval and end-of-life management. It is claimed that biodegradable films are capable of being incorporated into the soil post-harvest. However, the biodegradation of such plastic in different soils and climatic conditions is highly variable. The long-term impact on soils of the use of biodegradable mulch films also needs to be assessed. This is discussed further in Section 6.4.3 on standards.

- Banning the use of PVC in mulching films (and other single-use agricultural plastic products) would reduce the potential for releases of PCDD/Fs in the event that used films are openly burned.

- Increasing film strength and tear-resistance to improve retrievability from the soil post-harvest. This could be achieved by increasing its thickness and ensuring planting holes are smoothly cut. This is also discussed in Section 6.4.3 on standards.

- For some crops, reusable mulching films, that can be used over many growing seasons, may be suitable. For example, this is the case for the soil covers of "white" asparagus that is harvested while the "spear" is still underground.

Figure 23: Alternatives for mulch films

Alternatives and interventions		Promote conventional, organic mulch techniques	Biodegradable film	Ban PVC films	Increase film strength and tear-resistance to improve retrievability
6R options	Refuse	•		•	
	Redesign		•		•
	Reduce				
	Reuse				
	Recycle				
	Recover				
3D consequence	Damaged	Prevents harm in soil	Reduces harm in soil		Reduces likelihood of damage
	Degraded	Reduces harm in soil	Reduces harm in soil		Reduces likelihood of degradation
	Discarded	Prevents harm in soil	Reduces harm in soil	Reduces risks from open burning used films	

Source: FAO, 2021.

- Product labelling can provide usage information to farmers and be a potential mechanism to provide traceability through the plastics and waste management supply chain.
- Mandatory EPR collection schemes reduce the barriers for all actors in the supply chain to adopt sound environmental management of used films.
- Incentives and cross-compliance can encourage environmentally responsible behaviour, minimizing leakage into the soil and improving recycling rates.
- Redesigning equipment to retrieve used films can reduce the level of plastic that remains in the soil and improves its recyclability by minimizing soil and plant residue contamination. The use of such equipment could be provided as a service.
- Redesigned business models, such as moving from product supply to a full professional service of supply, application, maintenance, retrieval, and end-of-life management could improve the effectiveness of mulching while reducing plastic leakage and improved recyclability.

These interventions and alternatives are summarized in Figure 23.

Policy and legislative measures to drive sustainability

The Circular Plastics Alliance working group on agricultural plastics identified the following policy and legislative options for improving the sustainability of non-biodegradable mulching films (Eunomia, 2020):

- voluntary or mandatory EPR;
- requirements for participation in collection schemes;
- ban on open burning of plastic waste and heightened enforcement measures;
- setting a minimum thickness for non-biodegradable mulch films; and
- ensuring sufficient incentives for farmers to retrieve all plastic from fields and minimize contamination of retrieved films.

Figure 23 ***(continued)***

Reusable mulch films for appropriate crops	Product labelling	Mandatory EPR scheme	Incentives linked to sustainable mulch management practices	Equipment redesigned to improve retrieval	Mulching service business model
•	•		•	•	•
•					
		•	•	•	•

			Reduces likelihood of damage	Reduces likelihood of damage	Reduces likelihood of damage
			Reduces likelihood of degradation		Reduces likelihood of degradation
Reduce the amounts to be disposed of at end of life	Reduces likelihood of littering and improper disposal	Reduces likelihood of littering and improper disposal	Reduces likelihood of littering and improper disposal	Reduces likelihood of littering	Reduces likelihood of littering and improper disposal

Mulch films damaged during mechanical removal of crop residues, Italy.

Mulch films, once removed from fields, are often heavily contaminated with soil and plant residues, inhibiting their recyclability.

5.2.3 Irrigation drip tape

Irrigation drip tape is a thin plastic tube with dripping apertures inserted along its length during manufacture. It is often laid directly on the soil close to the row of plants requiring irrigation and is connected to a pressurized water supply at one end and sealed at the other. It is often used in conjunction with mulching films for a single planting season and retrieved post-harvest.

Benefits and issues

Irrigation drip tape improves water use efficiency and can conserve scarce water resources by providing water directly to the plants. The drippers allow the water to penetrate the soil down to the root zone. When used in conjunction with mulching film it can also reduce water evaporation thus significantly improving water use efficiency and reducing irrigation costs (Scarascia-Mugnozza, Sica and Russo, 2011).

As in the case with mulching film, being placed directly on the soil, there are risks that the irrigation tape is damaged during use and retrieval, leaving quantities in the soil. It is reported that some drip tape is manufactured from PVC. Flexible PVC contains various additives including plasticizers that can be toxic and can be released into the environment through wear and weathering. When PVC is openly burned at a dumpsite or on the farm, it produces high levels of PCDD/F emissions (Ikeguchi and Tanaka, 1999). The design of drip tape can include components, for example the drippers and tube walls, made from different polymers. However, this makes its recycling complex and costly.

Retrieved irrigation drip tape, mulch film and non-woven protection textile awaiting collection, Italy.

Figure 24: Alternatives for irrigation drip tape

Alternatives and interventions		Change to a more permanent and robust irrigation system	Increase tape strength and reuse	Increase recyclability by manufacturing from a single polymer
6R options	Refuse			
	Redesign	•	•	•
	Reduce	•		
	Reuse		•	
	Recycle			•
	Recover			
3D consequence	Damaged	Reduces likelihood of damage	Reduces likelihood of damage	
	Degraded	Reduces likelihood of degradation		
	Discarded	Reduces the amounts of waste		Increases value for recycling and reduces likelihood of discarding

Source: FAO, 2021.

Alternatives and interventions

All efficient precision irrigation systems rely on non-biodegradable plastics for their main components. However, there are a number of interventions that could reduce the risk of dispersal of plastic in soils or emissions fromopenburning:

- Moving to another efficient but more permanent irrigation system – such as hydroponics – would avoid the need for drip tape to be placed directly on soils and for its retrieval and disposal at the end of each cropping cycle.
- Increasing the strength of the tape would reduce the risk of damage during use and retrieval and allow it to be reused over multiple planting seasons.
- Redesigning drip tape to improve its recyclability by constructing all its components from the same polymer.
- Banning the use of PVC polymers and substituting with polyethylene would avoid the risk of dioxin emissions if involved in a fire.
- Labelling in conjunction with a traceability and monitoring system would allow for more effective enforcement of good plastic management practices.
- Establishing an EPR scheme that accepts drip tape would improve its collection and circularity and help to avoid inappropriate disposal practices.
- Redesigning application, maintenance and retrieval equipment could assist in limiting damage to the tape and littering of fields. EPR schemes could also help to make such equipment available to farmers.
- Producers and suppliers could change their business model to a full-serviced provision of mulching and irrigation including application, maintenance and retrieval. Such service providers could employ best practice and equipment to optimize the performance of the mulch and irrigation, while minimizing plastic leakage and improving circularity.

Figure 24 ***(continued)***

Ban drip tape made from PVC	Product labelling	Mandatory EPR scheme	Redesign of mulch and drip tape retrieval equipment	Full service by tape producers and providers
•				
	•		•	•
		•		•

			Reduces likelihood of damage	Reduces likelihood of damage
	Timely retrieval reduces degradation			Timely retrieval reduces degradation
Reduces risks from open burning used films	Reduces likelihood of improper disposal	Reduces likelihood of littering and improper disposal	Reduces likelihood of littering and improper disposal	Reduces likelihood of littering and improper disposal

Retrieved irrigation drip tape, mulch film and non-woven protection textile awaiting collection, Italy.

5.2.4 Tree guards and shelters

Tree guards and shelters are semi-rigid tubes that are wrapped around the base of newly planted tree saplings to help them become established, and are generally manufactured from PP. They are secured around saplings by either clips, ties, or cables, which may also be plastic.

Benefits and issues

Tree guards and shelters are used in forestry plantations, vineyards, and orchards. They protect newly planted tree saplings by providing a physical barrier to prevent damage by grazing animals, reducing competition with weeds, and creating a protective microclimate for the sapling.

Even if these products are designed to remain in situ for a number of years, damage during use and photodegradation eventually cause the shelters and guards to fragment into smaller pieces, where they may further degrade into smaller macro- and microplastics and be ingested by ground feeding animals. A life cycle study of planting saplings with and without protection for afforestation in temperate oceanic regions identified that planting without a tree guard was the environmentally preferable option. It also assessed that, at the time with the absence of data on the impacts of the degradation products of fossil-based and biodegradable polymers, polypropylene shelters were preferable to bio-based alternatives (Boucher et al., 2019; Chau et al., 2021).

Alternatives and interventions

A number of alternatives and interventions have been identified and assessed in terms of delivering similar benefits but reducing the adverse impacts of these plastic products. The 6Rs approach (refuse, redesign, reduce, reuse, recycle and recover) was used to identify and categorize the options listed below and in Figure 25:

- Fencing areas with newly planted saplings contributes to reducing or avoiding the need to use tree shelters.
- Redesigning the products by changing the polymer composition and thickness would increase the lifespan or promote reuse.

Figure 25: Alternatives for tree guards and shelters

Alternatives and interventions		Fencing around an area of newly planted saplings	Increase sapling planting density and avoid using tree guards	Change polymer composition and product thickness to allow reuse	Redesign to be biodegradable	EPR schemes for collection and recycling
6R options	Refuse	•	•			
	Redesign			•	•	
	Reduce					
	Reuse			•		
	Recycle					•
	Recover					
3D consequence	Damaged	Avoids risk of damage	Avoids risk of damage	Reduces likelihood of damage		
	Degraded	Avoids risk of degradation	Avoids risk of degradation	Avoids risk of degradation	Avoids risk of inappropriate degradation	
	Discarded	Avoids risk of littering and improper disposal	Avoids risk of littering and improper disposal		Avoids risk of littering and improper disposal	Increased collection reduces harm to soil

Source: FAO, 2021.

- Redesigning the shelters to be fully biodegradable (from paper-based or biodegradable polymers) would contribute to mitigating plastic fragments leaking into soil and avoid the costs and impacts associated with collection and recycling.

- In areas where pressure from grazing animals and rodents is not excessive, increase the sapling planting density and avoid the use of tree guards. This allows for some saplings to perish, but the remainder will grow to maturity. This strategy is being adopted by the Woodland Trust in the United Kingdom (the Woodland Trust, 2021).

- Establishing EPR schemes would improve the availability of collection schemes for used products, thus reducing the discarding and dumping of plastic waste.

Legal measures to drive sustainability

Appropriate EPR legislation by national governments should require manufacturers and distributers of tree guards/shelters to provide a service to their customers for the collection and recycling of the used products. In addition, improved implementation of industry standards – such as the Forest Stewardship Council's international standard – can include requirements for organizations to manage plastic waste correctly, including prescriptions for collection, recycling, and disposal of used products.

Tree guards – biodegradabe paper-based (left) and non-biodegradable plastic (right), Italy.

5.2.5 Ear tags for livestock

Ear tags are plates made of hard plastics (often polyurethane) and may include a radio frequency identification device (RFID) embedded into the plastic tag for storing additional information.

Benefits and issues

Ear tags are used on animals for traceability purposes, allowing unique identification of a single animal, or at least collective identification of an animal belonging to a herd or flock. The traceability of animals is a requirement for food chain accountability, quality assurance, accreditation schemes, and other aspects regarding food products from livestock. For example, regional legislation in the European Union requires conventional and electronic ear tags to be used as official identification systems for cattle, sheep, and goats (European Union, 2019d).

Ear tags can be broken or lost during the animal's lifetime and ingestion of plastic fragments is then possible by ground feeding animals; the abrasion or fragmentation of conventional plastic polymers may lead to the production of microplastics that accumulate in soil and runoff by rain and irrigation.

Ear tags are identifying markers typically made from rigid plastics.

Alternatives and interventions

- Biometric identification using artificial intelligence is beginning to be used in conjunction with ear tags. It is possible that as the technology advances it may replace the use of ear tags, thus avoiding the use of plastics (Farm4Trade, 2020).
- Adopt alternative marking systems such as injectable transponders.
- Plastic ear tags can be collected after slaughter of the animal and sent for recycling.
- An incentive scheme such as a Deposit Return Scheme could encourage farmers to collect broken or lost ear tags from their fields to avoid litter and increase their recycling.

Figure 26: Alternatives for ear tags

Alternatives and interventions		Biometric identification	Alternative marking systems avoiding ear tags	EPR Collection scheme at slaughter houses	Deposit Return Scheme to collect broken or lost ear tags
6R options	Refuse	●	●		
	Redesign		●		
	Reduce				
	Reuse				
	Recycle			●	●
	Recover				

3D consequence	Damaged	Avoids risk of damage	Avoids risk of damage		
	Degraded	Avoids risk of degradation	Avoids risk of degradation		Avoids risk of degradation
	Discarded	Avoids risk of littering and improper disposal	Avoids risk of littering and improper disposal	Reduces risk of littering and improper disposal	Avoids risk of littering and improper disposal

Source: FAO, 2021.

5.2.6 Fishing gear

Fishing gear includes a wide range of plastic products and polymers. Fisheries and aquaculture enterprises use floating plastics (for cages, rafts, and mooring systems), in fibrous form (in ropes and nets), as structural or containment components (in cage collars, buoys, tanks, pipework) and as a film (in pond liners, barrier membranes, and packaging).

Benefits and issues

Without the extensive use of plastics, the modern fishery and aquaculture sectors would not be feasible; durable fishing nets and floating cages allow for significant increases in terms of productivity for the two sectors.

Abandoned, lost, or otherwise discarded fishing gear (ALDFG) may trap marine organisms, interfere with other fishing nets, and may damage outboard motors. It is a threat to food security and responsible for significant volumes of unintended and wasted catch, harming marine resources and sustainability of fisheries. Bottom gears such as bottom trawls, and set gillnets and longlines, are often more at risk of becoming ALDFG compared to midwater or pelagic gears because these gears are more likely to become snagged on obstacles on the seafloor. Passive and/or unattended gear types where fishers have less control over the gears while fishing, such as many types of traps, gillnets and entangling nets, are also more likely to become ALDFG (Gilman *et al.*, 2021; Macfadyen, Huntington and Cappell, 2009). Much of the waste from fishing activities derives from net mending activities carried out at sea or in port. The waste comprises both large sections of damaged net that has been cut out and replaced with a new patch, and shorter off-cuts. Without appropriate management, the pieces can easily be dispersed into the sea (Strietman, 2021). Other causes of ALDFG are illegal, unreported and unregulated fishing, adverse weather and lack of, or costly, disposal facilities.

Plastic polymers will behave differently when in the water; for example, PE, PET and PP fishing gear components will abrade slowly, EPS in floats and buoys will fragment, leading to floating and sinking fragments. Global plastic leakage into the ocean from all maritime sources (not only fisheries) is highly uncertain but is estimated to be between 10 percent and 30 percent of total global macroplastic leakage (Sherrington *et al.*, 2016).

As mentioned in Chapter 3, estimating quantities of ALDFG is challenging and the reliability of historic estimations have recently been questioned (Richardson *et al.*, 2021). This report has estimated annual global quantities of ALDFG at 1.1 million tonnes.

Dolly rope are sacrificial lengths of rope attached to the underside of trawl nets, mostly in bottom fisheries where the net is in contact with the seabed, to protect the main net from abrasion on the rocky or stony seafloor. As the dolly rope is abraded, it disperses microplastic pollution into marine environments. It has to be replaced regularly, with Strietman (2020) estimating that a trawler would use between 325 kg and 3 500 kg of dolly rope per year.

Alternatives and Interventions

A number of alternatives and interventions have been identified and assessed in terms of delivering similar benefits but reducing the adverse impacts of ALDFG (Figure 27). These include:

- Introducing interventions such as gear marking and on-board GPS devices to help identifying gear ownership and location, thus reducing the loss of fishing gear at sea;
- Adopting of improved designs and technologies to expand lifespan and promote the reuse of worn fishing gear and reduce the risk of ghost fishing of lost or abandoned gear. The European Commission has published a study on the circular design of fishing gear to reduce its environmental impacts (AZTI TECNALIA *et al.*, 2020);
- Establishing free of charge collection measures at ports to enable the collection of end-of-life equipment for recycling or disposal; the absence of a fee will help to minimize the barriers for returning unwanted fishing gear and encourage the retrieval of ALDFG at sea;
- Establishing a mandatory EPR scheme for the collection and recycling of unwanted fishing gear; and
- Developing polymers that are biodegradable in marine environments for applications such as dolly rope or for securing escape hatches on fish traps to avoid indefinite ghost gear fishing. The Dsolve project, supported by the Norwegian Government, is working on this issue (UiT The Arctic University of Norway, 2021).

Figure 27: Alternatives for fishing gear

Alternatives and interventions		Gear marking	On-board GPS technology	Adoption of improved designs and technologies of fishing gear	Free of charge collection points for unwanted gear at ports	Mandatory EPR scheme	Biodegradable alternatives for dolly rope and escape panels
6R options	Refuse						
	Redesign			•			•
	Reduce	•	•				
	Reuse			•			
	Recycle				•	•	
	Recover						
3D consequence	Damaged		Avoids damage to gear	Higher standard gear reduces risk of damage			Reduces risk of microplastic pollution.
	Degraded	Encourages timely replacement, avoiding degradation					
	Discarded	Identifies owners, discourages dumping	Identifies owners, discourages dumping		Reduces risk of discarding at sea	Reducess risk of littering and improper disposal	

Source: FAO, 2021.

Policy and legal measures to drive sustainability

There are a number of international guidelines that address sustainability within this sector, such as the UN Resolution A/RES/59/25 on sustainable fisheries and the International Code of Conduct on Responsible Fisheries (FAO, 1995). Principle 6.6 of the International Code states "selective and environmentally safe fishing gear and practices should be further developed and applied, to the extent practicable, in order to maintain biodiversity and to conserve the population structure and aquatic ecosystems and protect fish quality".

At the global level, the main international instrument to address ALDFG is the FAO Voluntary Guidelines on the Marking of Fishing Gear (FAO, 2019a). The marking of fishing gear has been required in specific regions, such as the European Union since 2009 following the Regulation (EC) 1224/2009, and in Eastern Canada (Government of Canada, 2021).

The European Union Single-use Plastic Directive (2019/904 includes fishing gear among the items covered by the legislation (European Commission, 2021). It requires Member States to: 1) Establish EPR schemes for fishing gear containing plastic placed on the market of the Member State (Article 8(8)); 2) Raise awareness of reusable alternatives, reuse systems, and waste management options as well as on the impact on the environment from inappropriate waste disposal (Article 10); and 3) Report to the Commission data on fishing gear containing plastic placed on the market and on waste fishing gear collected in the Member State each year (Article 13).

5.2.7 Insulated fish crates and boxes

Insulated fish crates are often made from EPS which is a solid foam containing approximately 98 percent air. Crates and boxes made of EPS are both lightweight, watertight and have good thermal insulation properties.

Benefits and issues

Insulated crates or boxes are widely used in fisheries and aquaculture for transporting fresh fish produce from catch to transformation and distribution sites up to the final consumers. Besides being food contact safe and guaranteeing good thermal insulation, EPS products are lightweight, thus reducing emissions (and costs) during transport.

Having an extremely low density, expanded polystyrene (EPS) products are easily littered through dispersal by wind. They are not biodegradable but are susceptible to photodegradation; once littered they tend to fragment into small pieces that can be ingested by animals or remain floating in water and in the oceans. Expanded polystyrene foam products are difficult to sanitize after use, since they soften and melt at temperatures above 100 °C, so are difficult to reuse. These products are expensive to collect separately due to their low specific density (or high volume); in addition, mechanical recycling of these products also requires pre-treatment to remove organic residues attached to the plastic.

Expanded polystyrene insulating fish crates.

Re-purposed chemical barrels.

Alternatives and interventions

A few alternatives and interventions (Figure 28) have been identified and assessed in terms of delivering similar benefits but reducing the current limits for reusing or recycling EPS from used fish boxes. The applicability of each of these alternatives will depend on the national or regional context.

- Redesigning fish boxes to improve their reusability requires them to have durable and smooth surfaces that are impervious and resistant to steam and sanitizing chemicals. Ideally, they should also have good thermal insulation properties. Containers meeting these two requirements are available:
  - Boxes with hard and smooth inner and outer surfaces made from PE or PP that "sandwich" an inner core of insulation such as polyurethane foam. Such boxes have excellent properties for sanitization, thermal insulation and durability. However, they are potentially expensive and, being multi material, are complex to recycle at end-of-life.
  - Boxes made from HDPE with an aerated core. The surfaces can be sanitized while the aerated core provides some thermal insulation. Being constructed of a single material facilitates their recycling at end-of-life.
  - Boxes made from expanded PP are potentially reusable. The expanded PP is resistant to steam sanitization, provides excellent thermal isolation and is likely to be less costly than the previous two alternatives. However, the surfaces are not smooth, so are less hygienic and less durable. Being made from a single polymer facilitates their end-of-life recycling.
- Redesigning single-use boxes to be compostable could simplify end-of-life management for countries without recycling facilities. Such boxes have been made from paper based materials and from expanded biodegradable polymers. Both designs have some thermal insulation properties.
- Where EPS boxes continue to be used, establishing mandatory EPR schemes would help both the fishery sector and the distribution chains to collect end-of-life products for recycling or disposal.

Figure 28: Alternatives for insulated fish boxes

Alternatives and interventions		Reusable durable and sanitizable insulated boxes	Compostable single-use insulated boxes	EPR scheme on EPS for the fishery and aquaculture sector
6R options	Refuse			
	Redesign	•	•	
	Reduce			
	Reuse	•		
	Recycle			•
	Recover		•	
3D consequence	Damaged	Reduces risk of dispersal of broken boxes		
	Degraded	Reduces risk of degradation	Reduces harm from degraded boxes	Reduces risk of degradation
	Discarded	Reducess risk of littering and improper disposal	Reducess risk of littering and improper disposal	Reducess risk of littering and improper disposal

Source: FAO, 2021.

Measures to drive sustainability

Initiatives by supermarket chains in various countries of the European Union have driven a reorganization of the supply chain by adopting rigid insulated plastic crates and boxes and organizing a reverse logistics system to clean and reuse the products.

5.2.8 Greenhouse films

Greenhouse films are highly engineered products, typically made from three layers of coextruded polyethylene and other polymers, each with different additives to improve the performance and durability of the film. Film thickness typically ranges between 100 μm and 200 μm, which influences their strength and durability from up to three to four years. The properties provided by additives include: UV light stabilization that slows the degradation of the film by sunlight; condensation control that prevents water droplets falling and damaging the plants; light transmission and diffusion that maximizes photosynthesis; and insulation that reduces both nighttime heat loss and daytime heat gain (Bartok, 2015).

The effectiveness of the properties decrease over time and the plastic degrades. The plastic can be weakened through abrasion, weather damage, and contact with chemicals. Manufacturers will indicate an expected life for the film. Effective management of greenhouses involves the selection of an appropriate frame structure and film, appropriate construction, regular inspections, and a plan for the ultimate replacement of the film. Clean used greenhouse film can have a high value for recycling (Bartok, 2015).

Other plastic products are often used in conjunction with greenhouses such as woven ground covers, mulching films, low tunnels, shade netting, insect screens, irrigation tubes, growbags, plant supports, and structures for hydroponic cultivation.

Benefits and issues

The protected and controlled environment inside greenhouses provides significant benefits to farmers including: higher yields than unprotected cultivation; longer productive seasons; better crop quality, and reduced pesticide and water usage. Greenhouse films are significantly cheaper than rigid materials such as glass or polycarbonate.

Inappropriate specification of films, poor construction, lack of maintenance, and contact with agrochemicals increase the potential for wear and tear, thus decreasing the effective life of the film. The performance and strength of a greenhouse film decreases when it is used beyond the manufacturer's recommended life of the product. Ultimately, greenhouse films become brittle and fragment into macroplastics with the potential for leakage into the environment. Given that all greenhouse films become waste at the end of their useful life, the annual global waste generation will be similar to that of global production, estimated at almost 3 million tonnes (Le Moine, 2018). Although the films potentially have a positive value for recycling, a proportion of greenhouses become abandoned, and their films films are left to degrade. In Almeria, Spain, it is estimated that 15 percent of films are not collected and are illegally dumped or burned (Sanchez, 2020).

View from inside a greenhouse.

Abandoned greenhouses, Italy.

Alternatives and interventions

Protected cultivation, such as greenhouses, will continue to play an important role in food security and climate change adaptation strategies (Maraveas, 2019; Nikolaou et al., 2020) considering their strategic benefits listed above. The main alternatives identified (Figure 29) are listed below:

- Greenhouse films can be replaced by durable alternatives such as silica glass and rigid polycarbonate. However, they tend to be significantly more costly. Maraveas (2019) provides guidance on the properties and sustainability of plastics and other materials.
- Mandatory EPR schemes provide a mechanism for collection and recycling of end-of-life films and will also drive investment in improved product design which could increase the opportunity for closed loop material recycling. Product labelling with expiry dates and incentives for farmers for timely replacement can help ensure the timely return of used films to EPR schemes. Labelling can also help to assign responsibility for the retrieval of films from abandoned greenhouses.
- Such EPR legislation could also drive the development of fully serviced greenhouse businesses, where the farmer rents a greenhouse service, with the service provider responsible for its construction, maintenance, timely replacement and recycling of films.

Figure 29: Alternatives for greenhouse films

Alternatives and interventions		Change to more durable alternative where possible	Mandatory EPR schemes	Product labelling and dating	Incentive schemes for farmers for timely recycling	Fully serviced business model
6R options	Refuse	●				
	Redesign	●		●		●
	Reduce					
	Reuse					
	Recycle		●	●	●	●
	Recover					
3D consequence	Damaged	Avoids risk of damaged plastic		Discourages procurement of substandard products	Timely replacement avoids product weakening	Timely replacement avoids product weakening
	Degraded	Avoids risk of degraded plastic		Avoids degradation by encouraging timely replacement	Avoids degradation by encouraging timely replacement	Avoids degradation by encouraging timely replacement
	Discarded	Avoids plastic at end-of-life	Reduces risk of littering and improper disposal	Discourages littering and improper disposal	Reduces risk of littering and improper disposal	Reduces risk of littering and improper disposal

Source: FAO, 2021.

5.2.9 Silage films

Silage is an animal feed made by the anaerobic fermentation of green fodder crops. The fermentation process helps the long-term preservation of the nutritional qualities of the feed. Plastic films are used to exclude air and rain and provide appropriate conditions for fermentation and include: durable covers for silage clamps; single-use tube bags for bulk and baled silage; and film wrap for individual bales.

Benefits and issues

Plastic films provide an effective and low cost means of maintaining the conditions for preparation and storage of silage.

As in the case of greenhouse films, the durable films used on silage clamps can get damaged during poor operation of the clamp. Without appropriate incentives and penalties, users could delay the replacement of films beyond their recommended life.

The single-use tubes have to be disposed of when the silage has been removed. The films tend to become contaminated when vehicles are used to transport the silage to the animals. Such contamination can include soil, animal faeces, bedding materials, and other farmyard wastes and increases the costs of logistics and end-of-life management and may also limit the options for recycling.

Individual silage bales are generally made by first securing with an HDPE net or polypropylene twine over which LDPE film is wrapped. The two layers need to be removed before feeding to animals. Residues of film, netting, or twine that are left in the bale can damage the health of animals that feed on them (College of Veterinary Medicine, University of Florida, 2012). Unless the materials made from different polymers are collected separately, the options and economics for sustainable end-of-life management are extremely limited. As with silage tubes, if the materials are contaminated with residual silage, faeces, soil and stones, the cost of end-of-life management increases and the opportunity for recycling reduces. In 2014, it was reported that 79 percent of farmers in the province of Saskatchewan, Canada burned used silage wrap on their farms (Friesen, 2014).

Alternatives and interventions

- Labelling durable silage films to identify the manufacturer and date for replacement will help to avoid excessive use (with the risk of degradation and dispersal), and their return to EPR schemes.

- Redesigning equipment and plastics for bale wrap: Redesigning nets, twines, and films (and baling equipment) to minimize the number of different plastic compounds would reduce the need for separation on the farm. Replacement of nets with films has been promoted by Göweil Maschinenbau GmbH (2021). Increasing the proportion of recycled plastic in the manufacturing process would improve circularity. Redesign of bale nets and baling machines could reduce the level of contamination by silage in the retrieved net and improve economics for recycling. For silage bales that are only to be kept for up to six months, a study has demonstrated that biodegradable films were effective and produced similar silage to that in LDPE films (Borreani and Tabacco, 2014). In cases where silage bales need to be stored outside for extended periods, and reaching high temperatures under sunlight irradiation, the use of biodegradable plastics is unlikely to provide a solution.

- Establishing mandatory EPR schemes will help to drive recycling. Educating and incentivizing farmers to separate the different plastic products and to keep contamination to a minimum will improve the options and economics of recycling. Where contamination levels preclude mechanical recycling, chemical recycling, which is discussed in Section 6.4.7, potentially offers a solution for end-of-life management. A student innovations workshop at the University of Laval, Canada, reviewed the options for the 11 000 tonnes of silage film waste that is generated each year in Quebec. They identified chemical recycling into bitumen for road surfaces as the most suitable potential option (Bombardier-Cauffopé, 2021).

Figure 30: Alternatives for silage films

Alternatives and interventions		Labelling, date marking and tracing of durable films	Redesign of baling equipment	Single wrap or compatible plastics in silage bales	Mandatory EPR schemes	Incentives for contaminant-free films and timely recycling
6R options	Refuse					
	Redesign	•	•	•	•	•
	Reduce		•			
	Reuse					
	Recycle		•	•	•	•
	Recover				•	
3D consequence	Damaged	Avoids weakening by encouraging timely replacement				
	Degraded	Avoids degradation by encouraging timely replacement				
	Discarded	Discourages littering and inappropriate disposal	Reduces quantities and increases recyclability of waste	Higher value of waste encourages recycling	Discourages littering and inappropriate disposal	Higher value of waste encourages recycling

Source: FAO, 2021.

Film wrapped silage bales and littered bale wrap, United Kingdom of Great Britain and Northern Ireland.

Abandoned silage bales, United Kingdom of Great Britain and Northern Ireland.

5.2.10 Plant support twines

Benefits and issues

Some crops require support during cultivation. These include: naturally climbing species such as hops and certain legumes and cucumbers; vines and fruit trees; high-yielding cultivars that cannot support the weight of their crop such as tomatoes; and plants grown using hydroponics. Suspended polypropylene twines and nets provide a low cost and strong support framework for the plants to grow up. Flexible and stretchable tubing or clips are also used for tying plants to support frames.

At the end of the season, the twines and plant residues must be removed. Entanglement makes on-farm separation of the twines and nets from the plant residues difficult. In any case, reuse of polypropylene twines and nets is not generally recommended due to the potential presence of pests and diseases from the previous harvest. Where ties are cut, there is a risk of litter in the fields.

Interventions and alternatives

- Substituting with compostable twines, ties and nets avoids the need to separate the plant residues at end of life. Such products can be made from natural materials such as sisal, jute and hemp. Support twines and nets have also been successfully manufactured from plastics that are biodegradable and compostable on farms. The European Union-funded LIFE BioTHOP project demonstrated the effectiveness of using twines made from polylactic acid in hop production in Slovenia. At the end of the harvest, the twines and plant residues were composted on the farm, and the resultant compost used for soil amendments or as a raw material for biodegradable products such as plant pots (Inštitut za hmeljarstvo in pivovarstvo Slovenije, 2021; Rayns *et al.*, 2021). Fiscal measures through levies on non-biodegradable products could help drive the adoption of natural twines or those made from compostable plastics.

- Extended producer responsibility (EPR) and recycling could improve end of life management in cases where migration to compostable/biodegradable alternatives is not possible. Mandatory EPR schemes could be used to ensure twines and entangled plant residues are collected. A composting pre treatment process could biodegrade the plant residues and facilitate the separation and retrieval of the non-biodegradable twines and ties for their subsequent recycling. However, depending on the specification of the twine, there is a risk that it could fragment during the composting process, contaminating the compost with microplastics.

Plant support ties in the field, Italy.

Figure 31: Alternatives for twines

Alternatives and interventions		Adopt compostable support twines and nets	Financial mechanisms to favour the use of biodegradable plant support twines	Mandatory EPR schemes
6R options	Refuse		•	
	Redesign	•		•
	Reduce			
	Reuse			
	Recycle			•
	Recover	•		•
3D consequence	Damaged			
	Degraded	Avoids risk of degradation to microplastics	Avoids risk of degradation to microplastics	
	Discarded	On-farm composting avoids littering and inappropriate disposal	Avoids risk of inappropriate disposal	Collection avoids inappropriate disposal

Source: FAO, 2021.

5.2.11 Emptied pesticide containers

Emptied pesticide containers have long been recognized as representing a potential hazard to public health and the environment due to the nature of their residual contents, as per FAO's first guidance document published in 1999 (FAO, 1999). This was followed in 2008 with guidance on options for their management (FAO and WHO, 2008) under the International Code of Conduct on Pesticide Management (FAO and WHO, 2014). CropLife International, an association of pesticide manufacturers, as part of its product stewardship programme and in close collaboration with national governments, has supported the establishment of pesticide container collection and management schemes and in 2015 published a roadmap for establishing such schemes (CropLife International, 2015). In 2019, established schemes were operating in more than 40 countries globally, with pilots operating in a further 20 countries (CropLife International, 2021a).

Benefits and issues

The design and material of primary pesticide packaging should be based on international standards regulated under national crop protection laws and should aim to minimize the unnecessary risks of pesticide exposure to users, the public and the environment. The container design should consider all aspects of its life including transportation, storage, use and end-of-life management. Pesticide formulations come in many physical forms from liquids, powders, granules, solid blocks and gases all requiring different container designs and sizes. The most common types of packaging are: rigid bottles made from PP, HDPE and coextruded HDPE and nylon; and sachets and bags made from plastic films, often multi-layered and aluminized. All containers should be robust, tough, and resistant to the chemical components of pesticides.

Being robust and well designed, empty pesticide containers are also attractive to be reused for the storage of other commodities including food.

Such reuse poses risks to human health and the environment. The guidance mentioned before recommends the practice of triple rinsing to eliminate residual contamination and puncturing the container to prevent its reuse.

Empty pesticide containers are also attractive for the repacking of counterfeit pesticides. Estimates of the proportion of global counterfeit pesticide sales range from between 10 percent and 15 percent and up to 25 percent (Frezal and Garsous, 2020 and references therein).

Pesticides are not always available in appropriately sized containers to meet farmers' needs. Small scale farmers often only require small quantities of pesticides, which can lead to retailers repacking pesticides into unapproved containers such as used PET bottles for carbonated drinks. This practice poses significant risks and is proscribed under the International Code of Conduct on Pesticide Management. To satisfy this market, some manufacturers supply pesticides in small, single dose quantities in flexible multilayer plastic sachets. These sachets, especially for liquid formulations, can be difficult to open without exposure to the user, are difficult to decontaminate, and are often left as litter in the fields. For this reason, some manufacturers discourage the rinsing of any emptied flexible pesticide packaging. Sachets produced from multilayer plastics, and especially if aluminized, have the disadvantage that they are difficult to recycle (Kaiser, Schmid and Schlummer, 2017).

Alternatives and interventions

- Given the health and environmental risks posed by the use of small-dose sachets, national governments may wish to phase out and ban their use. This would additionally drive efforts to design safer and more sustainable alternatives such as redesigned packs and the sprayer service provider described later in this section. Other non-recyclable packaging could also be phased out. In 2020, the Government of China took such steps with the enactment of "Management Measures for Recycling and Disposal of Pesticide Packaging Waste" (the Ministry of Agriculture and Rural Affairs and the Ministry of Ecology and Environment, 2020). Article 13 "encourages pesticide producers to use easy-to-resource and easy-to-dispose packaging, water-soluble polymer packaging, or packaging that is degradable in the environment, and phase out aluminium foil packaging".

- Promotion of triple rinsing and puncturing can reduce the hazards of contaminated empty containers and improve their recyclability. Triple rinsing the containers immediately on emptying can significantly reduce their level of contamination and potential to cause harm. The rinsate can be used in the spray tank so that none of the pesticide is wasted. Puncturing the container prevents it from being reused for storage for food and water. These practices should be promoted through communications and education programmes for users. When containers are returned to an empty pesticide container EPR scheme, they should be inspected to ensure that there are no visible residues (CropLife International, 2015; FAO and WHO, 2008). Governments may wish to legislate to: 1) require pesticide users to properly rinse, puncture and return emptied pesticide containers to the designated EPR scheme; and 2) require manufacturers to include rinsing and returning instructions on the pesticide label.

- Smart labelling and tracking of containers could be used to help users to identify counterfeit pesticides, track containers through distribution channels to users, and for their return to empty pesticide container EPR schemes (Frezal and Garsous, 2020). Using technologies such as tokenization with blockchains could also support incentive schemes to encourage the return of empty containers.

- Establishing and enforcing mandatory national EPR schemes for emptied pesticide containers, with clearly defined roles and responsibilities for stakeholders will help to ensure that the containers of all pesticides legally introduced onto the market can be returned to the scheme for appropriate recycling or disposal. The larger volumes of containers will help to drive investment in recycling infrastructure and improve the circularity of plastics. Extended producer responsibility schemes are discussed in further detail in Section 6.4.1.

- Incentives schemes can encourage the return of containers. Given the value of empty containers for reuse in some countries, it may be beneficial to provide an incentive to users to return the empty container to the collection scheme. Such incentives could be in the form of a credit for the purchase of other agricultural goods or a cross-compliance requirement for agricultural subsidies.

- Sprayer service providers can avoid the need for each farmer to apply pesticides. In a community of small-scale farmers, one farmer can be trained and equipped to provide a pesticide spraying service to neighbours. Such services avoid the need for each farmer to have stocks of pesticides and application equipment. It avoids the need for unsafe small-dose packs or repacking into inappropriate receptacles. However, reliance on such services could exacerbate the use of pesticides rather than using more sustainable and potentially less costly pest management practices.
- Refillable containers are specifically designed to be refilled and reused more than once to sell or distribute pesticides. Such container systems are utilized on large farms in the United States of America where the pesticide regulations include special provision for refillable containers and repackaging.

Figure 32: Alternatives for pesticide containers

Alternatives and interventions		Ban on dangerous and non-recyclable containers	Promote triple-rinsing and puncturing	Smart labelling and tracking of pesticide containers	Mandatory EPR schemes	Incentives for return of containers	Spray service for small-scale farmers	Refillable containers
6R options	Refuse							
	Redesign							
	Reduce							
	Reuse							•
	Recycle		•		•	•		
	Recover							
3D consequence	Damaged							
	Degraded							
	Discarded	Reduces littering and inappropriate disposal	Reduces risk of harm from littering and during disposal	Reduces littering and inappropriate disposal	Reduces littering and inappropriate disposal	Reduces littering and inappropriate disposal	Reduces littering and inappropriate disposal	Reduces littering and

Source: FAO, 2021.

Farmer spraying crops.

Pesticide containers made from HDPE, Eritrea.

5.2.12 Plastic sacks and bags for harvesting and distribution

In some countries, small-scale producers use plastic sacks and bags to collect and transport their harvested vegetables and fruit to market.

Benefits and issues

Plastic sacks and bags are cheap, lightweight, and readily available.

The fruit and vegetables are easily damaged and crushed, losing both quantity and value. Plastic bags are easily damaged and have to be replaced frequently.

Alternatives and interventions

- Using reusable rigid plastic or wooden crates protects the harvest from being crushed, reducing food loss and maintaining value. Market traders can provide the crates to farmers and manage the distribution chain. Adopting this practice for tomatoes in southern Asian countries reduced food loss by up to 87 percent (FAO, 2019b). Where there are risks of disease transfer, a sanitization process is needed before crates are returned to farms. In such cases, crates with hard, smooth and impervious surfaces such as those made from HDPE would be easier to sanitize.

Canary melons in crate loaded on truck.

Harvested potatoes in flexible intermediate bulk containers.

Figure 33: Alternatives for plastic sacks and bags for harvesting and distribution

Alternatives and interventions		Ban plastic bags	Promote reusable crates
6R options	Refuse	•	
	Redesign		•
	Reduce		
	Reuse		•
	Recycle		
	Recover		

3D consequence	Damaged		more resistant to damage
	Degraded	Avoids degradation of bags throug excessive use	Less susceptable to degradation
	Discarded	Reduces littering and inappropriate disposal	Reduces risk of littering and inappropriate disposal

Source: FAO, 2021.

5.2.13 Pesticide-impregnated fruit protection bags

Banana plantations use pesticide-impregnated plastic bags to protect the flower and fruit as they grow. The single-use bag is removed at harvest.

Benefits and issues

The bag protects the fruits from damage by weather, insects, and other pests. It also provides a microclimate that enhances growth.

At harvest, unless there is a regime to collect the used bags, they can end up littering the plantations. Plantations are often located in areas without access to appropriate recycling or disposal facilities.

Alternatives and interventions

- Rejuvenation of plantations and clean-up of historic litter from protection sheathes can improve future yields. Chiquita's rejuvenation programme for plantations that are taken under the company's direct control has removed plastic residues up to 1 tonne/ha which, in subsequent harvests, has helped to enhance yields by up to 25 percent (Chiquita Brands LLC, 2019).
- Designing compostable protection bags with pesticide formulations that also degrade into low hazard compounds would allow the used bags to be composted at the plantations.
- Local recycling operations could be viable but pesticide residues remaining in the plastic limit the opportunities for recycling into new products that will have little human contact. Such products are identified in CropLife International's roadmap for establishing an empty pesticide container collection scheme (CropLife International, 2015), and include fence posts and drainage pipes. Options have been investigated to recycle the bags into corner protectors for pallets of boxes of bananas for export. This has been met with mixed results as some importers refuse to accept plastic corner protectors because they complicate their recycling operations. Recycling the bags into building materials for the local market has been practised. There are risks of pesticide exposure to workers during the recycling operations and potentially to users of the recycled products. Governments may wish to regulate such processes and products to avoid the risk of exposure to pesticides. The International Code of Conduct on Pesticide Management and the pesticide industry provide guidance on the types of products into which such recycled plastics could be manufactured (CropLife International, 2015; FAO and WHO, 2008).

Bananas encased in plastic bags to protect them from insect and parasitic infestation.

Harvested bananas on a conveyor inside protection bags/sheathes and with plastic foam protection pads, Ecuador.

Figure 34: Alternatives for fruit protection bags (banana cultivation)

Alternatives and interventions		Rejuvenation of plantations to remove plastic from the soil	Compostable protection bags	Establish local recycling operation
6R options	Refuse			
	Redesign		•	•
	Reduce			
	Reuse			
	Recycle	•		•
	Recover	•	•	
3D consequence	Damaged			
	Degraded	Avoids continued degradation of historic littered plastic	Avoids risk from degradation	
	Discarded	Reverses historic littering and dumping	Avoids risks of littering and inappropriate disposal	Collection reduces inappropriate disposal

Source: FAO, 2021.

5.3 Other products of potential concern

During the compilation of this report, other plastic products were identified as being of potential concern due to their difficulty to recycle or for their dispersal in the environment. These products should be investigated further to identify alternatives or opportunities to improve their circularity.

5.3.1 Non-woven protection textiles

Non-woven textile “fleece” sheets are used in open fields to cover early planted seedlings to protect from late frosts. They allow farmers to plant out their horticultural crops earlier in the season. They are often used in conjunction with drip irrigation and mulching films. The physical structure of the non-woven textile tends to trap soil resulting in high levels of contamination that is difficult to remove, limiting the potential for recycling.

Non-woven textile protection.

Protective textile removed after one month in the field showing levels of soil contamination, Italy.

5.3.2 Elastration bands

Elastration bands are used to castrate or dock the tails of young animals, particularly sheep. They are tight elasticated bands that are applied to the animal's tail and testes. The antiseptic bands stem the flow of blood, causing the extremity to atrophy and drop off. Where animals are left free to roam, the used elastration bands are dispersed over the farmland. The bands can be brightly coloured which can facilitate their identification and manual retrieval from fields. However, their collection relies on the intervention of farmers. Fully biodegradable elastration bands could avoid the need for their collection.

5.4 Summary

A qualitative risk assessment identified 13 products for further assessment, of which polymer coated fertilizers, pesticide containers, and mulching films were identified as high priority.

The measures identified to improve each product's sustainability and reduce their environmental impact, referring to the 6R (refuse, redesign, reduce, reuse, recycle and recover) framework, are shown in Table 7.

In practice, specific alternatives or interventions will depend on the product and local/national infrastructure and socio-economic frameworks. However, the analysis revealed some underlying themes, which span a range of agricultural plastic products:

- Adopting agricultural practices and alternative products that avoid the use of plastics such as planting cover crops and using biomass as a mulch or using natural twines. This can have additional benefits in improving soils and capturing carbon.
- Banning products and polymers that present a high risk of pollution.
- Setting minimum standards for products, their associated equipment, and use practices to minimize their risk of leakage to the environment and improve their recyclability.
- Establishing and enforcing extended producer responsibility schemes.
- Minimizing barriers and providing incentives for users to manage agricultural plastics sustainably.
- Replacing products made from non-biodegradable conventional polymers with natural products or those made from fully biodegradable polymers that meet specified standards tailored to their specific conditions of use.
- Introducing labelling of products to aid identification, traceability and enforcement.
- Redesigning business models so that manufacturers or distributers of plastic products provide them as part of a service, rather than as a single transaction sale of goods.

Elastration bands for tail docking and castration of lambs, United Kingdom of Great Britain and Northern Ireland.

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Table 7: Identified alternatives and interventions for selected agricultural products

PRODUCT	ALTERNATIVES AND INTERVENTIONS
Polymer coated fertilizers	• Banning the use of non-biodegradable polymers • Specifying the use of biodegradable coatings designed to fully biodegrade in soil
Mulch films	• Adopting mulching practices that avoid the use of plastics • Redesigning mulching films to be biodegradable • Banning the use of PVC mulching films • Increasing film strength to improve its retrievability and reduce leakage into the environment • Redesigning mulching films to be reusable over multiple planting seasons • Introducing product labelling • Implementing mandatory extended producer responsibility (EPR) collection schemes • Implementing incentives and cross-compliance to encourage environmentally responsible behaviour • Redesigning retrieval equipment • Redesigning business models to supply agricultural plastics as a service, including retrieval and end-of life management
Irrigation drip tape	• Avoiding drip tape by migrating to more permanent irrigation systems (e.g. hydroponics) • Redesigning to improve retrievability and reusability over multiple cropping cycles • Redesigning all components of tape from the same polymer to improve recyclability • Banning the use of PVC • Introducing product labelling • Implementing mandatory extended producer responsibility collection schemes • Incentives and cross-compliance to encourage environmentally responsible behaviour • Redesigning retrieval equipment • Redesigning business models to supply agricultural plastics as a service, including retrieval and end-of life management
Tree guards and shelters	• Avoiding use by fencing off areas with newly planted saplings to reduce damage by animals • Avoiding use by increasing sapling planting density • Redesigning products to increase lifespan, or promote reuse • Redesigning products to be fully biodegradable • Establishing EPR schemes
Ear tags for livestock	• Adopting alternative marking systems that avoid plastics such as injectable transponders • Advancing and adopting biometric identification which could eventually obviate the need for identification devices • Recycling ear tags once animals are slaughtered • Incentivizing farmers to collect damaged and lost ear tags for recycling

Source: FAO, 2021.

Table 7 *(continued)*

PRODUCT	ALTERNATIVES AND INTERVENTIONS
Fishing gear	• Marking gear and using on-board GPS devices to identify gear ownership and location • Adopting technical standards to expand lifespan and promote reuse • Establishing free of charge collection measures for unwanted gear at ports/harbours to encourage its return for recycling or disposal • Establishing mandatory EPR schemes • Developing products that fully biodegrade in water to avoid microplastics and reduce ghost gear fishing
Insulated fish crates and boxes	• Redesigning insulated crates to enable effective cleaning (sanitization) and reuse • Redesigning single-use boxes to be compostable • Establishing EPR schemes for single-use EPS insulated boxes
Greenhouse films	• Reducing plastics by using durable alternatives, such as silica glass or rigid polycarbonate • Establishing EPR schemes with mechanisms to encourage the return of film at the end of its useful life • Introducing product labelling including expected effective working life • Redesigning business models to supply greenhouse films as a service, including retrieval and end-of life management
Silage films	• Labelling durable silage films including expected effective working life • Redesigning equipment and plastics for bale wrap to improve retrievability and minimizes the number of different plastic compounds used • Establishing EPR schemes
Plant support twines	• Redesigning products to be biodegradable • Discouraging the use of non-biodegradable products • Establishing EPR schemes for non-biodegradable products
Emptied pesticide containers	• Banning dangerous and non-recyclable containers • Promoting triple rinsing and puncturing • Introducing smart labelling and tracking • Establishing EPR schemes • Launching incentive schemes to encourage the return of used containers to distributors or manufacturers • Redesigning business models to introduce sprayer service providers • Introducing reusable containers
Plastic sacks and bags for harvesting and distribution	• Introducing reusable crates
Pesticide impregnated fruit protection bags	• Redesigning products using biodegradable polymers • Establishing recycling operations in centres of banana production

6. Current frameworks and mechanisms to facilitate good management practices

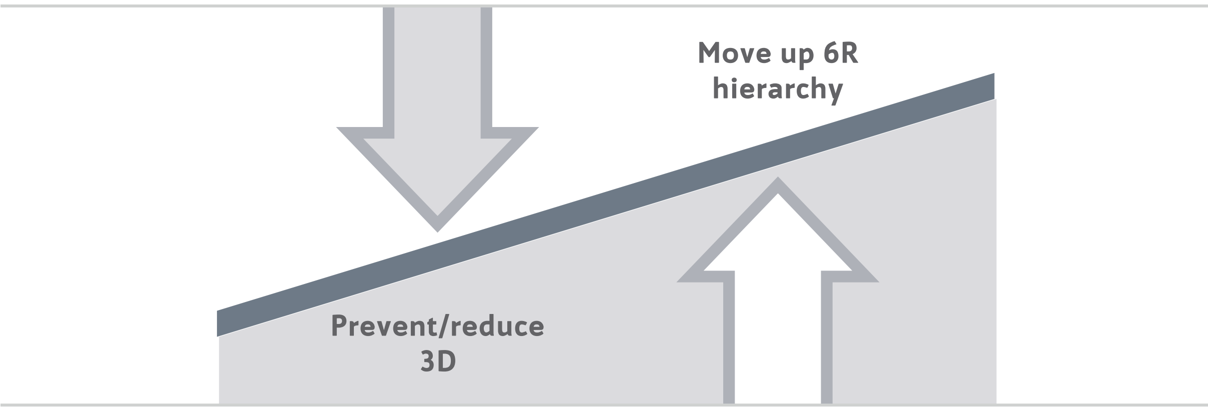
6.1 Transition towards sustainable agri-food systems

Good agricultural management practices aim to produce food and other products sustainably in all its dimensions: economically, socially and environmentally. Policy decisions aimed at addressing agricultural plastics need to be holistic to support the transition to sustainable agricultural practices. Such transitions should aim to deliver similar benefits from using plastics while preventing the release of agricultural plastics into the environment through being damaged, degraded and/or discarded whilst simultaneously improving sustainability by moving the products up the 6R hierarchy (Figure 35).

The means by which this transition is achieved varies depending upon the plastic product, the type of agriculture, and local/regional infrastructure and governance. It will involve a mix of technical solutions, legislative instruments, and behavioural change initiatives.

Karasik *et al.*, (2020) compiled an inventory of subnational, national, regional, and international policy and legal measures that address plastic pollution developed during the period 2000 – 2019. They identified 291 policy and legal documents with an explicit focus on addressing plastic pollution. They characterized the measures in three categories: regulatory, economic, and information instruments. They identified five binding international agreements adopted before 2000 and a further 28 developed during the study period, although most were non binding instruments. The key findings were that there were no "global, binding, specific, and measurable targets agreed to reduce plastic pollution" and that measures primarily related to marine pollution and microplastics.

Figure 35: Principles of good agricultural plastics management practices



Source: FAO, 2021.

6.2 International policy and legal instruments

The main international policy and legal instruments relevant to agricultural plastics are summarized in Table 8. They are classified as international conventions or agreements that are legally binding; codes of conduct and voluntary guidelines that provide recommendations on best practice; and non-binding international declarations. National and regional regulatory bodies may use the codes of conduct and voluntary guidelines as the basis to establish their own legislation.

Despite these policy and legal instruments, there are many aspects of the life cycle of plastic products, including those used in agri-food value chains, that remain unaddressed at the global level. This is a major weakness, and the opportunities to address the situation with a new comprehensive international instrument are discussed in Chapter 7.

This analysis indicates that agricultural plastics, apart from those used in the marine environment, are primarily unregulated by international instruments with only very scattered and residual elements being addressed in legal instruments with a different scope. On the other hand, the well-established principles of international environmental law – in particular the "polluter pays" principle, principle of preventive action, principle of cooperation and the precautionary principle – are applicable to agricultural plastics and their waste and provide the theoretical basis for further legal or policy action.

Table 8: Summary of main international policy instruments relevant to agricultural plastics

MECHANISM	TITLE	RELEVANCE TO PLASTICS
International convention with binding commitments on parties	London Convention (1972) and Protocol (1996 and amended in 2006)	Prevents the dumping of waste at sea.
	The United Nations Law of the Sea (United Nations, 1982)	Part XII has general principles for the conservation of marine environment, including general obligations for countries to prevent, reduce and control pollution in the marine environment. It also includes several duties on coastal states to ensure the compliance of domestic law with pollution prevention.
	The International Convention for the Prevention of Pollution from Ships (MARPOL) (IMO, 1983)	Annex V (revised in 2018) bans disposal of plastic into the sea.
	The Convention on the Law of Non-Navigational Uses of International Watercourses (1997)	Sets mutually agreeable measures and methods for joint water quality objectives.
	Basel Convention on the control of transboundary movements of hazardous wastes and their disposal 1989 and revised in 2019 (Basel Convention Secretariat, 1989) and associated technical guidelines	Plastic waste amendments were adopted in 2019 and came into force on the 1 January 2021. They aim to introduce "a set of actions for preventing and minimizing the generation of plastic waste, improving its environmentally sound management and controlling its transboundary movement; reducing the risk from hazardous constituents in plastic waste; and public awareness, education and information exchange" (Basel Convention Secretariat, 2020a). The 2002 technical guidelines on the environmentally sound management of plastic waste are in the process of being updated (Basel Convention Secretariat, 2002). The POPs Review Committee also considered plastic debris and microplastics as a long-range transport carrier for this plastics stabilizer.
	Stockholm Convention on Persistent Organic Pollutants (POPS) (Stockholm Convention Secretariat, 2001)	Elimination of POPs. Covers unintentionally released POPs for example from open burning of plastics. In January 2019 the plastic additive UV-328 (used for preventing degradation of plastic polymers by UV light) was recommended for review for listing under the convention (Stockholm Convention Secretariat, 2021).

Source: FAO, 2021.

Table 8 (continued)

MECHANISM	TITLE	RELEVANCE TO PLASTICS
Non-binding international declarations	The Paris Agreement on climate change (United Nations, 2015)	While the Paris Agreement does not mention plastics, their production from fossil sources and poor end-of-life management contribute to global GHG emissions. The UNFCCC does however refer to circular economy as a solution. Adopting circular economy approaches for plastics will contribute to countries' efforts to meet their national determined contributions to GHG emission reductions.
	Convention on Biological Diversity (United Nations, 1992)	Urges parties to increase efforts to avoid, minimize and mitigate the impacts of marine debris, in particular plastic pollution, on marine and coastal biodiversity and habitats (Decision 14/10).
	Regional Seas Conventions: There are 18 regional sea conventions and action plans, some of which cover areas beyond national jurisdiction. They include the Abidjan, Antigua, Barcelona, Bucharest, Cartagena, Helsinki, Jeddah, Kuwait, Lima, Nairobi, Noumea, OSPAR conventions; and East Asian Seas, Northwest Pacific and South Asian Seas action plans	These conventions and action plans, amongst other things, aim to address marine pollution from both marine and land based sources.
	The Rio Declaration on Environment and Development (UNCED, 1992)	The Declaration includes the international recognition of a number of important environmental principles, in particular: the "polluter pays" principle (Principle 16) as well as the precautionary principle (Principle 2/24).
	The 2030 Agenda for Sustainable Development (UN, 2015)	SDG 12.4 calls for countries to: "[b]y 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment". SDG 12.5 calls for countries to: "[b]y 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse". SDG 14.1 calls for countries to "[b]y 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution".
International codes of conduct and associated guidelines	International Code of Conduct on Pesticide Management (FAO and WHO, 2014) and implemented guidance documents	Provides principles and guidance on the management of empty pesticide containers.
	Code of Conduct for Responsible Fisheries (FAO, 1995)	Recommends actions to avoid discards and abandoned fishing gear, and that selective and environmentally safe fishing gear and practices be further developed and applied.
	Voluntary guidelines for the marking of fishing gear (FAO, 2019a)	Provides guidance on marking of fishing gear and addresses abandoned, lost and otherwise discarded fishing gear.
International Voluntary Guidelines and Standards	Codex Alimentarius (FAO and WHO, 2021)	Codex Alimentarius is a statutory body that sets food safety standards, that aim to "protect the health of the consumers and to ensure fair practices in the food trade" (FAO and WHO, 2021b). It is overseen by the Codex Alimentarius Commission, a joint initiative between the FAO and WHO, started in 1962. Its codes of conduct and guidelines influence plastic products used in agri-food value chains, particularly with regards to food contact materials. It also assesses the impact of microplastics on food safety.

6.3 National and regional legislation

At the regional and national level, various types of policy and legal instruments have been established that can help to reduce plastic leakage to the environment and improve its circularity. Some examples of these measures are summarized in Table 9.

Table 9: Main types of regional and national level measures to address plastic pollution

CATEGORY	MECHANISM	DESCRIPTION	EXAMPLES
Policy	Long-term strategies and targets	National and regional regulatory bodies set multifaceted strategic objectives to address in a coordinated manner the major threats to the planet including climate change, biodiversity loss, and pollution.	The EU's "Green Deal" is a roadmap that aims to make Europe carbon neutral by 2050. It covers eight areas: "clean, affordable and secure energy; a clean and circular economy; energy and resource-efficient buildings; sustainable and smart mobility; a fair, healthy and environmentally-friendly "farm to fork" food system; preserving and restoring ecosystems and biodiversity; and zero pollution for a toxic-free environment" (European Commission, 2019). In January 2020, China announced a five-year plan that aims rid the nation of single-use plastic waste. In a phased approach production, distribution, consumption and recycling of single-use plastic products will be prohibited by 2025 (Waste360, 2020). Several countries around the globe have developed national bioeconomy strategies (BioSTEP, 2021).
Regulatory/ voluntary	Extended producer responsibility (EPR)	Places obligations on producers and other stakeholders in a plastic product's supply chain to manage its end-of-life. Some schemes have been established voluntarily by producers without regulatory obligations, while others are made mandatory through legislation. By internalizing the costs of end-of-life management it minimizes the financial barriers for users to return unwanted wastes. It can also stimulate innovation in more sustainable products and the recycling market.	A.D.I.VALOR (France) is a voluntary EPR scheme involving converters, distributors and farmers that collects a wide range of used plastic products from the crop production and livestock sectors. inpEV (Brazil) is a legally mandated scheme that collects empty pesticide containers. The Regulations established in 2000 and 2002 (Lei n° 9.074/00 and regulatory standards) place an obligation on pesticide manufacturers and distributors to set up a collection and recycling scheme, and on farmers to make use of it. inpEV is the most effective EPR scheme for pesticide containers, with a recycling rate of 94 percent of containers entering the market (inpEV, 2019).
Regulatory	Product marking, reporting and tracing	Places obligations on actors in the supply chain and users to maintain records of purchases of plastic products and the return of the waste for recycling/environmentally sound disposal. Such measures can facilitate the enforcement of legislation.	China's 2020 Agricultural Film Management Measures (Order No. 4) sets out wide ranging measures to prevent the pollution of soils by mulch films, and to minimize use and promote recycling (General Administration of Market Supervision et al., 2020). It includes requirements to mark films and record their sale and use for traceability purposes. Brazil's record system for purchase of pesticides and return of empty containers provides the enforcement mechanism that drives the high recycling rate of the inpEV scheme.

Source: FAO, 2021.

Table 9 (continued)

CATEGORY	MECHANISM	DESCRIPTION	EXAMPLES
Regulatory	Product bansv	Bans on products that are linked to high levels of pollution and lack of circularity.	Oxo-degradable plastics which have been banned by the European Union due to the risks of microplastics (European Union, 2019b). Similarly, European Union fertilizer regulations will ban non-biodegradable polymer coated fertilizers by 2026 (European Union, 2019c).
Regulatory	Product standards	Sets minimum standards for products and their performance. Such standards to reduce the risk of pollution and improve circularity. Setting minimum levels for the use of recycled materials in the manufacturing process can stimulate circularity and investment in recycling infrastructure. Standard setting bodies include: ASTM, ISO and CEN.	In 2017, China introduced more stringent standards (GB 13735-2017) for a minimum thicknesses for non-biodegradable mulch films to improve its retrievability from soil (Chinese Academy of Agricultural Sciences and Ministry of Agriculture and Rural Affairs, 2020). CEN has developed the standards EN 13432 (for compostable plastics) and EN 17033 for biodegradable plastic mulch films.
Economic	Incentive mechanisms	Providing additional benefits to users for the return of used plastics to EPR schemes can increase the quantities available for recycling	This report did not identify any incentive schemes associated with agricultural plastics used in primary production and distribution. Deposit Return Schemes have been introduced for consumer packaging such as drinks bottles.
Economic	Environmental taxes and reliefs	Taxation on specific products and activities to provide an economic driver to promote the use of more sustainable solutions. Likewise, tax relief can incentivize investment and expenses related to more sustainable practices.	The United Kingdom has a range of environmental taxes, reliefs and schemes for business including a "landfill tax" that aims to increase the cost of landfill (Government of the United Kingdom of Great Britain and Northern Ireland, 2021a, 2021b). This aims to improve the competitiveness of alternatives such as waste avoidance and recycling. The European Common Agricultural Policy supports farmers in three regions of Italy to utilize biodegradable mulching films (Il Ministro delle politiche agricole alimentari forestali e del turismo, Italy, 2018).
Information	Voluntary compliance schemes based on good agricultural practice and product stewardship standards and certification	Private sector bodies set standards for good agricultural practice and product stewardship against which agricultural producers can be controlled and certified. These certificates provide confidence to stakeholders further down the value chain and ultimately to consumers that the product was produced to appropriate standards.	GLOBALG.A.P. is a German based standard setting company for good agricultural practices in crop production, livestock and aquaculture. Its current Integrated Farm Assurance standard includes general requirements for waste management and, in particular, empty pesticide containers (GLOBALG.A.P., 2020b). The Forest Stewardship Council requires its member organizations to "dispose of wastes in an environmentally appropriate manner", which should, in theory, include plastic waste.

6.4 Key measures

This section describes the key measures that have already been identified or are being implemented in some areas of the globe that support sustainable management practices for plastic products and minimize their adverse impacts.

6.4.1 Extended producer responsibility schemes

Principles

The Organization for Economic Co-operation and Development (OECD) has defined EPR as "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle" (OECD, 2001). In essence, it enables producers to ensure the appropriate collection and recycling or disposal of their products at their end-of-life, and internalizes environmental and other externality costs into the price of the product (Monier *et al.*, 2014). The manner in which EPR is implemented will depend, *inter alia*, upon the characteristics of the products in question and therefore could be differentiated accordingly in order to be most effective. Most EPR schemes currently target packaging, mainly at the consumer or municipal level.

Extended producer responsibility schemes may be run by individual companies, or collectively through a Producer Responsibility Organization (PRO). The individual companies or PRO need not directly provide the collection and recycling service themselves but can contract a third party for its execution. In addition to organizing the scheme, they also cover, as a minimum, the costs of collecting specified products separately and ensuring that they are adequately recycled or treated, and the collation and reporting of data used to track the scheme's effectiveness (Monier *et al.*, 2014). They may also be voluntary or mandated under legislation (Watkins *et al.*, 2017).

There are a number of different EPR models, each with their own benefits and disbenefits. Notwithstanding, there are some common issues that all schemes need to address (Hogg *et al.*, 2020; OECD, 2016) which include the following:

- Ensuring that fees charged to the producer/importer adequately cover collection and recycling/treatment costs as well as reflecting the environmental externalities created by the product. The latter would help drive innovation and move the product up the 6R hierarchy and minimize the financial barriers for users to return the end-of-life products.
- Ensuring that the market remains competitive. This aims to mitigate the "free rider" problem in voluntary schemes – producers that do not contribute to the collection and recycling of their products. This requires schemes to be effectively and fairly enforced.
- Designing the scheme so that it is accountable and transparent in its reporting. This is particularly important for products where there is a large number of small producers/importers, and where illegal products are sold, for example pesticides (UNICRI, 2016).
- Establishing roles and responsibilities for all stakeholders in the product's supply chain: producers, importers, distributers, retailers, users, and waste management organizations.
- Incorporating and upgrading existing informal collection and recycling workers into the new EPR scheme. This issue exists in developing countries that lack adequate waste recycling and disposal infrastructure such as informal waste pickers that collect selected materials from dumpsites (ISWA, 2015).
- The schemes need to give access to small-scale farmers who are not part of a larger formalized collective.

There are useful guidelines on EPR, including:

- the Basel Convention's draft practical manuals on EPR and financing systems in order to implement the Convention, which includes plastics (Basel Convention, 2018);
- the OECD's "Extended Producer Responsibility: Updated Guidance for Efficient Waste Management" (OECD, 2016); and
- "Development of Guidance on Extended Producer Responsibility", a report prepared for the European Commission (Monier *et al.*, 2014).

Current EPR and collection schemes for agricultural plastics

Several schemes currently operate within specific countries or across regions (a partial list is shown in Table 10). These include schemes funded by producers or importers of products containing plastics (i.e. EPR schemes) or schemes that are funded solely by farmers and private sector waste collectors/recyclers.

The latter are purely commercial operations and are only viable where the scheme operator is able to make a profit.

In essence, the net cost of recycling (cost of collection and treatment of the used product less the value of the recyclate) is less than all other legal disposal options.

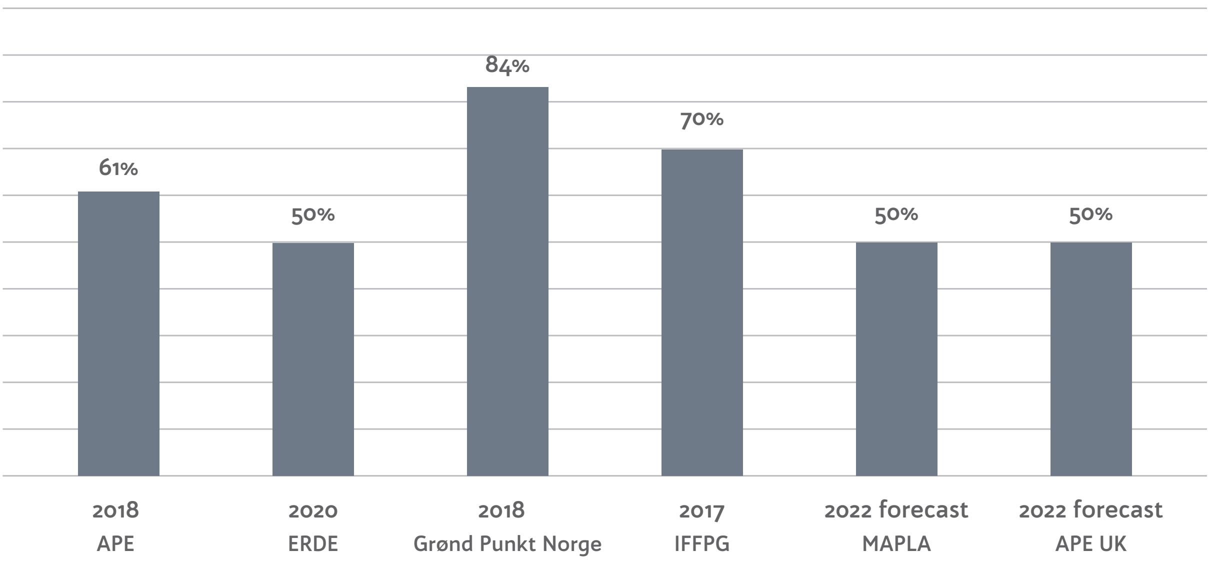
Table 10: Range of agricultural plastic products managed by selected collection and recycling schemes in different regions

Region	Country	Initiave	Start	Type of initiative	Pesticide containers	Mulch films	Plastic films (bale wrap, etc)	Bags (for fertilizer and other items)	Twines and nets	Irrigation tubes	Others
North America	USA	ACRC - Ag Container Recycling Council	1992	Voluntary	■						
		Revolution Plastics	1991	Voluntary			■				
	Canada	Cleanfarms	1989	Voluntary	■	■		■			■
Latin America	Brazil	inpEV - Sistema Campo Limpio	2002	Mandatory	■						
	Guatemala	Sistema Campo Limpio	1998	Voluntary	■						
Europe	France	APE, A.D.I.VALOR	2001	Voluntary	■	■	■	■	■	■	■
	Germany	ERDE	2013	Voluntary		■	■		■		■
		PAMIRA - Packmittel-Rücknahme Agrar	1996	Voluntary	■						■
	Ireland	IFFPG - Irish Farm Film Producers Group	2001	Mandatory	■	■	■	■	■		
	Norway	Grønt Punkt Norge	1997	Mandatory	■	■	■	■	■	■	■
	Russia	EcoPole	2016	Voluntary	■						
	Spain	Mapla	2020	Voluntary		■	■		■		
	UK	Green Tractor - network	2018	Voluntary		■	■		■		
Africa	South Africa	Croplife	2010	Voluntary	■						
		Drom Monster	2013	Voluntary	■						
Asia	China	CropLife	1998	Voluntary	■	■					
	Korea	KECO	2008	Mandatory	■	■	■	■			
Oceania	New Zealand	AgRecovery and Plasback	2006	Voluntary	■			■			
	Australia	Farm waste recovery	2015	Voluntary				■			
		Agsafe	1999	Voluntary	■						

Source: FAO, 2021.

Collection and recycling efficiency varies, depending on the scheme and types of products collected. Data from APE Europe (Europe's non-packaging plastics products' association for agriculture) suggest that collection rates, calculated as the share of the quantities of plastic waste collected (and may include contaminants such as dirt or plant residues) and the amounts put on the market in selected countries, are between 50 percent and 84 percent (Figure 36), with reported recycling rates of the amounts collected varying between 80 percent and 100 percent. However, what is not known is the extent of contamination nor the quantities rejected by the recycling facility. Moreover, at best, 16 percent of agricultural plastics appear to remain uncollected for recycling.

Figure 36: Collection rates of agricultural plastics in selected European countries



Source: APE, 2021 and A.D.I.VALOR, 2020; Kunststoffverpackungen, 2021.

Globally, in 2019 there were 57 operational schemes for the management of used pesticide containers (Figure 37). Many of these schemes were established through the product stewardship programmes of pesticide manufacturer associations including CropLife International.

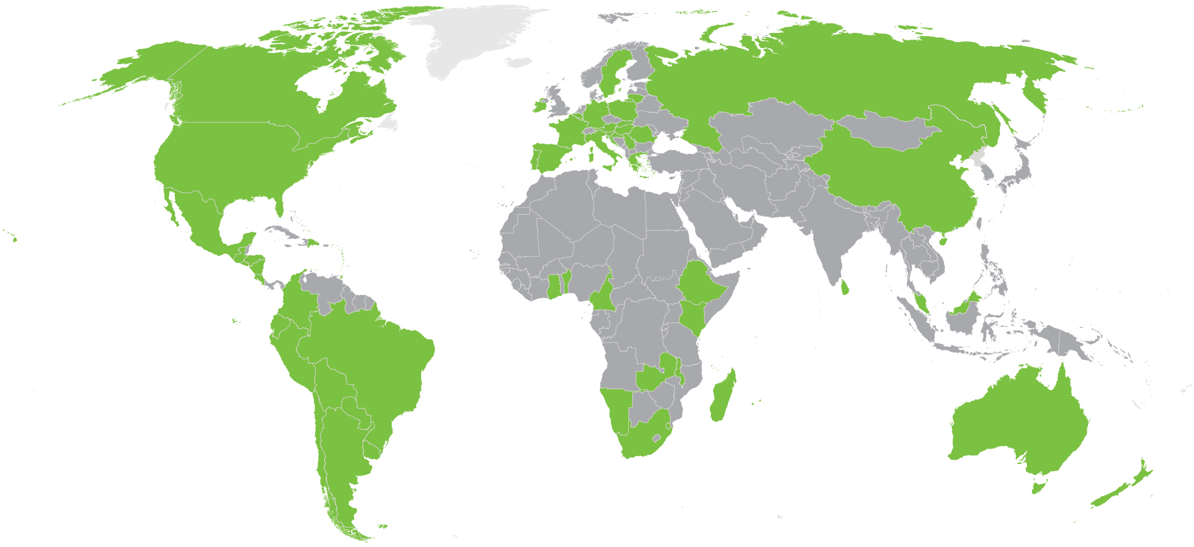
The most successful scheme is "Campo Limpo" in Brazil run by the PRO inpEV on behalf of the pesticide manufacturers and importers.

The scheme manages almost 46 million tonnes of plastics annually, recycling 94 percent of collected containers and collecting almost 94 percent of all primary pesticides packaging marketed in the country (inpEV, 2019).

The success of the Brazilian scheme is primarily due to it being legally mandated with obligations on the pesticide industry to finance it and on farmers to deliver their used pesticide containers to the reverse logistic collection scheme. It is enforced through a tracking system that links farmers' purchases of pesticides to the return of the empty containers.

Many of the schemes shown in Table 10 were initiated as PROs for a single product, often empty pesticide containers, and funded by the pesticides industry. To improve economies of scale and to provide a "one-stop-shop" for farmers to manage all their plastic wastes, some schemes started to collect and recycle a wider range of agricultural plastic wastes.

Figure 37: Countries with dedicated used pesticide container management systems



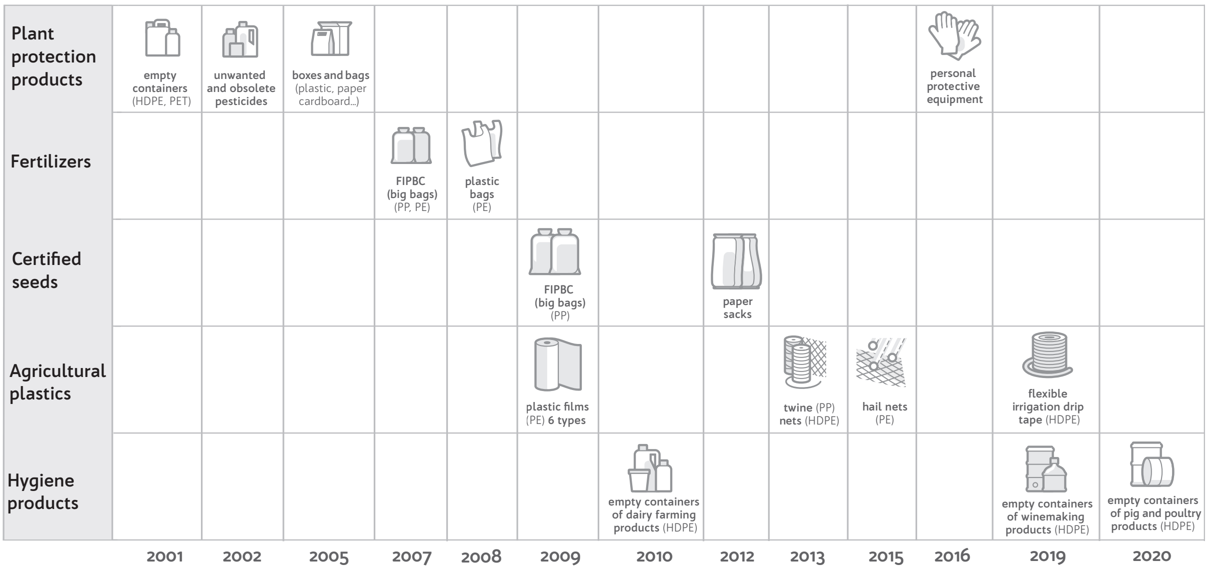
The designations employed and the presentation of material on this map do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined. A dispute exists between the Governments of Argentina and the United Kingdom of Great Britain and Northern Ireland concerning sovereignty over the Falkland Islands (Malvinas).
Source: FAO (2021). Map conforms to United Nations World map, October 2020

Argentina
Australia
Austria
Belgium
Benin (pilot)
Bolivia (Plurinational State of)
Brazil
Bulgaria
Cameroon (pilot)
Canada
Chile
China (pilots)
Colombia
Costa Rica
Croatia
Cyprus (pilot)
Dominican Republic
Ecuador
El Salvador
Ethiopia (on hold)
Eswatini (pilot)
France
Germany
Ghana
Greece (pilot)
Guatemala
Honduras
Hungary
Ireland
Italy (pilot)
Kenya
Lithuania (pilot)
Luxemburg
Madagascar (pilot)
Malaysia
Malawi (pilot)
Mauritius (pilots)
Mexico
Namibia (pilot)
New Zealand
Nicaragua
Panama (on hold)
Paraguay
Peru
Poland
Portugal
Romania
Republic of Korea
Russian Federation (pilot)
Serbia (pilot)
Slovakia (pilot)
Slovenia
South Africa
Spain
Sri Lanka (pilot)
Sweden
Uruguay
United States of America
Venezuela (Bolivarian Republic of) (on hold)
Zambia (pilot)

Source: A. Ward, CropLife International.

A.D.I.VALOR in France – which started in 2001 and is funded by both the pesticides industries and the agricultural plastics manufacturers – collects the widest range of agricultural plastics. At present, after almost 20 years, the scheme accepts a wide range of different agricultural plastic wastes: mulching films; greenhouse films; silage films; bale wrap, nets and twine; anti-hail nets; non-woven textile protective "fleece"; feed, seed and fertilizer bags; drip irrigation tubing; used personal protective equipment; pesticide containers and unwanted and obsolete pesticides. Excluding mulching films (where soil and plant residues prevent recycling), of all the remaining plastic product that it accepts, approximately 90 percent are recycled (A.D.I.VALOR, 2020). The stages in the development of the scheme are shown in Figure 38.

Figure 38: Development of farm wastes managed by A.D.I.VALOR



Source: A.D.I.VALOR, 2020.

The **key success factors** for agricultural EPR schemes to have wide adoption from the farming, fishery and forestry sectors, high recycling rates, and help to maintain pollution-free agricultural areas and waters are:

1. The scheme should be legally mandated with obligations on producers, importers, distributors, retailers and users;

2. The scheme should be effectively enforced to ensure compliance by all stakeholders in the supply chain. Enforcement measures could include a licensing system for suppliers, products and users, as well as incentives and penalties to encourage compliance;

3. The supply chain should be required to maintain records of sales to allow enforcement;

4. The schemes should take a wide range of farm/fishery waste;

5. The barriers for agricultural plastics users to comply with the scheme should be minimized – these include ease of separation and storage of waste, ease of collection/deposit of the waste and minimal financial barriers to comply;

6. The stakeholders in the schemes should be encouraged to undertake research to improve the designs of the products to improve their benefits to users, while improving their environmental performance;

7. There should be access to waste recycling infrastructure with sufficient capacity; and

8. The need for communications and sensitization campaigns to raise awareness of best practice on the use and end-of-life management of plastic products.

There are also challenges and additional factors to consider. In parts of the world served by a network of informal, self-employed waste collectors, the design of an EPR scheme needs to carefully consider these workers. Additionally, areas where small-scale subsistence farming practices predominate, also need to be examined. This is because most EPR schemes tend to primarily serve urban areas where the generation of wastes is relatively concentrated, compared with smallholdings and small farms that are likely to generate small quantities of wastes in a disparate manner. In addition, the latter may also be more likely to present challenging collection and transport conditions.

The lack of a formalized EPR scheme and reliance on a voluntary farmer and waste collector/re-processor-led initiative has potential to be vulnerable to macro- and micro-economic change. These include changes to waste legislation or a drop in revenue from recyclate sales, which can render such initiatives uneconomic. Without producer funding, these schemes can struggle to achieve a 'critical mass' of material and leverage economies of scale.

This includes, for example, the development of cleaning and drying infrastructure for some agricultural plastics prior to re-processing.

6.4.2 Banning selected products/plastic polymers

As part of the European Union's strategy to reduce the release or formation of microplastics in the environment, a number of specific bans have been introduced in recent years:

First, the European Union Fertilising Products Regulation specifies that controlled release fertilizers should not be manufactured using non-biodegradable polymers after 16 July 2026 (European Union, 2019e). The Regulation requires the EC to assess appropriate biodegradability criteria and define test methods by July 2024.

Second, the Single-Use Plastics Directive prohibits products made out of oxo-degradable plastics being placed on the European market by July 2021 (European Union, 2019a). Although this does not specifically relate to agricultural plastics, it does mean that products manufactured from oxo-degradable plastics would not be permitted for sale in European Union member states. In 2017, the Ellen MacArthur Foundation proposed the ban of oxo-degradable plastic packaging from the market following evidence that "oxo-degradable plastic packaging goes against two core principles of the circular economy" and by supporting application of the precautionary principle (Ellen MacArthur Foundation, 2017a).

Finally, a more general ban under the European Union REACH Regulation, restricting the use of intentionally added microplastic particles to consumer or professional use products of any kind, is in preparation (European Chemicals Agency, 2019, 2021). The European Chemicals Agency Committees (ECHA) for Risk Assessment and for Socio-economic Analysis have proposed various transition periods for the entry into force of the restriction for fertilizing products, plant protection products, biocides and seed treatments. The longer periods of transition reflect uncertainty about the ability to develop alternatives, and acknowledgement of socio-economic benefits, despite the goal to reduce microplastic emissions (Committee for Risk Assessment, ECHA and Committee for Socio-economic Analysis, ECHA, 2020).

6.4.3 Plastic product standards and certification

Standards specifying minimum quality criteria and/ or performance requirements have been adopted for various plastic products used in agriculture, either through legislative requirements, or via private sector initiatives with limited or no governmental intervention.

Non-biodegradable mulch film thickness standards

Non-biodegradable mulch film specifications are varied in different regions and countries, depending, in part, upon crops, climate, soil conditions, as well as product pricing and availability. A comparison of different film thicknesses (gauges) in different countries is shown in Table 11.

Table 11: Comparison of mulch film gauges in different countries and regions

	EUROPE	UNITED STATES OF AMERICA	CHINA	JAPAN
Average film thickness (µm)	15 – 20	15 – 20	10	15
Risk of excessive fragmentation *in situ*	Lower	Lower	Higher	Lower
Source of data	a); b)	a); b)	b); c)	a)

Sources quoted in the Table: a) Liu, He and Yan, 2014; b) Tsakona and Rucevska, 2020; c) Chinese Academy of Agricultural Sciences and Ministry of Agriculture and Rural Affairs, 2020.

Thin gauge films have a tendency to rip and split in the field, which can make them difficult to remove (Liu, He and Yan, 2014). Although thicker mulch films use more plastic per unit surface area than thinner films, overall, they are easier to remove, clean and recycle. The rate of retrieval of used mulching films post-harvest depends on many factors including the method of original application, the nature of the soil, the damage it has sustained during use, and its strength and toughness at the time of its removal.

Consultations with experts undertaken during this study, reveal that film thickness is thought to be the most critical factor affecting retrievability from the field. However, there is a lack of consistent data on the relationship between mulch film thickness and its rate of retrieval. Table 12 shows data originally presented in 2014. The low retrievability of 32 percent for 10 μm film appears reasonable and matches data from China where such films were used. However, for the thickest film of 25 μm, anecdotal evidence indicates that the retrieval rate could be as high as 98 percent.

In response to widespread plastic contamination (so-called "white pollution") of fields in China caused by the use of thin mulch films, the Ministry of Agriculture set out an Agricultural Film Recycling Action Plan in 2017 (Ministry of Agriculture and Rural Affairs, 2017). This specified that the thickness of mulch films would be increased from 8 μm to 10 μm, which was introduced through a new product standard GB 13735-2017 (Chinese Academy of Agricultural Sciences and Ministry of Agriculture and Rural Affairs, 2020); a change that could still risk leaving around 68 percent of the plastic in the soil according to Deconinck (2018). Notwithstanding, the 2017 Action Plan also calls for improved removal techniques and increased recycling, actions that have been enacted into the Agricultural Film Management Measures (Ministry of Agriculture and Rural Affairs China, 2020).

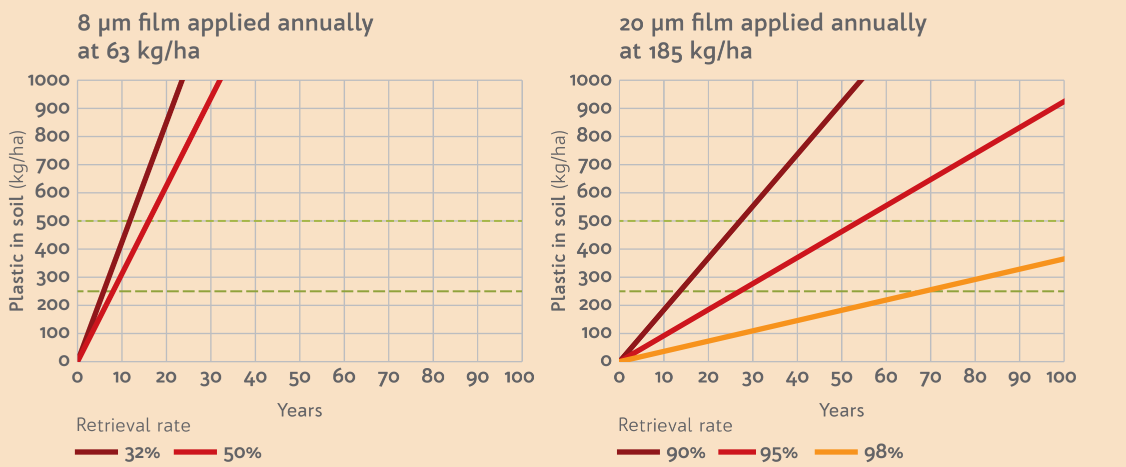
The minimum thickness for non-biodegradable mulch film in Europe is 20 μm – 23 μm under the voluntary CEN standard EN 13655 (Eunomia, 2020). The Circular Plastics Alliance is currently (2021) in the process of developing further standards for non-biodegradable mulching films that aim to improve retrievability and recyclability.

Table 12: Average rate of plastic mulch recovered from fields at different film gauges

Film gauge (μm)	Rate retrieved from the field (%)
25	90
20	75
10	32

Source: Deconinck, 2018.

BOX 7: SIMULATION OF PLASTIC ACCUMULATION INTO SOIL FOLLOWING DIFFERENT RATES OF MULCH FILM RETRIEVAL AT TWO SCENARIOS OF FILM USE



Source: Simulation based on thin and thicker plastic mulch use; the threshold value of 250 kg/ha for significant yield loss is taken from Gao *et al.*, 2019.

The accumulation of plastic in soil from thin and thick mulching films is estimated and compared in Box 7. The left hand graph shows the situation for thin films (8 μm) used in Asia and described by Liu, He and Yan (2014). Such films were applied annually at the rate of 63 kg/ha. These thin films were difficult to remove, with retrieval rates as low as 32 percent (Deconinck, 2018). The graph on the left shows accumulation of plastic in soil at two retrieval rates of 32 percent and 50 percent. The graph on the right shows the situation analogous to that in Europe where thicker films (20 μm) are used and where, depending on the quality of management practices, retrieval rates between 90 percent and 98 percent can be achieved. The average annual rate of application of such films is 185 kg/ha (Guerrini, Razza and Impallari, 2018). The accumulation rates assume that all the plastic fragments were to remain in the top 20 cm of the soil.

Severe impacts on crop yields where experienced in China when levels of accumulated plastic in the top 20 cm of the soil exceeded a threshold of 250 kg/ha (Changrong, 2018) and (Gao *et al.*, 2019).

The comparison illustrates that with thin films, the threshold contamination level of 250 kg/ha is reached within ten years, while the most efficient retrieval rate of the thicker films requires 70 years. Although thicker mulching films can reduce the annual leakage rate to the environment, more research should be done to determine whether such leakage is sustainable.

Biodegradable and compostable product standards

Standards relating to biodegradable and compostable products are complex, due in part to differences in definitions, test criteria and test media. The main definitions are summarized in Box 8.

BOX 8: DEFINING BIODEGRADABLE AND COMPOSTABLE PLASTICS

There are many different definitions of “biodegradable”, “bio-based”, “bioplastic”, “compostable” and “degradable”. Some are functional definitions, whilst others are set out in international standards or legislation (European Union, 2020; Kjeldsen et al., 2019; WRAP, 2020).

The following definitions have been derived from different sources on the basis of their relevance to agricultural plastics, primarily (Defra, 2021; Gilbert *et al.*, 2015):

Bio-based plastics – These are made out of polymers derived from non-petroleum, biological sources. They include plant and microbial-based polymers and can be engineered to be either biodegradable or non-biodegradable.

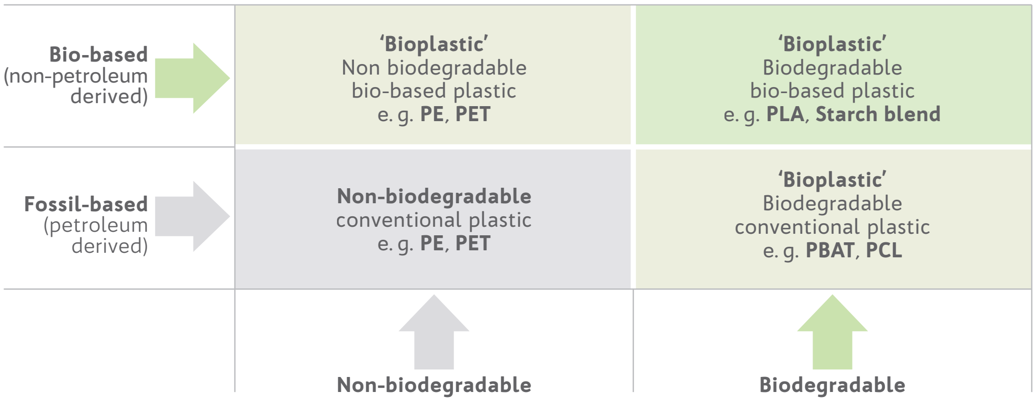
Biodegradable plastics – These are broken down by naturally occurring microorganisms – such as bacteria and fungi – into water, biomass, and gases such as carbon dioxide and methane. The rate of biodegradation depends on environmental conditions such as temperature, humidity, the consortia of microorganisms present and the presence or absence of oxygen (Degli Innocenti and Breton, 2020). Biodegradable plastics can be made from bio-based and fossil-based precursors, and sometimes a mixture of the two.

Compostable plastics – These are a subset of biodegradable plastics that break down into water, biomass, and gases under composting conditions. Industrial composting conditions are the most optimal, with temperatures in excess of 55 °C, high humidity and the presence of oxygen.

Degradable plastics – These undergo significant changes in their physical structure under specific environmental conditions resulting in loss of structural properties. Degradable plastics generally disintegrate into smaller fragments; however, these fragments may, or may not, be biodegradable, depending on the polymer type. Non-biodegradable polymers that disintegrate into small fragments in situ can lead to microplastic contamination of the environment (see Chapter 4). Oxo-degradable plastics fall in this category.

The term ‘bioplastic’ – Literature often refers to ‘bioplastic’ – an imprecise term that is used interchangeably to mean either bio-based, biodegradable, or both (see Figure 39). The International Union of Pure and Applied Chemistry has discouraged the use of this term (Vert *et al.*, 2012).

Figure 39: The relationship between the terms bioplastic, biodegradable and bio-based



Source: FAO, 2021.

Some of the wide variety of agricultural plastic products manufactured using materials conforming to one or more of the recognized standards, are summarized in Table 13. However, in practice, products may be marketed as either 'biodegradable' and/or 'compostable', although the corresponding reference standard does not always accompany the product, or, even worse, the product may not have been tested at all. This can create confusion with consumers and can be exploited by marketeers selling inappropriate products; so-called 'greenwash' marketing (Szabo and Webster, 2020).

Certification offers independent, third-party conformance assessment to a defined standard and provides consumers with assurance that a product labelled as 'biodegradable' and/or 'compostable' will perform as stated. This is an important process and helps formalize a product's performance. There are a number of different certification bodies active around the world, including the Biodegradable Products Institute (United States of America and Canada), DIN-CERTCO and TÜV Austria (Europe), Compostabile-CIC (Italy), Australasian Bioplastics Association (Australia and New Zealand), and Japan BioPlastics Association (Japan). Certification bodies engage independent laboratories to carry out testing and allow certified products to carry a recognized logo.

Table 13: Examples of biodegradable and compostable agricultural products and standards

SECTOR	ITEMS	STANDARD	TEST ENVIRONMENT	REFERENCE
Farming	Mulch films	EN 17033	Soil	(Multibiosoil, 2019); (Guerrini, Razza and Impallari, 2018); (Gastaldi, 2018);
	Clips	EN 17033	Soil	(Malinconico, 2018); (de Beaurepaire, 2018)
	Ropes and twines	EN 17033 EN 13432	Soil Industrial composting	(Inštitut za hmeljarstvo in pivovarstvo Slovenije, 2021)
	Pheromone dispensers	EN 13432 ASTM D6400	Industrial composting	Malinconico, 2018)
	Silage films	EN 17033	Soil	(Borreani and Tabacco, 2014)
	Plant pots	EN 13432 ASTM D6400	Industrial composting	(Inštitut za hmeljarstvo in pivovarstvo Slovenije, 2021)
Fisheries	Nets	ASTM D6691 ASTM D7991	Sea water Marine sediment	(Kim *et al.*, 2016); (LifeGhost, 2020).
Consumer	Food packaging	EN 13432 ASTM D6400	Industrial composting	www.compostabile.com https://bpiworld.org/

Source: FAO, 2021.

6.4.4 Agricultural practices and supply chain assurance schemes

In addition to certification of selected agricultural plastic products, a number of stewardship schemes currently operate encompassing wider agricultural practices. The overall aim of these schemes is to provide standards against which agricultural products or producers can be certified to demonstrate that they have been produced sustainably. Collectively, these schemes have potential to improve the environmental performance of agricultural value chains, especially as retailers have started to embrace them as part of their procurement policies in order to demonstrate commitment to their corporate, social and environmental responsibilities; awareness of which is now increasingly being demanded by customers and shareholders alike.

Some examples of standards and schemes are mentioned below:

GLOBALG.A.P.

GLOBALG.A.P. is a private sector organization that sets voluntary standards covering all aspects of crop, livestock, and aquaculture production, with the most common standard being the Integrated Farm Assurance standard (IFA). GLOBALG.A.P. works with 160 certification bodies in 135 countries, with inspectors auditing at farm level. It aims to provide consumers with confidence that food is produced safely, whilst also enhancing good agricultural practices. The standards are implemented nationally, with GLOBALG.A.P. providing national interpretation guidelines.

To date, GLOBALG.A.P.'s standards have not specifically addressed agricultural plastics or plastic waste, although they have been aligned with some of the SDGs. The revision of the IFA standard, planned for release in 2022, is expected to include specific references to agricultural waste, which will extend to plastic products (GLOBALG.A.P., 2020a).

Forest Stewardship Council

The Forest Stewardship Council (FSC) is a global organization promoting sustainable forestry practices. It oversees an international voluntary certification programme covering a network of forests in over 50 countries.

The international standard is interpreted locally and becomes an approved national standard in each country, which is then certified by an independent certification body.

Although the international standard only requires organizations to "dispose of waste materials in an environmentally appropriate manner" (FSC, 2015), some countries, such as Indonesia, have enshrined this in their national standards to a much greater degree, specifying how forestry organizations should manage and dispose of all wastes. Given the widespread recognition of the FSC logo and its market penetration, there is scope for further clarification through national FSC bodies and their respective national standards.

The Global Reporting Initiative

The Global Reporting Initiative (GRI) is an independent international organization that provides standards for sustainability reporting that businesses and other organizations can use to report their impacts. The organization is in the process of developing sustainability standards for agriculture, aquaculture and fisheries that is expected to be released early in 2022 (Global Reporting Initiative, 2021).

6.4.5 Product labelling and marking

Labelling products with instructions for use, disposal, and manufacturer details is common across a range of agricultural products, especially when mandated by legislation e.g. on pesticide containers. Such labelling and information is important for users to understand how the product should be managed at the end of its life.

For enforcement purposes, traceability of a product through the supply chain, its use and end- of-life management is key. Product labelling and marking together with associated records can help enforcement agencies to identify responsible parties where products have been used or disposed of inappropriately. There are a number of examples of the labelling of agricultural products for traceability, although there appear to be insufficient data to assess their effectiveness.

Labelling and marking of fishing gear

From 2020, all non-tended fixed gear ropes in eastern Canada should be marked with coloured twine to identify both the target species and specific region (Government of Canada, 2021). Across the European Union, fishing gear should be labelled in order to comply with the rules of the common fisheries policy (European Council, 2009). However, it has been acknowledged that "the existing legal requirements do not provide sufficient incentives to return such fishing gear to shore for collection and treatment" (European Union, 2019a). Globally, marking has also been promoted by the FAO Voluntary Guidelines on the Marking of Fishing Gear (FAO, 2019a).

Labelling and marking of agricultural films

In China, the 2020 Agricultural Film Management Measures set a number of criteria with regard to their labelling and traceability. This includes mandating that producers of mulch and greenhouse films add "identifiable corporate logos on each roll of mulch film and each linear metre of film to facilitate product traceability and market supervision" (Ministry of Agriculture and Rural Affairs China, 2020). Additionally, manufacturers, sellers, and users of agricultural films are required to keep records of the sale and use of films, so that they can be fully traceable. Implemented in September 2020, the effectiveness of these measures is yet to be assessed.

6.4.6 Product substitution or alternative practices

Regulatory interventions can also be used to drive innovation, investment and use of more sustainable products and practices. Incentive mechanisms, including taxation and other fiscal measures, linked with the phasing out of less sustainable products and practices, can also encourage adoption of alternatives. This section provides some examples.

Biodegradable/compostable polymers

Examples of agricultural products that have been manufactured from biodegradable/compostable plastics instead of conventional polymers are listed in Table 13 in Section 6.4.3). Mulch films, in particular, have been targeted as a product where biodegradable products manufactured to comply with standard EN 17033 can be used effectively. In some instances, these have been used successfully, where the rate of in situ biodegradation is broadly similar to the cropping cycle. Conversely, in situations where two or three crops are sown and harvested annually, build-up of partially decomposed films can occur (James *et al.*, 2021). There is therefore a need to formulate products that disintegrate and biodegrade at rates suited to specific crop cycles and climatic conditions.

Uptake by farmers of biodegradable film has been slow despite manufacturers promoting that it can be more cost effective than non-biodegradable films. At the time of writing this report, the reasons for this slow uptake have not been thoroughly investigated. There are potentially a number of factors including the higher price of biodegradable products, the necessity to adapt laying equipment, and concerns about their performance and impact on crops and soils.

Table 14: Potential cases for substitution by biodegradable products

CHARACTERISTIC	EXAMPLE OF PRODUCTS
Products that have a high risk of littering	• Elastration bands for tail docking and castration of livestock • Mulch films
Products that become entangled in plant residues	• Plant support twines and nets • Plant clips • Mushroom growing bags
Avoidance of ghost fishing potential of fishing gear	• Ties for escape panels on traps and nets

Source: FAO, 2021.

Non-plastic products

Some plastic products can be substituted with alternative materials that do not present the same environmental risks. Alternatively, changes in agronomic practices can eliminate the need for some plastic products, such as the use of cover crops (Rodale Institute, 2014). Examples of some of these alternatives are listed in Table 15.

Table 15: Examples of alternatives to agricultural plastic products

PRODUCT	SUBSTITUTE	ADVANTAGES	DISADVANTAGES
Tree guards and shelters	Cardboard	No need to collect for recycling – can be left in situ	May need to coat with a biodegradable film to maintain longevity. Reduces light transmission to encased seedling
	Bamboo		Bulkier and costlier to transport. Reduces light transmission to encased seedling.
Plant and seedling pots	Coconut shells	Can be composted at end-of-life	Limited to areas where coconuts grow.
	Paper	Can be composted at end-of-life or left in situ	May not have sufficient structural integrity.
	Soil blocks	No form of containment	May not have sufficient structural integrity.
Mulch films	Cover crops	Eliminates the need for purchasing and removing films	Requires a change in agronomic practices. May be more difficult to mechanize. Some phytopathology issues may arise.
	Biomass	The biomass eventually decomposes and improves the soil Materials are available locally	
Plant support twines and nets	Plant-based twines	Eliminates need to separate plastic waste from plant residues The plant residues and nets can be composted together	None
Fishing pots	Plant-based branches, sticks, brush	The biomass eventually decomposes and does not harm the marine environment	May not have sufficient structural integrity. Rigid so occupies larger volumes on fishing boats.
Ties for escape hatches on fishing nets and traps	Plant-based twines such as cotton	The twines biodegrade and weaken in water	None

Source: FAO, 2021.

Non-plastic alternatives: paper-based pots

Non-plastic alternatives: coconut shells as plant pots, Uganda

Reusable products

Changing the specification of products can convert them from single- to multi-use products. Expanded polystyrene boxes are widely used in the transport of fish and other marine products. They are light to carry and have good insulating properties, making them useful for products that need to be kept on ice. However, their low density makes them costly to collect, easily littered and they can be difficult to recycle if contaminated with fish residues. Moreover, the low moulding temperature of the plastic makes them difficult to clean with steam, a necessary practice for food safety purposes.

Expanded HDPE or PP reusable crates are now being adopted for use in some fish value chains. These crates can be sanitized by steam, and, when used in local supply chains, reverse logistics routes can be implemented. Examples of this include the co-operative supermarkets in Italy and the United Kingdom of Great Britain and Northern Ireland.

Use of specific machinery

Innovations in on-farm machinery can facilitate either the recovery of plastic products for re use/ recycling, or the use of alternative products.

In France, the Committee for Plastics in Agriculture (CPA) and A.D.I.VALOR have worked with an equipment manufacturer to design a mulch removal machine that simultaneously reduces physical contamination of the plastic from between 50 percent and 70 percent by mass to between 10 percent and 30 percent, whilst maintaining worker productivity (Arbenz *et al.*, 2018).

In Japan, a small, simple machine has been developed to plant seedlings grown in a chain of paper pots. The technology has been exported to the United States of America and is purported to work best with closely spaced crops (Small Farm Works, 2021).

6.4.7 Recycling technologies and infrastructure

There are two principal commercially available recycling technologies for plastics: mechanical recycling and chemical recycling. In 2019, only about ten percent of the post-consumer plastic in North America was recycled, primarily mechanically, and recycled plastics only met six percent of the demand for raw materials (Closed Loop Partners, 2019). The International Atomic Energy Agency is developing nuclear techniques for recycling plastic waste (IAEA, 2021a).

Mechanical recycling

Mechanical recycling involves the separation of plastic wastes into different fractions according to the type of polymer from which they are made. The fractions are cleaned, shredded, and hot extruded to generate polymer beads that can be used by converters to make new products using the same polymer. There are some plastic wastes that are difficult to recycle, in particular:

1. Plastic films with high concentrations of entrained contaminants that cannot be easily removed. Non-biodegradable mulching films fall in this category due to the level of soil and plant residues. A.D.I.VALOR has confirmed that in France these mulching films are disposed of in landfill sites; and

2. Plastic products that are manufactured with composites of different polymers and other materials that cannot easily be separated. Aluminized polyethylene films for pesticide sachets and coextruded plastic bottles are examples of such products.

Chemical or feedstock recycling

Chemical recycling uses depolymerization techniques to break down plastics into their base chemicals that can be used as feed stock for new plastics manufacturing processes. There are three broad categories of chemical recycling: purification that produces polymers; depolymerization/ decomposition that produces monomers; and feedstock recycling/conversion that produces petrochemicals and refined hydrocarbons (British Plastics Federation, 2021; Closed Loop Partners, 2019).

Chemical recycling has been suggested as a potential solution to process plastic wastes that are not suitable for mechanical recycling such as coextruded mixed polymers, multi layer and aluminized films, and comingled mixed polymer plastic waste that is difficult to separate.

Regulatory based recycling targets for plastics are generally based on mechanical recycling.

The Circular Plastics Alliance is investigating how chemical recycling could be incorporated to achieve the EU's objective to recycle ten million tonnes of plastics annually into new products from 2025 onwards.

However, concerns have been raised about the environmental impacts and efficacy of chemical recycling, particularly its energy requirements (Zero Waste Europe, 2019). It has also been suggested that landfilling plastics that cannot be recycled mechanically is potentially more environmentally sustainable.

The Ellen MacArthur Foundation has proposed a standard for measuring recycled content of products from chemical recycling by using a mass balance approach (Ellen MacArthur Foundation, 2020). Concerns have also been raised about this approach, and in particular how it is to be implemented (Tabrizi, Crêpy and Rateau, forthcoming).

Recycling infrastructure

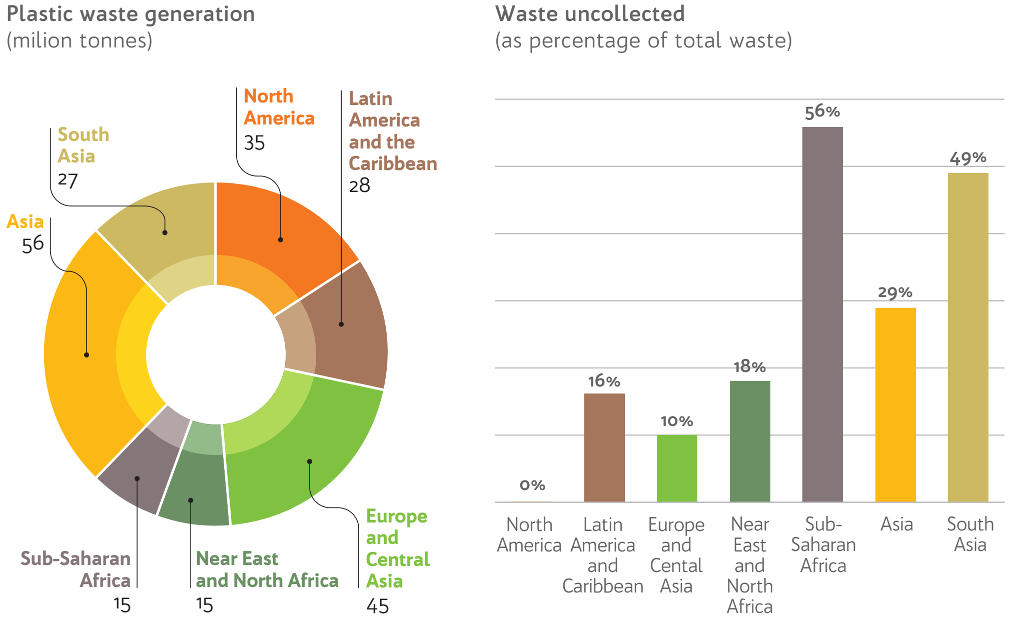
Globally, only 78 percent of all plastic waste, including packaging and non-packaging items, is collected, of which only 30 percent is recycled (The Pew Charitable Trusts and SYSTEMIQ, 2020). Thus, 22 percent of all plastic waste remain uncollected; with rural areas being the least likely to be served by a collection service.

The differences at the regional level, and thus the need to improve the collection and recycling infrastructures, are shown in Figure 40. In North America and Europe (and Central Asia) almost all waste generated is collected, other regions need to improve waste collections, including for plastics, and then assure sufficient treatment capacities to recycle or to dispose of plastic waste in an environmentally safe manner. Plastic items collected directly for recycling or by the informal sector may not be classified as waste and hence may be excluded from official statistics.

The extent of plastic recycling depends on countries' infrastructure, legal obligations, and EPR commitments for specific plastic items.

Looking at the global flows of plastic packaging waste treatment shows that about 21 percent are recycled, 21 percent are incinerated, and 59 percent are landfilled (Ellen MacArthur Foundation, 2017b). Looking at the regional data for the collection rate of used packaging for pesticides compared to the packaging sent to the market (see Figure 41) confirms the need to improve both collection infrastructure and recycling schemes for agricultural plastics at the global level.

Figure 40: Plastic waste generation and amounts of waste collected for different regions in 2016



Source: The data for plastic waste generation have been derived from Kaza *et al.*, 2018 and the percentages of uncollected waste refer to all types of waste streams, including plastics, for each region.

Figure 41: Packaging for pesticides collection in different regions, 2019

Source: Andrew Ward, CropLife International, 4-2021, personal communication.

6.5 Summary

A number of legislative measures, policy frameworks and schemes can facilitate good management practices aimed at preventing the release of agricultural plastics into the environment and simultaneously improving sustainability and circularity. These include:

- international conventions, codes of conduct, and guidelines;
- national and regional legislation;
- extended producer responsibility schemes;
- bans on the use of selected products/plastic polymers;
- product standards and certification;
- minimized barriers, incentives, effective and timely enforcement and penalties to drive more sustainable behaviours; and
- agricultural practices and supply chain assurance schemes.

Each measure has its own advantages and corresponding disadvantages, and some have been shown to be particularly effective in managing agricultural plastics. Moreover, these measures need not operate in isolation, as there is significant overlap in their scope and implementation.

This chapter also identified some of the product-specific changes that could help drive sustainability, including:

- product substitution or use of alternative practices, that reduce reliance on plastics;
- product labelling and marking;
- product re-use; and
- use of specific machinery.

Innovative examples were identified during the course of this study, although most appeared to be small scale, having been designed to meet local needs or by utilizing local resources.

Finally, agricultural plastics present specific challenges when it comes to their recycling.

Issues relating to contamination (e.g. by pesticides or soil/plant residues), retrievability from their place of use (which may be some distance from transport networks), and their low inherent value, all play a part in influencing the financial feasibility of recycling schemes. Coupled with a lack of recycling infrastructure in many parts of the world, these issues need to be addressed before widespread recycling can become commonplace. Appropriately constructed policy mechanisms, legislative frameworks and incentive mechanisms can help support this transition.

7. Towards a circular economy for agricultural plastics

We have seen that agricultural plastics have both positive and negative impacts on food security, food safety and nutrition, as well as social and economic dimensions of sustainability. The environmental issues of agricultural plastics are both global and transboundary in nature.

This chapter builds on the findings identified previously and sets out a series of policy actions that aim to provide a framework for improving the sustainable management of agricultural plastics globally. The issue of plastics is only one facet of all the changes that need to be made in the transformation towards sustainable agri-food systems. Any change needs to be holistic considering all the other dimensions of sustainability. However, as is evident from earlier chapters of this report, certain aspects of plastics in agriculture are unsustainable, causing unprecedented harm, and need to be addressed with urgency.

7.1 Need for new legal and policy measures

As has been shown in Chapter 6, there are gaps in the international, regional, and national policy and legal instruments in place that aim to reduce the adverse impacts of agricultural plastics. The majority of existing measures relate to single-use plastic products including packaging, avoidance of marine litter and microplastics (albeit there is no commonly agreed definition), and the management of plastic wastes. Karasik *et al.*, (2020) concluded that there is no international legislation that sets "global, binding, specific, and measurable targets ... to reduce plastic pollution".

International instruments specifically related to agricultural plastics, other than consumer packaging, have primarily focused on sectors where the risks were perceived as particularly high. Examples include plastics used in fisheries that are covered by the Voluntary Guidelines on marking of fishing gear (FAO, 2019a), and the sustainable management of empty pesticide containers under the International Code of Conduct on Pesticide Management (FAO and WHO, 2014). The latter is not driven by intrinsic harm of the container itself, but rather the risks posed by pesticide residues that it contains.

Other products with a high potential for pollution, such as mulching films and polymer coated fertilizer, are beginning to receive attention from policymakers and regulators in China (Ministry of Agriculture and Rural Affairs China, 2020) and the European Union (Eunomia, 2020).

Many agricultural plastic products are only used once before becoming waste and so have similar regulatory needs as those applicable to single-use consumer plastic products. The United Nations Environment Programme's "Addressing single-use plastic products pollution" (UNEP, 2021b) advocates a life cycle approach together with a range of regulatory measures that would also be applicable to products used in agri-food value chains.

The United Nations Environment Assembly is expected to discuss the issue of marine plastics and microplastics when it reconvenes in 2022 (UNEP, 2021a), with the possible result of initiating an intergovernmental negotiating process toward a treaty on plastic pollution (International Institute of Sustainable Development, 2021).

7.1.1 International regulatory options

Whilst it is important to address these priority sectors and products, the potential for pollution from all the other products used throughout agri-food value chains also requires mitigation. There is also the potential to improve the circularity of products for which policy and legal measures already exist.

Many organizations and Member States have been advocating for new international agreements with global reach to support countries and regions to strengthen their regulation on plastics (Environmental Investigation Agency, Gaia, and Center for International Environmental Law, 2020; Notten and UNEP, 2018; UNEP, 2021b; WWF, 2020; WWF, Ellen MacArthur Foundation, and Boston Consulting Group, 2020). Following the Ministerial Conference on Marine Litter and Plastic Pollution held in Geneva in September 2021, more than 100 countries have signed a Ministerial Statement supporting a motion at the United Nations Environment Assembly 5.2 in February 2022 to establish an international negotiating committee for a new international agreement on plastics (Various Governments, 2021).

As discussed in Chapter 6, international regulatory instruments include both legally binding conventions and agreements, as well as the so-called "soft law", that includes voluntary codes of conduct and guidelines. A comparison of these options, with examples based on recent international practice in the food and agriculture sector, is shown in Table 16 below.

Table 16: Comparison of international policy options

	EXAMPLES	ADVANTAGES	DISADVANTAGES
International conventions	• Basel Convention • Barcelona Convention • International Plant Protection Convention	• Legally binding agreement between countries. • They create concrete obligations and responsibilities for parties.	• Requires countries to agree on the terms of the convention which tends to narrow and moderate the resulting commitments. • Conventions bind only Government that are signatory members. In cases where conventions are only ratified
International codes of conduct and voluntary guidelines	• International Code of Conduct on Pesticides Management • Code of Conduct on Responsible Fisheries • Voluntary Guidelines on the Marking of Fishing Gear	• Voluntary measures are easier and quicker to establish as they do not put binding commitments on countries. • They can therefore be wide ranging in scope and include more ambitious targets. • They can provide concrete guidance to countries on what and how to legislate, and the type of binding obligations for different stakeholders they should incorporate into their national legislation • They can be supported by subsidiary guidance documents. • They can encompass a wide range of stakeholder groups, and not only States.	• Not directly enforceable – each country determines the extent that it implements the recommendations of the code/ guidelines. • However, pressure from the international community (and the interdependent global supply chain) can encourage countries to incorporate the recommendations in these voluntary instruments into their national legislation. An example is the success in the implementation of the Code of Conduct on Responsible Fisheries.

Source: FAO, 2021.

There is an urgent need to strengthen regulation on plastics throughout whole agri-food value chains globally.

It is recommended that a concerted and coordinated effort is made by international organizations, national and regional governments, the private sector, and civil society to establish the necessary regulatory frameworks.

At the international level, parallel approaches are possible, including:

1. Developing a comprehensive voluntary code of conduct to cover all aspects of plastics throughout agri-food value chains. Subsequently to develop detailed best practice guidelines for the most polluting activities.

2. Extending the scope of existing international conventions to address specific plastics issues is potentially quicker and easier than developing an entirely new convention on plastics. So, as a parallel first step, existing conventions could be adapted, with, for example, the Basel Convention being expanded to better address plastic wastes and the MARPOL Convention for the management of plastics used in fisheries and aquaculture.

3. Finally, a new international convention that incorporates concrete obligations for countries applicable to all plastics, including those used in agri-food value chains, as well as in fishing and marine activities, could be developed. The passage of a new convention can be smoother where countries have already developed national legislation based on the common recommendations of a code of conduct.

In this way, the overarching principles of good management of plastics can be established quickly with the voluntary code of conduct, and countries can initiate incorporating these recommendations into their national or regional legislation, while the slower process of consensus building for the development of a legally binding international agreement can follow.

At the national and regional level, governments should legislate to address their priority issues for the improved management of plastics. The recommendations that follow in this chapter may assist. There is no need to delay action waiting for the establishment of the international regulatory instruments.

Donor organizations should support both the development of the international policy and legal instruments as well as implementation at national and regional level, especially in low- and middle-income countries.

7.2 Elements for a proposed international voluntary code of conduct

The code of conduct should provide guidance on the sustainable use of plastic products to all stakeholders throughout each of the agri-food value chains, crop production, livestock farming, fisheries, and forestry. It should provide general guidance on good practices that can be applied to each of these sectors. It should identify all potential areas and measures that countries should take into consideration when revising their national legislation.

The code of conduct should pay attention to the full life cycle of a product from its design, regulatory approval, manufacture, distribution, sale, use, and management at end-of-life. It should also aim to support the transformation towards sustainable agri-food systems considering all the benefits and trade-offs in relation to all dimensions of sustainability. Some of the elements that could be incorporated in the code of conduct are shown in Table 17.

Table 17: Elements of a new international code of conduct on agricultural plastics

ELEMENT	DESCRIPTION
Life cycle thinking in policymaking	Holistic approaches, incorporating cradle-to-grave environmental impacts should be part of policymaking on plastic products. It should consider their environmental, economic and social benefits and trade-offs, and those of their alternatives. The approach should consider eco-design, bioeconomy,[6] circularity, environmental harm, and opportunities to move up the 6R hierarchy. Such approaches should influence decisions to ban or restrict products or specific uses. It will also help in formulating product standards and good practice guidance that can put sustainability into the heart of their design, manufacture, use and post-use.
Regional approaches	In some cases, it may be more effective to make policy decisions at a regional level rather than nationally. Such examples could include federal countries, economic communities, areas outside national jurisdictions such as in the case of regional fishery management bodies, or in the case where a group of countries collaborates to exploit economies of scale in the establishment of regional plastic recycling capacity.
Product standards	Minimum specifications for products, their constituents, their performance and associated equipment; and standards for use that *inter alia* minimize leakage to the environment and improved circularity. The code of conduct could be a mechanism to encourage the development of new standards such as those for biodegradability in different media and environmental conditions as discussed in Section 7.5.3 below.
Process standards	Recommendations for countries to adopt mandatory and voluntary process standards for agricultural practices that use plastics that minimize leakage to the environment and improve circularity.
Bans and restricted use	Recommendations that products with a high risk of environmental damage should be banned or severely restricted.
Certification	Product and process certification to verify compliance with product and process standards.
Product marking and labelling	Labelling products with instructions for use, disposal, and manufacturer details is important for users to understand how the product should be used and managed at its end-of-life. The label may also include unique identifiers that can be used in a traceability scheme.
Measuring, monitoring and tracking	Monitoring and tracking of plastic products through the supply chain will allow regulators and other stakeholders to control the effectiveness of the cradle-to-grave management of plastics. It will support monitoring against national and regional targets. It also provides an enforcement mechanism at the level of individual actors in the supply chain. The process may require products to be marked to allow traceability (as mentioned above) and for the supply chains to maintain records of product supply and collection of waste.
Target setting	Setting targets can be a driver for improved circularity and sustainability, for example: setting minimum levels for the use of recycled materials in new products; and collection and recycling rates for specific products.

Source: FAO, 2021.

[6] To achieve carbon neutrality by 2050 as per the obligations of the Paris Agreement, there will be a need to derive plastics precursors from non-petroleum sources.

Table 17 ***(continued)***

ELEMENT	DESCRIPTION
Authorization and registration of products	Product authorization and registration would allow regulators to ensure products entering the market in their jurisdiction conform to standards and allows them to control how they are used, including implementing bans and restrictions. This could be targeted at plastic products that have potential for harm to human health and the environment.
Licensing users	Licensing of users will allow regulators to ensure that they have the necessary knowledge, skills and equipment to manage plastic products (especially high-risk products) appropriately, including their end-of-life management.
Licensing organizations within the supply chain and end of life management	Licensing actors in the supply chain and end of life management of plastic products will allow regulators to ensure that they have the competence to undertake their roles safely and responsibly.
Extended producer responsibility	Extended producer responsibility (EPR) management schemes can minimize the barriers to users for end-of-life waste management. Schemes can also ensure that the costs of all externalities are borne by those responsible for producing and distributing the products. It is a mechanism for ensuring the "polluter pays" principle. It also allows users to compare the true full costs of all alternatives. The principles of EPR have been set out in Section 6.4.1.
Incentives and penalties	Incentives and penalties can be a driver for stakeholders in the supply chain to adopt more sustainable products and practices.
Economic instruments	Taxation and other fiscal instruments can be used to drive more sustainable products and practices. For example, taxation on the landfilling and incineration of plastics can improve the viability of recycling and thus encourage development of appropriate infrastructure, while those on fossil based resources and harmful chemicals could drive innovation and fund improved end of life management. Subsidy schemes for agricultural production need to also encourage sustainable behaviours and avoid environmental impairment. Cross-compliance can help to achieve this, as in the example from the United Kingdom of Great Britain and Northern Ireland (Government of the United Kingdom of Great Britain and Northern Ireland, 2020).
Sustainable financing mechanisms for regulatory enforcement	Governments should establish mechanisms that provide sustainable and appropriate funding to enforce the regulations related to plastics. Such funding could be derived from levies placed on the plastics supply chain.
Monitoring mechanisms for the implementation by countries of the code of conduct	Although the code of conduct is not binding for countries, it could include mechanisms to allow the monitoring of how and to what extent it has been implemented in each country's national legislation.
Guidance documents and technical support programmes	The code of conduct can support the development of guidance documents related to the regulation, design, manufacture, selection, use and end-of-life management of agricultural plastic products. It can also encourage the improvement of existing sector-specific guidance documents to ensure that issues related to the use and management of agricultural plastics are appropriately addressed. Technical support programmes could aid countries to implement the code in their national legal frameworks.

7.2.1 Stakeholders and their responsibilities

The voluntary code should identify all key stakeholder groups and set out their obligations and responsibilities. These stakeholders, together with their proposed roles, may include those set out in Table 18.

Table 18: Stakeholder roles in the voluntary code of conduct

STAKEHOLDER	ROLE
Government	Policymaking and regulating; developing legislation and public reference standards for the sustainable and circular management of plastics; and ensuring its enforcement. In particular, establishing legislation for extended producer responsibility (EPR). Establishing economic instruments, incentives, penalties and cross-compliance requirements to drive sustainable behaviour within the supply chain. Promoting public–private partnerships conducive to the implementation of policy priorities and promoting co- regulation and capacity development.
Regional bodies	Facilitate regional harmonization and incorporation of good practices through regional regulation, capacity development and private sector engagement.
Plastic producers	Develop new more sustainable polymers and production methods using renewable and recycled resources.
Converters and manufacturers of plastic products, importers, distributors and retailers	Design, develop and market products certified to meet the required standards. Meet requirements for circularity with the use of recycled materials. Maintain and report information for the monitoring of the movement of products through the supply chain. Fund and organize EPR schemes with other actors in the supply chain for the free of charge collection of end-of-life products from users. Fund the costs for all other externalities related to the products.
Users of plastic products	In the absence of alternatives, sustainable selection, use and end-of-life management of plastic products.
Waste collectors including informal sector	Monitor and report waste plastics received from users and delivered to recyclers and disposal sites.
Plastic recyclers	Invest in appropriate technologies to facilitate reuse, and mechanical and chemical recycling.
Standard setting bodies	Develop and set standards for plastics, plastic products and processes for their production, distribution, use and end-of-life management.
Private sector agricultural value chain standards setting organizations	Set standards for good practice in agricultural supply chain processes against which agricultural producers and distributors can be assessed by certification bodies. Such certification can provide assurance of the sustainability of production processes to retailers and consumers.
Certification bodies	Organizations that certify compliance of products and practices to standards.
Trade bodies and organizations	Collectively represent interested private sector stakeholders. Capacity development and liaison with producers, distributors and users. In some EPR schemes it is the trade bodies that coordinate the contributions of their members.
Non-governmental organizations	Identify and describe good practices, facilitate the development of international regulatory instruments, capacity development, and harmonization.
Academia	Provide academic research on alternatives and innovations to reduce the use of plastics in agriculture and its impacts.

Source: FAO, 2021.

7.3 Priority actions

The deadline for achieving the SDGs is 2030, only eight years away; while that of the Paris Agreement is 2050, only 28 years away. So, while action is being taken to develop the overarching international policy and legal instruments and technical guidance, governments should begin to address priority issues. This section sets out some of the actions that the authors consider should be taken. The basis of their selection is one or more of the following criteria:

1. The actions are already mandated by existing international conventions or recommended in voluntary guidelines;
2. The actions focus on products that this report has identified as having a high potential for environmental harm;
3. More circular (bio-)economy approaches are readily available; or
4. The actions can be implemented quickly, with immediate contributions to achieving the SDGs and the Nationally Determined Contributions of the Paris Agreement. By implementing these actions, governments can reduce GHG emissions.

7.3.1 Fishing gear

The sustainable management of fishing gear is already well addressed under the MARPOL Convention (IMO, 1983), the Code of Conduct for Responsible Fisheries (FAO, 1995) and the Voluntary Guidelines on Marking of Fishing Gear (FAO, 2019a). Under these instruments it is recommended that national governments and regional fishery bodies:

- Establish reception facilities for the free of charge acceptance of unwanted fishing gear at all coastal and inland locations where fishing and aquaculture is practised. Ideally there should be an associated incentive and awareness raising scheme to encourage fishers to return unwanted fishing gear and all other wastes generated during fishing activities.
- Establish an EPR scheme for the collection and recycling of unwanted fishing gear and incentivize the circular and environmentally sound design of fishing gear.
- Make the marking of fishing gear and the reporting of lost fishing gear mandatory in their jurisdictions.
- Consider banning the use of non-biodegradable fishing gear components, such as dolly ropes, that are designed to rapidly wear out through the course of fishing operations, routinely releasing fragments into the environment.
- Develop and promote modifications to fishing gears that reduce the risk of ghost fishing, such as escape panels being fitted on traps, using fully biodegradable fastenings to minimize the risk of ghost fishing when gears become lost or abandoned.
- Require escapes to be fitted on nets and traps that are to be secured by fully biodegradable closures to minimize their potential for indefinite ghost fishing.

7.3.2 Products with a high potential for creating plastic and microplastic pollution

Non-biodegradable products with a high risk of leakage of plastics and microplastics to the environment should be banned. These include:

- Polymer coated fertilizer, seeds, and pesticides;
- Oxo-degradable plastic compounds;
- Tree guards and shelters; and
- Plant support twines, nets, clips and ties.

7.3.3 Products with high potential for release of POPs and other hazardous chemicals

To avoid the potential for the release of PCDD/Fs during disposal, all single/short-term use products manufactured from PVC, such as films, irrigation tape, twines, and nets should be banned. Hazardous chemicals in plastic products should be substituted with safer alternatives.

Governments should also institute a ban on the open burning of plastic waste.

7.3.4 Non-biodegradable mulching films

Poor selection, management, and retrieval of non-biodegradable mulch films can lead to significant levels of plastic residues left in the fields. To increase their resistance to damage and disintegration, and improve their value for recycling, it is recommended that governments set a standard for their minimum thickness at 25 μm.

Governments should encourage the use of alternative agricultural practices that do not require the use of plastics or substitution with fully biodegradable mulching films where appropriate and where demonstrated not to cause harm to human and ecosystem health.

7.3.5 Rapid establishment of extended producer responsibility schemes

Governments should encourage the establishment of EPR schemes for as many agricultural plastic products as possible. Ideally, such schemes should be made mandatory for product manufacturers and other actors in the supply chain.

For products that are already subject to national legislation, it may be possible to introduce regulatory amendments that require EPR. For example, in the case of empty pesticide containers, pesticide registration regulations could be amended to require registrants to demonstrate that they provide a free of charge return scheme as part of their application for registration of a pesticide product. In some countries, the principle of EPR may already be mandated under environmental or waste legislation.

Where EPR schemes already exist for a particular agricultural plastic product, governments should encourage the schemes to widen their scope to collect and recycle all the other agricultural plastic wastes that are generated by their users. The existing empty pesticide container EPR schemes could be extended in this way to offer a full plastic waste service to farmers. The producers and supply chain actors of the other plastic products should participate and contribute financially to the combined scheme.

In countries where there are no existing legal frameworks that could mandate EPR, governments could signal their intention to develop such frameworks and encourage the establishment of voluntary schemes in the interim.

7.3.6 National plastic management plans

Governments should develop national plastic waste management plans to improve its circularity. The process should initiate with a review of the national capacity for managing agricultural and other plastic wastes. Such a review should consider the volumes and types of plastic entering the country and the capacity of existing waste management infrastructure. The plan should identify needs for recycling capacity and identify options for its establishment, and strategies for managing plastic waste in the interim.

7.4 Development of guidance documents

In preparing this report, the authors identified a lack of independent good practice guidance related to agricultural plastics. FAO's technical guidance documents, particularly in the crop production, livestock farming, and forestry sectors often refer to the benefits of plastic products without elaborating on their trade-offs and alternatives. Rarely does the guidance include best practice in the selection, deployment, use and post-use of plastic products. Recent guidance documents in the fisheries sector generally do address plastics issues. It is recommended that FAO (and other organizations) review all their technical guidance documents to ensure that issues of plastic products are adequately addressed. It may be necessary to develop new guidance altogether.

Guidance is required for, *inter alia*:

- field irrigation;
- horticulture, fruit, and nursery production – greenhouses, high and low tunnels, mulching, irrigation, hydroponics, support twines, nets, and ties;
- feed and fodder production – silage films, bale nets, and twines;
- post-production – plastic products (including packaging) used in storage, transportation and distribution;
- legislation for plastics;
- responsible procurement practices and environmental safeguards; and
- production and use of alternatives to plastics, including bio-based plastics.

7.5 Gaps and further research

7.5.1 Data on agricultural plastics

This report has identified significant data gaps on agricultural plastic products – their quantities, composition, where and how they are used, their environmental fate throughout the supply chain, during use and at end-of-life. It is recommended that governments begin to collect data on agricultural plastics use and their fate. This should help support policy decision-making and national and regional strategies. Yates *et al.*, (2021) published a review of scientific literature on environmental, food security and health impacts of food system plastics. It provides a basis to identify data gaps and research priorities.

7.5.2 Life cycle assessments

There are limited data on life cycle assessments of fossil-based and bio-based agricultural plastics (both biodegradable and non-biodegradable) and the alternative products and practices that determine and compare their risks and benefits for specific applications in agrifood value chains. Such assessments would also support policy decision-making and national and regional strategies.

7.5.3 Data on impacts of plastics and of their alternatives

Similarly, there are significant data gaps on the pathways and impacts of plastics and their alternatives (including biodegradable plastic) on human and ecosystem health. Their potential for transference and accumulation through the food chain has been identified in aquatic environments. However, much less is known about their transference through terrestrial food chains and agri-food systems. Micro- and nanoplastics have been found in human organs, but their precise impacts are unknown. Further research should be undertaken to assess plastics in all food systems to identify pathway mechanisms and their impacts. Such research could include the nuclear methods to track and quantify the movement and impacts of microplastics and contaminants being undertaken by the International Atomic Energy Agency (IAEA, 2021b).

7.5.4 Standards and specifications for biodegradable products

The report has identified that one of the major barriers to the uptake of biodegradable products is the lack of certainty of their behaviour and rate of biodegradation in a particular environment and conditions of temperature and humidity. Standards and specifications for biodegradable products should be developed that would provide indications of their performance and rate of biodegradation in situ and ex situ in composting and recycling. This is particularly important for, *inter alia*:

- aquatic environments at various depths and temperatures e.g. for dolly rope;
- on soils in various climatic zones for mulch films to meet the needs of different crops and cropping cycles;
- in air for those products that are not in direct contact with the soil, for example tree guards; and
- additionally, the technical specifications for the biodegradable products should ensure their suitability for mechanized production methods.

7.5.5 Intractable plastic products

There are some applications where it is difficult to find suitable alternatives to plastic products and where these products are difficult to recycle. Such products include, *inter alia*, pesticide impregnated plastic sheathes/bags to protect bananas and non-woven textile sheets to provide thermal insulation to crops. The issue with banana sheathes is the limited recycling capacity in the vicinity of the plantations and the hazards associated with the residual pesticides. The non-woven textiles tend to entrap large concentrations of soil particles which interferes with the recycling processes. It is recommended that manufacturers of these products undertake research to develop more sustainable alternatives and recycling technologies that address these issues.

7.5.6 Behaviour change

All the recommended interventions are aimed at changing the behaviours of all the actors in the agricultural plastics and agri-agri-food value chains to adopt more sustainable practices.

Research is needed to better understand the needs of users and the barriers to their uptake of more sustainable and best practice initiatives. Such behaviour change will also need to be supported with education, capacity-building and communications to improve knowledge and understanding of the issues at stake and sustainable practices.

7.6 Summary

This chapter proposes a number of policy mechanisms that aim to improve the management of agricultural plastics globally as one element of the transformation towards sustainable agri-food systems.

At the international level, it is recommended that parallel approaches be made, which specifically include:

Developing a comprehensive voluntary code of conduct to cover all aspects of plastics throughout agri-food value chains; and

Extending the scope of existing international conventions, such as the Basel Convention and the MARPOL Convention for the management of plastics used in fisheries and aquaculture.

It is also expected that a proposal will be tabled at UNEA 5.2 to establish an international negotiating committee for the establishment of a new international convention on all plastics, including those used in agri-food value chains.

In this way, the overarching principles of good management of plastics in agri-food systems can be established quickly with the voluntary code of conduct, while the slower process of modifying and developing legally binding international agreements can follow.

It is recommended that the new international voluntary code of conduct should address a number of important aspects, including *inter alia*:

- life cycle thinking in policymaking;
- regional approaches;
- product and process standards;
- target setting, together with monitoring and reporting;
- licensing and registration of products;
- supply chain stakeholder and user licensing;
- agricultural subsidy schemes and other financial mechanisms that encourage sustainable agricultural practice; and
- extended producer responsibility.

A number of key stakeholders will need to be involved in the development of the code of conduct, including government and regional bodies, plastic producers and users, the waste management sector, and standards setting and certification bodies.

There is an urgent need for action, both to reduce the direct environmental impact caused by agricultural plastic pollution, and the indirect impacts of GHG emissions associated with fossil based plastics. In the short term, it is recommended that those products identified as having a high potential for environmental harm should be targeted, including:

- fishing gear with a high risk of ghost fishing or of releasing microplastics;
- products with a high potential for creating plastic and microplastic pollution;
- products with high potential for release of POPs; and
- non-biodegradable mulching films.

Additionally, there should also be rapid establishment of EPR schemes, and the introduction of national plastic management plans.

Further research is needed to improve knowledge and understanding on the quantities, composition, and use of agricultural plastics throughout different supply chains; to develop standards and specifications for biodegradable products tailored to specific end use applications; and, to develop new recycling techniques for intractable plastic products.

8. Conclusions

The use of plastics has become ubiquitous over the past 70 years, reaching into every aspect of modern life the world over. This trend has also extended into the agricultural sector, which now employs a wide range of plastic products to improve productivity and reduce losses. As most products become redundant within a year, their end-of-life management needs to be considered carefully.

This study estimated that approximately **12.5 million tonnes of plastic products are used in agricultural applications annually**, with films accounting for between 40 to 50 percent of this total. The vegetable, fruit, crop, and livestock sectors are the largest users, accounting for ten million tonnes a year collectively, followed by fisheries and aquaculture, then forestry. This indicates that soil is the predominant receptor for agricultural plastic products, both during their intended use and at the end of their useful lives.

Knowledge and understanding about the quantities of plastics, including agricultural plastic products, entering terrestrial environments are sparse in comparison with marine plastics. Moreover, scientific research about the environmental harm caused by plastics to land-based ecosystems currently falls far behind that of aquatic environments. **This research gap needs to be closed urgently; this is particularly important in light of the fact that over 90 percent of agricultural activities take place on land**. Of increasing concern is the formation and fate of microplastics, which have potential to transfer along trophic levels and to effect harm at the cellular level. Again, **further research to better understand the effects microplastics may have at the ecosystem and individual level is urgently needed.**

An analysis of 13 agricultural plastic products identified some underlying themes, which span a range of agricultural plastic products, including:

1. Avoiding the use of plastics through the adoption of more sustainable agricultural practices, such as conservation agriculture and cover crops instead of using mulching films.

2. Replacing products with more durable alternatives, such as glass or polycarbonate instead of greenhouse films.

3. Replacing short-term single-cycle products with reusable ones, such as stackable rigid harvesting crates instead of flexible bags.

4. Establishing extended producer responsibility schemes.

5. Where appropriate, replacing non-biodegradable conventional polymers with biodegradable polymers with biodegradation properties adapted to their specific use.

6. Setting standards for products, associated equipment, and use practices.

7. Introducing labelling of products to aid identification and traceability.

8. Redesigning business models so that manufacturers or distributers of plastic products provide them as part of a service, rather than as a single transaction sale of goods.

A review of policy frameworks and legislative measures did not identify any one particular measure that could be applied in isolation in order to facilitate good management practices; instead, a blended approach, simultaneously implementing several measures, should be considered. At the international level:

- **Development of a comprehensive voluntary code of conduct** to cover all aspects of plastics throughout agri-food value chains.

- Where appropriate, **existing international conventions could consider addressing specific aspects of the life cycle of agricultural plastics,** such as: the Basel Convention, beyond just wastes; and the MARPOL Convention for the management of plastics used in fisheries and aquaculture.

It is recommended that the issues of the sustainability of agricultural plastics be mainstreamed throughout FAO's instruments and guidance related to good agricultural practice, food security, food safety and nutrition.

The study also **identified existing knowledge gaps and suggested areas for further research**, including:

1. the global flows and fates of agricultural plastics; their quantities, composition, where and how they are used, their environmental fate throughout the supply chain, during use and at end-of-life;

2. life cycle assessments of fossil-based and bio-based agricultural plastics (both biodegradable and non-biodegradable) and the alternative products and practices to determine and compare their risks and benefits for specific applications in agrifood value chains;

3. the pathways and impacts of plastics, micro- and nanoplastics on agroecosystems, food safety and human health, including their potential for transference and accumulation along the food chain and in agrifood systems; and

4. the behaviour and rate of degradation of biodegradable products in different environments and conditions of temperature and humidity. This includes: aquatic environments and soils in various climatic zones; products not in direct contact with soils; and synergistic effects with other chemicals. Impacts of agricultural plastic pollution on microbiomes, soil and water quality, and on long-term soil productivity should also be studied. In this way the overarching principles of good management practices can be established quickly through a voluntary code of conduct, while the slower process of modifying and developing legally binding international agreements can follow.

It is recommended that those agricultural plastic products identified as having a high potential for environmental harm, should be targeted as a matter of priority, including:

- fishing gear;
- products with a high potential for creating plastic and microplastic pollution;
- oroducts with high potential for release of POPs; and
- non-biodegradable mulching films.

Additionally, it is recommended there should also be rapid establishment of extended producer responsibility schemes, and the introduction of national plastic management plans.

This study also identified innovative examples of plastic alternatives being used in small-scale applications. **Investment in innovative practices and products should be provided through research and innovation grants to advance new ideas and the development of new products**.

Barriers to recycling should also be addressed, including **investment in developing new machinery and techniques to improve retrievability and cleaning of end-of-life plastic products,** and **strategic investment in recycling infrastructure** in order to fill existing gaps and meet anticipated demand. In some countries donor assistance may be required to provide investment support.

The urgency for coordinated and decisive action cannot be understated. Measures to both reduce the direct environmental harm caused by agricultural plastic pollution, and the indirect impacts of GHG emissions associated with the use of petroleum-derived plastics, need to be implemented as a matter of priority. At the time of writing, the time to meet the United Nations' Sustainable Development Goals is only eight years away, whilst the 2050 carbon dioxide net zero target set in the Paris Agreement is only 28 years away. Given the long lead-in time required for capital infrastructure and the delivery of research and development projects, action needs to be prioritized.

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GLOSSARY

Additives	Additives are chemical compounds added to improve the performance, functionality and ageing properties of the basic polymer of plastic products. Some of the most commonly used additives include plasticizers, flame retardants, antioxidants, colourants, and light and heat stabilizers. A wide range of toxic chemicals are currently used as polymer additives, including chemicals that are not subject to international controls and recognized POPs that are allowed under exemptions (Hahladakis *et al.*, 2018; Regional Activity Centre for Sustainable Consumption and Production, 2020).
Agricultural plastics	A collective term that is generally used for products made from plastic that are used in the production phases of terrestrial agriculture, primarily crop and livestock production. However, for the purposes of this study, the term also includes products used in forestry and fisheries, and in the downstream phases of the agri-food value chains such as harvesting, storage, processing and distribution (FAO, 2021).
Bio-based plastics	Plastic polymers that are derived from plant based raw materials. These materials can be specifically grown crops (e.g. corn starch), by products from crop production (e.g. bagasse from sugar cane) or specifically grown algae. Not all bio based plastics are biodegradable or compostable. Bio based polymers are generally blended with fossil based polymers to produce a plastic product (European Environment Agency, 2020; Gilbert *et al.*, 2015).
Biodegradable	'Biodegradable' materials are able to be broken down into base substances such as carbon dioxide, water, and biomass by the action of microorganisms. The term by itself does not define how quickly this process will occur, or the specific set of conditions that are required (Ellen MacArthur Foundation and UNEP, 2020).
Biodegradable plastic	A biodegradable plastic is defined as a plastic that can be broken down into its constituent monomers and metabolized through the action of microorganisms, such as bacteria and fungi, over a period of time, into substances such as water, carbon dioxide and biomass. It can be produced from either bio-based or fossil-based precursors (European Environment Agency, 2020; Gilbert *et al.*, 2015).
Biosolids	Biosolids refer to the stabilized organic solids that are utilized, commonly in agriculture, for their nutrient, soil conditioning, energy content, or other beneficial characteristics. They are generated by sewage treatment processes (Wijesekara *et al.*, 2016).
Chemical recycling	The process in which (plastic) polymers are broken down via chemical reaction into monomers or partially depolymerized to oligomers, which can then be used in new polymerization processes to reproduce the original or a related polymeric product (Grigore, 2017).
Compostable	'Compostable', in the context of plastic, is a precisely defined term. It means that an item can break down into carbon dioxide, water, and biomass within a specific time frame and under specific, controlled conditions. 'Industrially compostable' and 'home compostable' are subsets of the term, for which internationally recognized standards have been developed (Ellen MacArthur Foundation and UNEP, 2020).
Conventional plastic	Refers to common plastic materials that are derived from non-renewable fossil based sources, such as petroleum, coal or gas (Zimmermann *et al.*, 2020). Typical polymers include polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET).
Deposit Return Scheme (DRS)	A system in which consumers pay a small surcharge/deposit on recyclable items such as plastic and glass bottles, which can be refunded upon their return to the point of purchase, thus adding value to waste (Resource futures, 2021).
Down cycling	Refers to a process where the recycled product has inferior quality compared to the original product, therefore only permitting use of the recycled polymers in lower value applications (Campbell-Johnston *et al.*, 2020).

Extended producer responsibility (EPR)	This is "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle". It can therefore be understood as a framework to ensure manufacturers expedite the appropriate collection and recycling or disposal of their products at the end of the products' life and aims to internalize environmental costs into the price of the product (Monier *et al.*, 2014).
Fossil-based plastic	Plastics that are derived from non renewable fossil based resources, such as petroleum, coal or gas. The term is synonymous with "Conventional Plastics". Some fossil based plastics are biodegradable (Gilbert *et al.*, 2015).
Leakage	The ability of plastics to enter aquatic and/or terrestrial environments through being either damaged, degraded and/or discarded.
Macroplastic	At present there is no commonly agreed definition of plastic size categories, as different researchers have used different size ranges depending upon their chosen analytical methods and field of study.
Mechanical recycling	Mechanical recycling, or material recycling, refers to mechanical processes of grinding, washing, separating, drying, re-granulating and compounding that attempt to recover plastics via the production of recycled polymers that can be converted into new plastic products. The process does not alter the plastic polymer (European Bioplastics, 2020).
Megaplastic	At present there is no commonly agreed definition of plastic size categories, as different researchers have used different size ranges depending upon their chosen analytical methods and field of study. For the purpose of this study, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection categories will be used, which define megaplastics as very large plastic items bigger than 1m (GESAMP, 2019).
Mesoplastic	At present there is no commonly agreed definition of plastic size categories, as different researchers have used different size ranges depending upon their chosen analytical methods and field of study. For the purpose of this study, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection categories will be used, which define mesoplastics as plastics between 5 and 25 mm (GESAMP, 2019).
Microplastic	At present there is no commonly agreed definition of plastic size categories, as different researchers have used different size ranges depending upon their chosen analytical methods and field of study. For the purpose of this study, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection categories will be used, which define microplastics as plastics fragments that are smaller than 5mm in diameter (GESAMP, 2019).
Down cycling	Refers to a process where the recycled product has inferior quality compared to the original product, therefore only permitting use of the recycled polymers in lower value applications (Campbell-Johnston *et al.*, 2020).
Nanoplastic	At present there is no commonly agreed definition of plastic size categories, as different researchers have used different size ranges depending upon their chosen analytical methods and field of study. For the purpose of this study, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection categories will be used, which define nanoplastics as extremely small plastics fragments that are smaller than 1 μm (GESAMP, 2019).

Annex 1. Value chains

As discussed in Chapter 5, the report reviewed representative agri-food value chains in crop and livestock production, fisheries and aquaculture and forestry to identify the key plastic products that were used in each. The objective was to assess their quantities, fate and potential for harm to human and ecosystem health, and their overall relative risk. Much of these data were unavailable and the authors were constrained to use expert judgement in making these qualitative assessments. The assessments were used in the comparative risk analysis, which are set out in Table 5 on page 44.

This annex includes diagrammatic representations of the selected generic value chains with the process steps or phases that they comprise. For each phase, there is an indication of the plastic inputs and their resultant plastic waste. In many cases, the waste or pollution from a plastic input may arise in a subsequent phase. The authors have endeavoured to identify representative plastic products for each value chain, however these will likely vary on a case by case basis. Due to variability of agricultural practice and the complexity of value chains throughout the world, the plastic products included in the generic value chains are not exhaustive. However, they do provide insights into how and where agricultural plastics are used and their fate.

The value chains included in this annex are:

1. Horticulture
2. Livestock with subsidiary chains for:
    - 2.1 Fodder and feed;
    - 2.2 Animal production;
    - 2.3 Products from live animals:
        - 2.3.1 Wool;
        - 2.3.2 Milk;
    - 2.4 Products from slaughtered animals:
        - 2.4.1 Leather; and
        - 2.4.2 Meat
3. Cotton
    - 3.1 Seeds
    - 3.2 Fibres
4. Forestry plantation
5. Marine capture fishery
6. Aquaculture
7. Banana
8. Maize

Explanatory note:

1. The phases or process steps in the value chains are presented vertically, each with a different colour code.

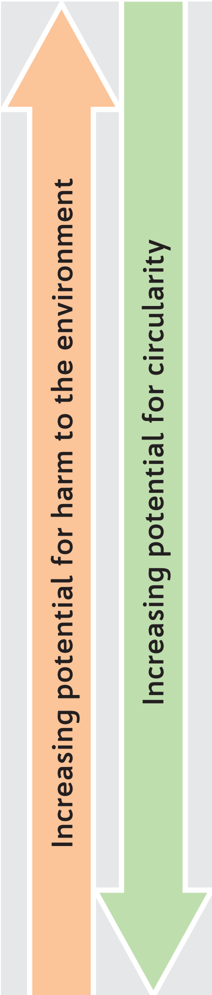
2. Plastic products introduced during a phase are shown in the INPUTS column in the colour associated with that phase.

3. Waste from the use of a plastic product are shown in the WASTES column in the value chain phase where they become waste. The input and its waste are linked with an arrow. The waste is shown in the same colour as the product from which it derives.

4. Classification of products

The products have been classified and marked with a symbol according to both their potential to cause harm to the environment and their potential for circularity. The classifications and symbols are shown in the following table.

Classification of products



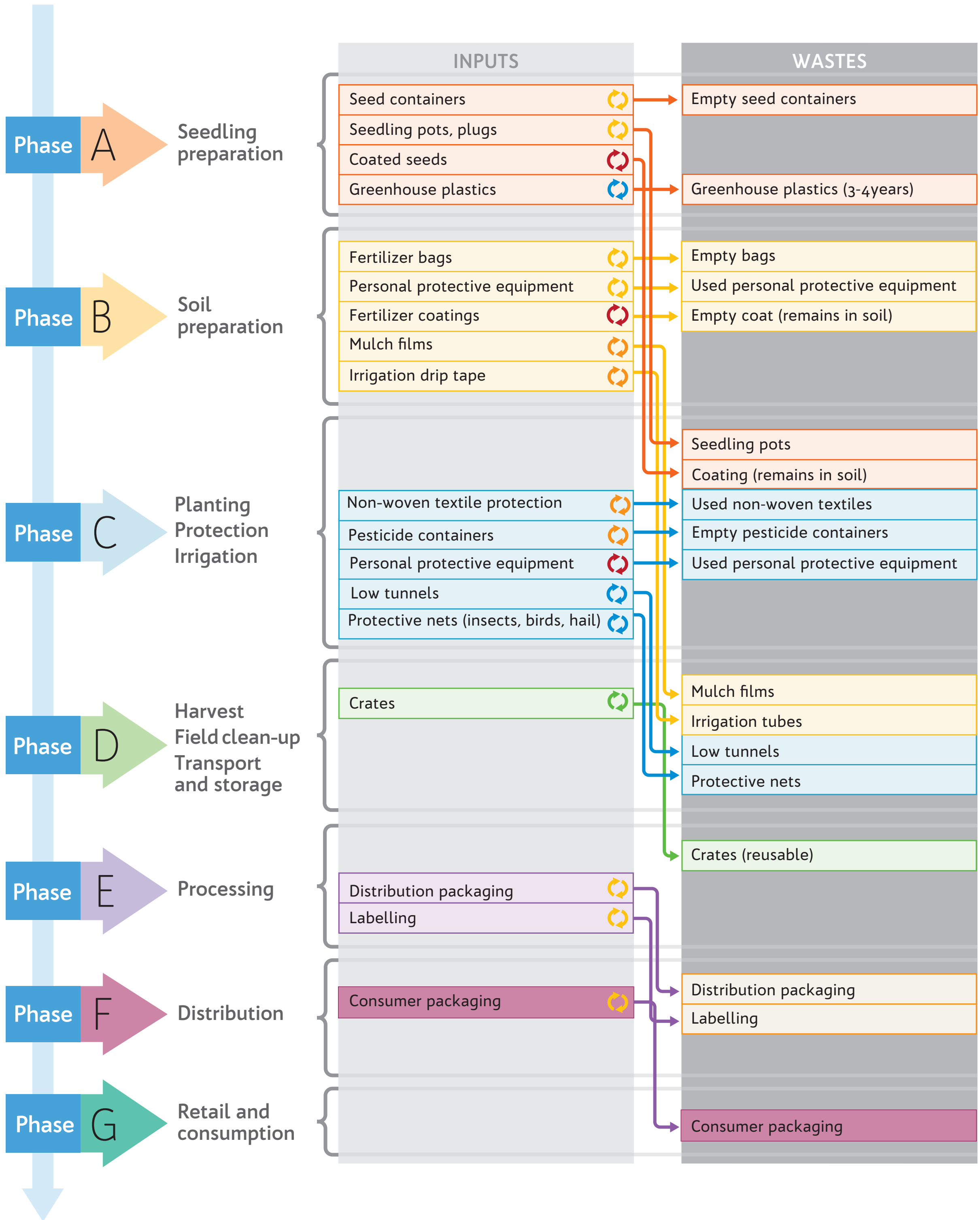
Symbol	Description	Examples
	Products where the plastics become completely dispersed in the environment	• Polymer coatings of fertilizers, seeds and pesticides • Elastration bands for livestock • Dolly rope on trawl nets in capture
	Products with a high risk of dispersal into the environment or contamination that limits options for recycling	• Mulching films and irrigation tape • Plant support twines and nets • Pesticide containers and impregnated plastics • Veterinary consumables • Tree guards
	Single use products with short period of use (<6 months) but with potential for collection and some recycling	• Packaging for fertilizers and seeds • Personal protective equipment • Distribution and consumer packaging
	Single use durable products (useful life >3 years) and with potential for collection and some recycling	• Greenhouse films • Pond liners and irrigation mains • Ear tags for marking livestock • Fishing nets and cages
	Reusable products that only become waste after several use cycles and with potential for collection and recycling	• Crates for harvesting crops • Crates for small livestock • Hermetically sealed crop storage bags • Sanitizable insulated boxes for distribution of fish

5. Linked value chains

For long and complex value chains, such as livestock, it has been necessary to break them down into a number of separate linear elements. Product inputs in the final phase of one element and their waste arising in the first phase of the subsequent one are cross-referenced.

1. Horticulture

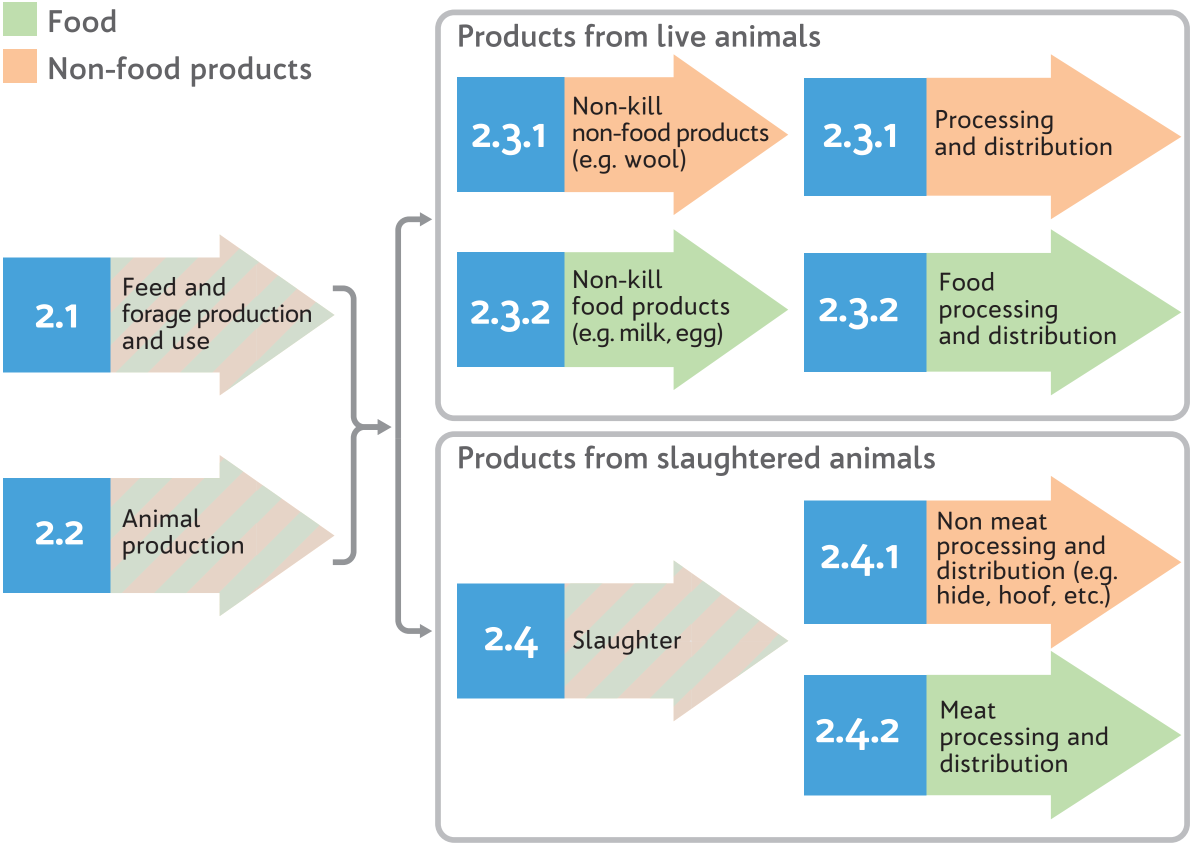
This value chain provides detailed analysis of a variety of plastics produced and used in vegetable production including greenhouses, mulching films and drip irrigation, and subsequent distribution of vegetables to consumers.



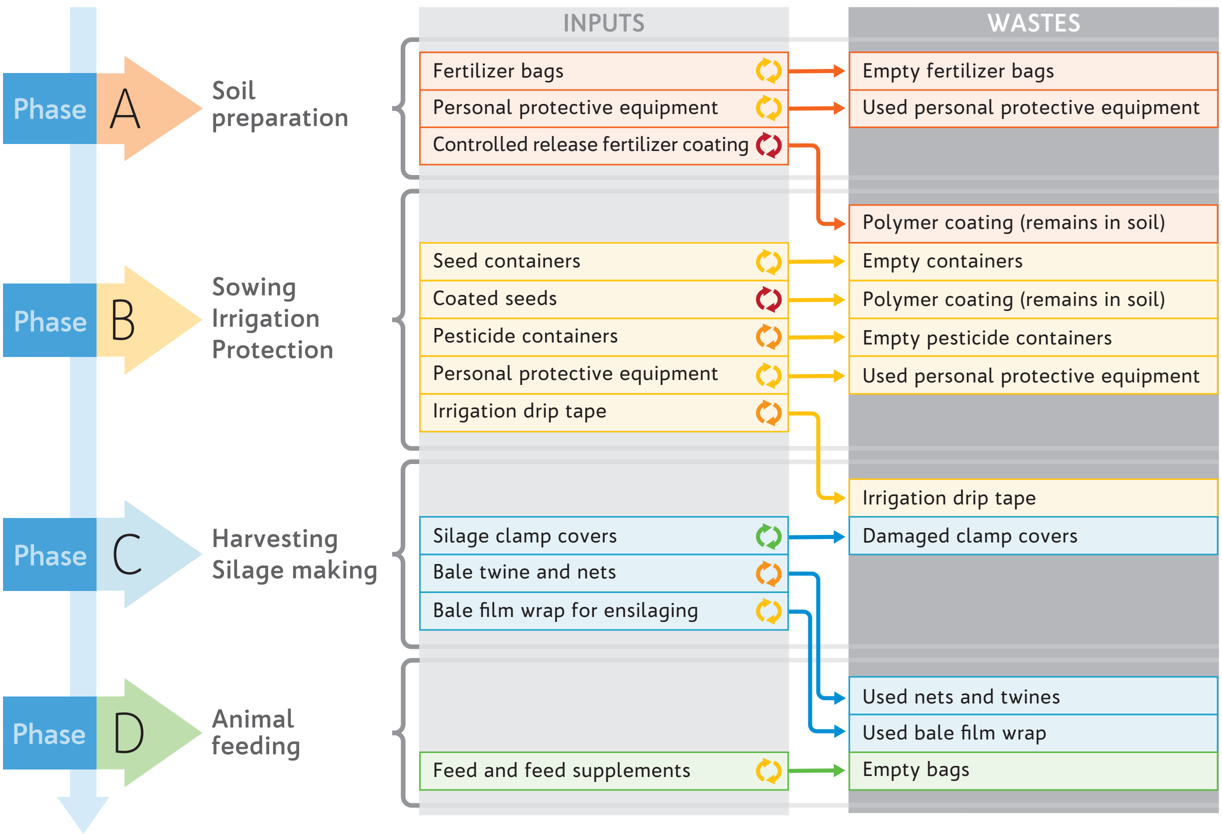
2. Livestock

This value chain provides a summary of long and complex value chain for livestock production. It includes a variety of plastics produced and used in livestock production of food and non-food products from both livestock and fodder production. It includes feed and forage production, the various stages in animal husbandry and the subsequent processing and distribution of their products.

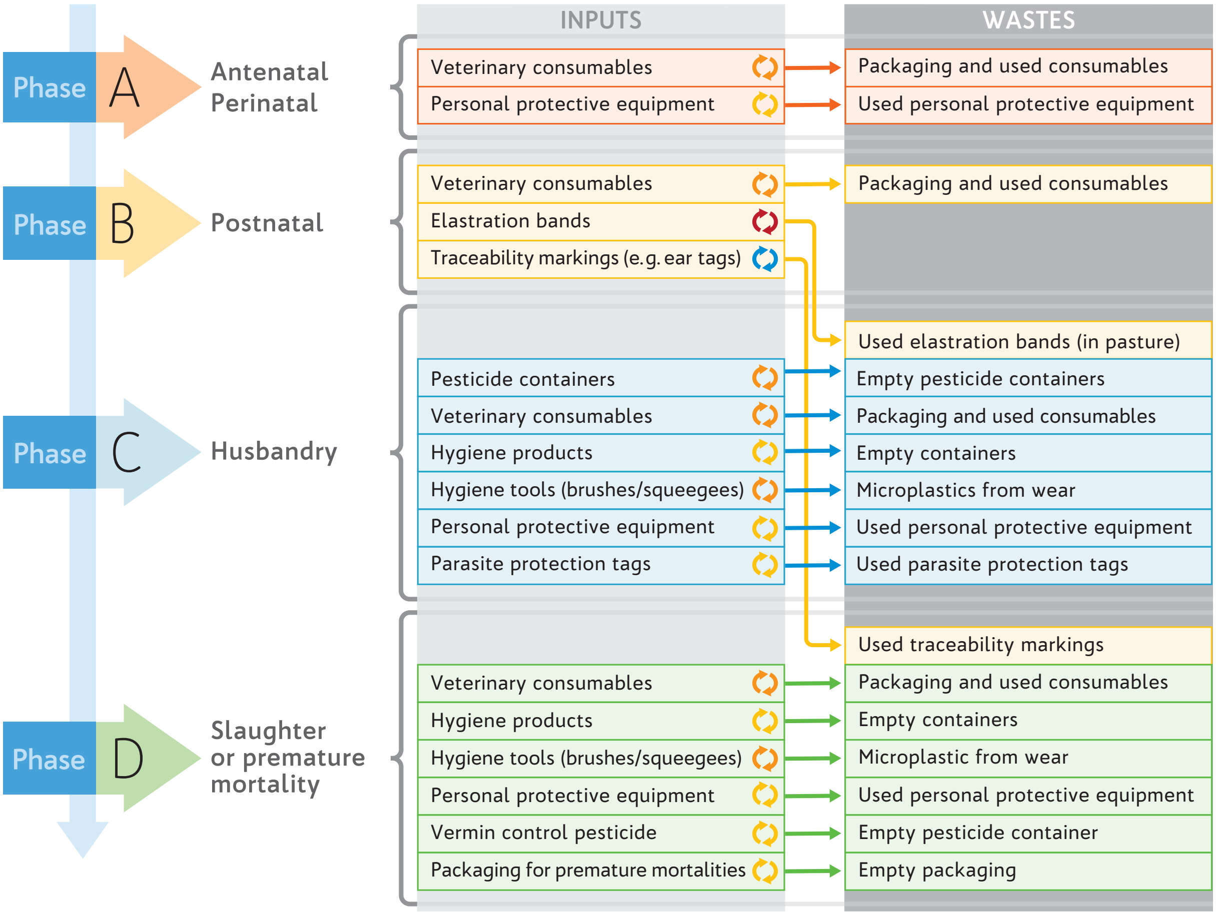
Overview of value chain elements for food and non-food livestock products



2.1 Fodder and food

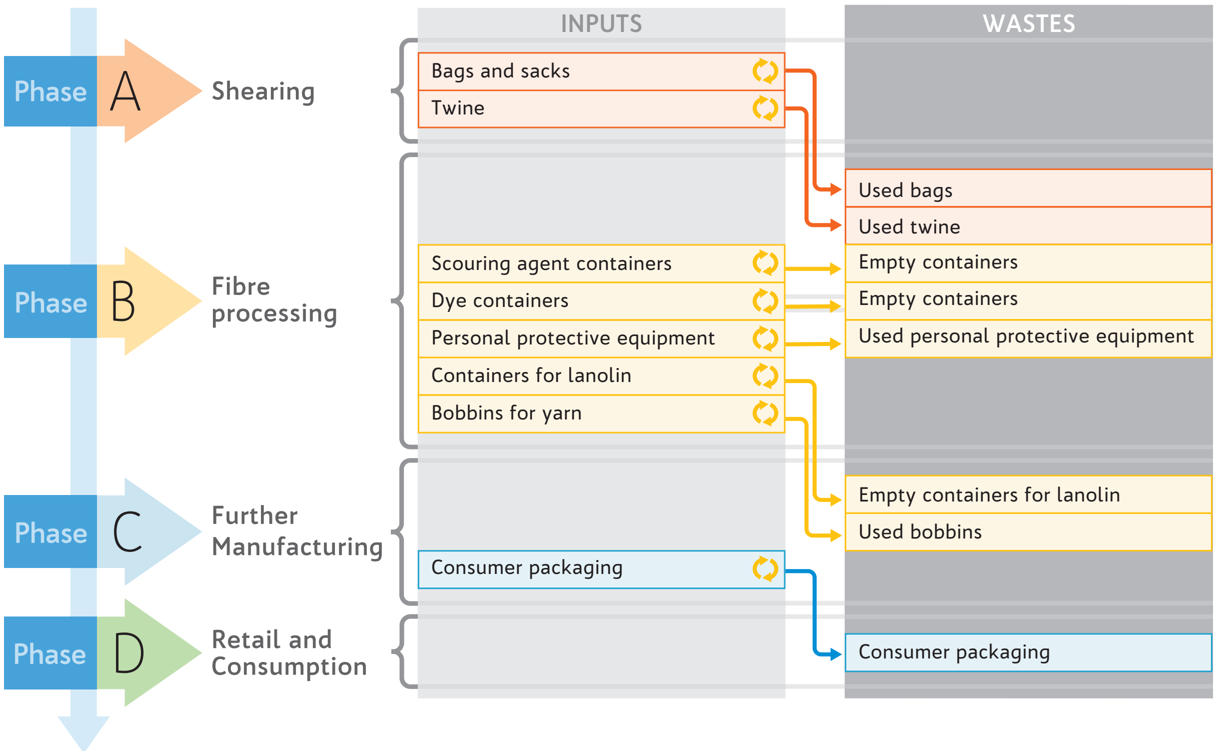


2.2 Animal production

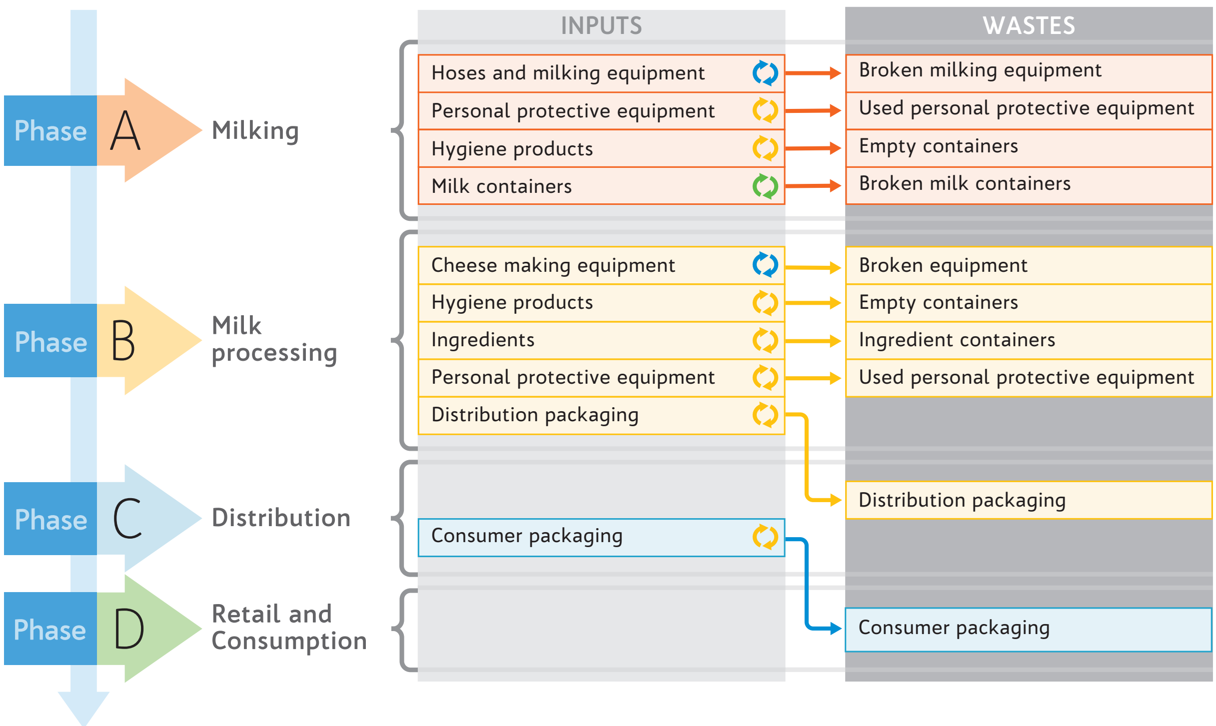


2.3 Products from live animals

2.3.1 Wool



2.3.2 Milk



2.3 Products from live animals

2.3.3 Leather

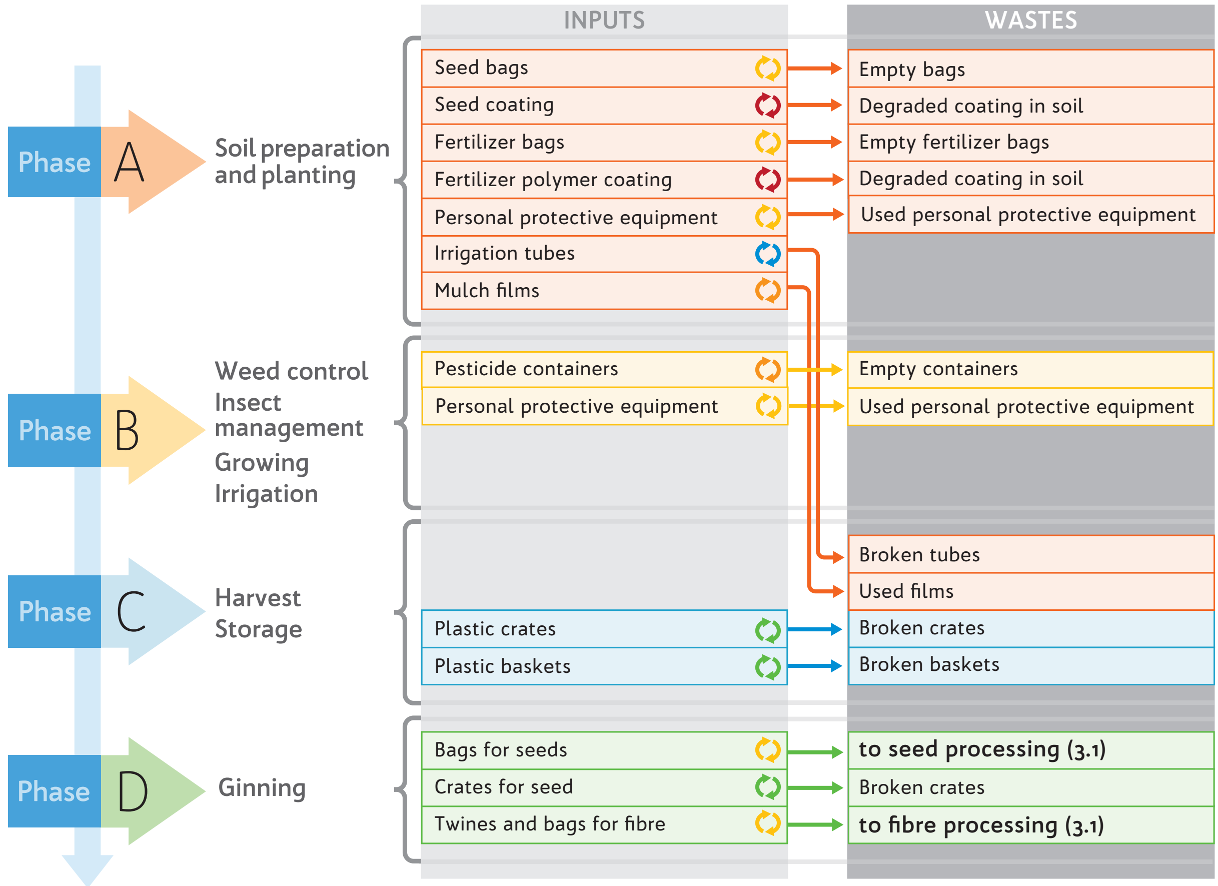
Phase	Stage	Inputs	Wastes
Phase A	Slaughter	**Traceability markings (from 2.2)**	Used traceability markings
		Veterinary consumables	Packaging and used consumables
		Personal protective equipment	Used personal protective equipment
		Hygiene product containers	Empty containers
		Hygiene tools (brushes/squeegees)	Microplastic (wear) & broken tools
		Crates and insulated boxes	Broken crates and boxes
Phase B	Non-meat processing e.g. tanning hides	Plastic processing equipment	Broken equipment
		Hygiene product containers	Empty containers
		Dye and chemical containers	Empty containers
		Personal protective equipment	Used personal protective equipment
		Vermin control pesticide containers	Empty pesticide containers
		Distribution packaging	
Phase C	Leather goods manufacturing		Distribution packaging
		Consumer packaging	
Phase D	Retail and Consumption		Consumer packaging

2.3.4 Meat

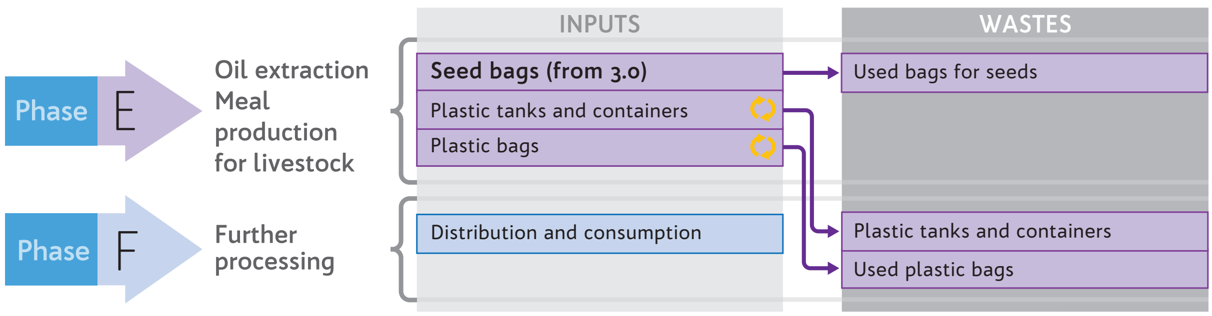
Phase	Stage	Inputs	Wastes
Phase A	Slaughter	**Traceability tags (from 2.2)**	Used traceability markings
		Veterinary consumables	Packaging and used consumables
		Personal protective equipment	Used personal protective equipment
		Hygiene product containers	Empty containers
		Hygiene tools (brushes/squeegees)	Microplastic (wear) & broken tools
		Crates and insulated boxes	Broken crates and boxes
Phase B	Meat processing	Plastic processing equipment	Broken equipment
		Hygiene product containers	Empty containers
		Ingredient containers	Empty ingredient containers
		Personal protective equipment	Used personal protective equipment
		Vermin control pesticide containers	Empty pesticide containers
		Distribution packaging	
Phase C	Distribution		Distribution packaging
		Consumer packaging	
Phase D	Retail and consumption		Consumer packaging

3. Cotton

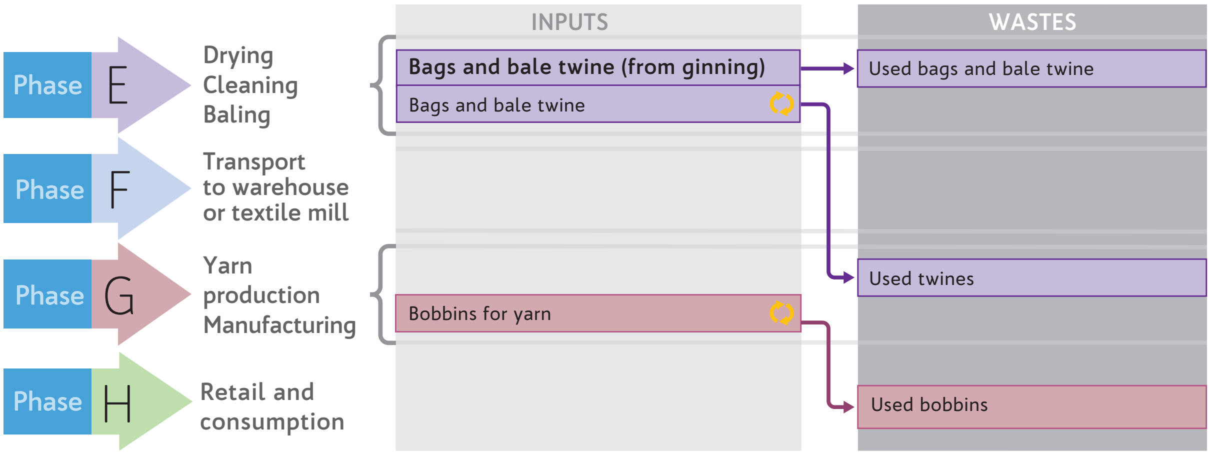
This value chain includes analysis of plastics produced and used during cotton production (including seed and fibre) as an example of non-food products. It includes preparation of soil and planting, subsequent processing, retail and consumption.



3.1 Seeds

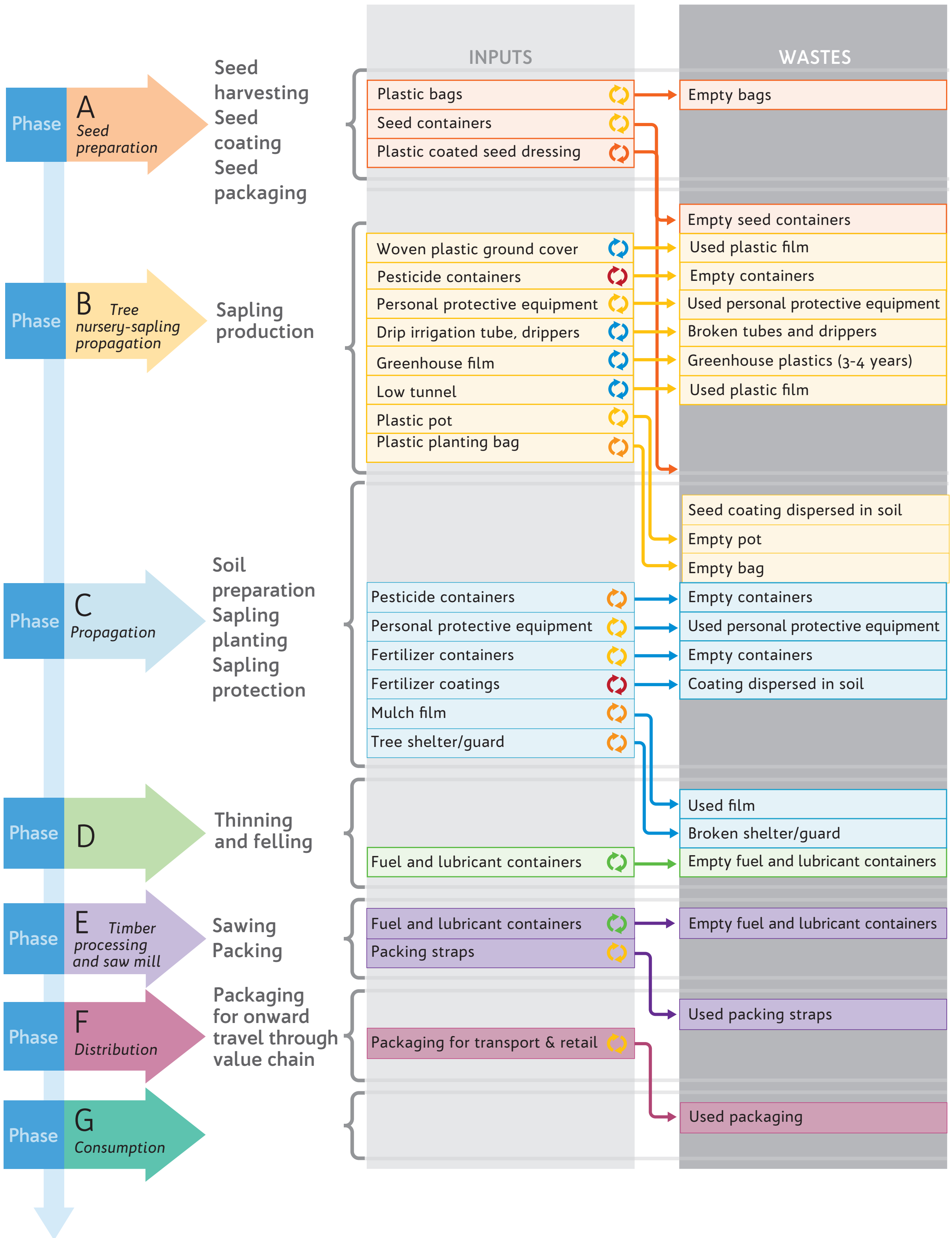


3.2 Fibres


INPUTS
WASTES
Phase E
Drying
Cleaning
Baling
Phase F
Transport
to warehouse
or textile mill
Phase G
Yarn
production
Manufacturing
Phase H
Retail and
consumption
Bags and bale twine (from ginning)
Bags and bale twine
Bobbins for yarn
Used bags and bale twine
Used twines
Used bobbins

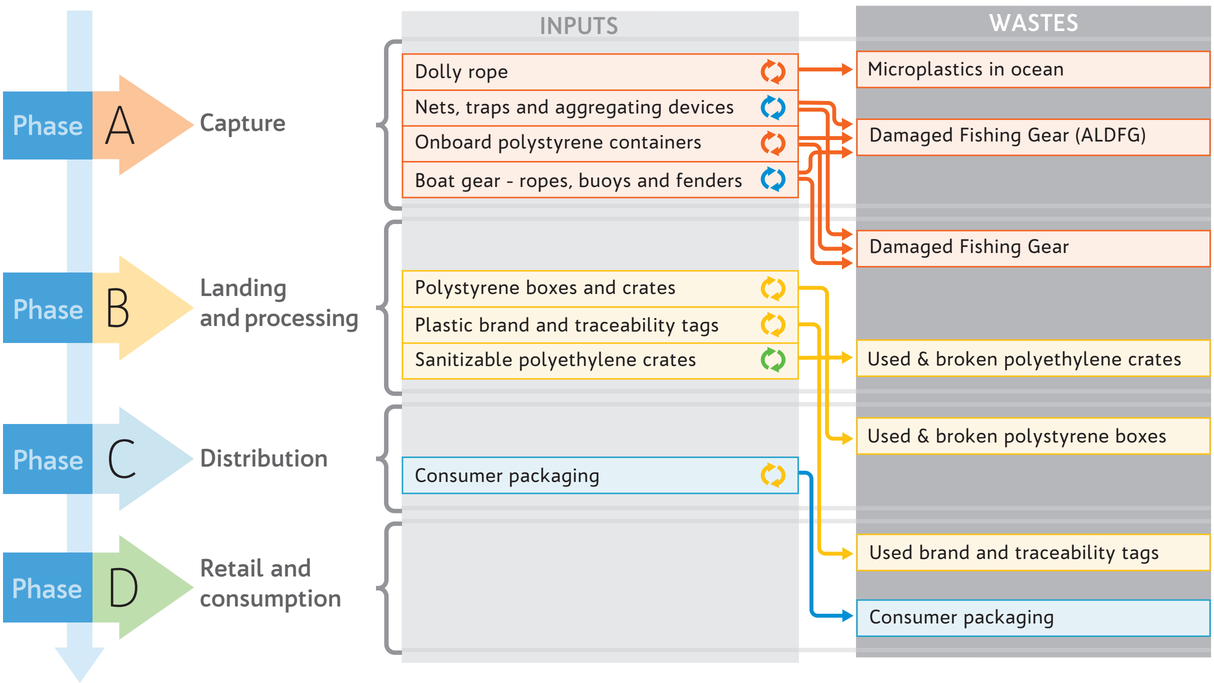
4. Forestry plantation

This value chain includes analysis of the plastic products produced and used in forestry plantations. It includes the preparation of seed, sapling production, propagation, subsequent processing, distribution and transport.



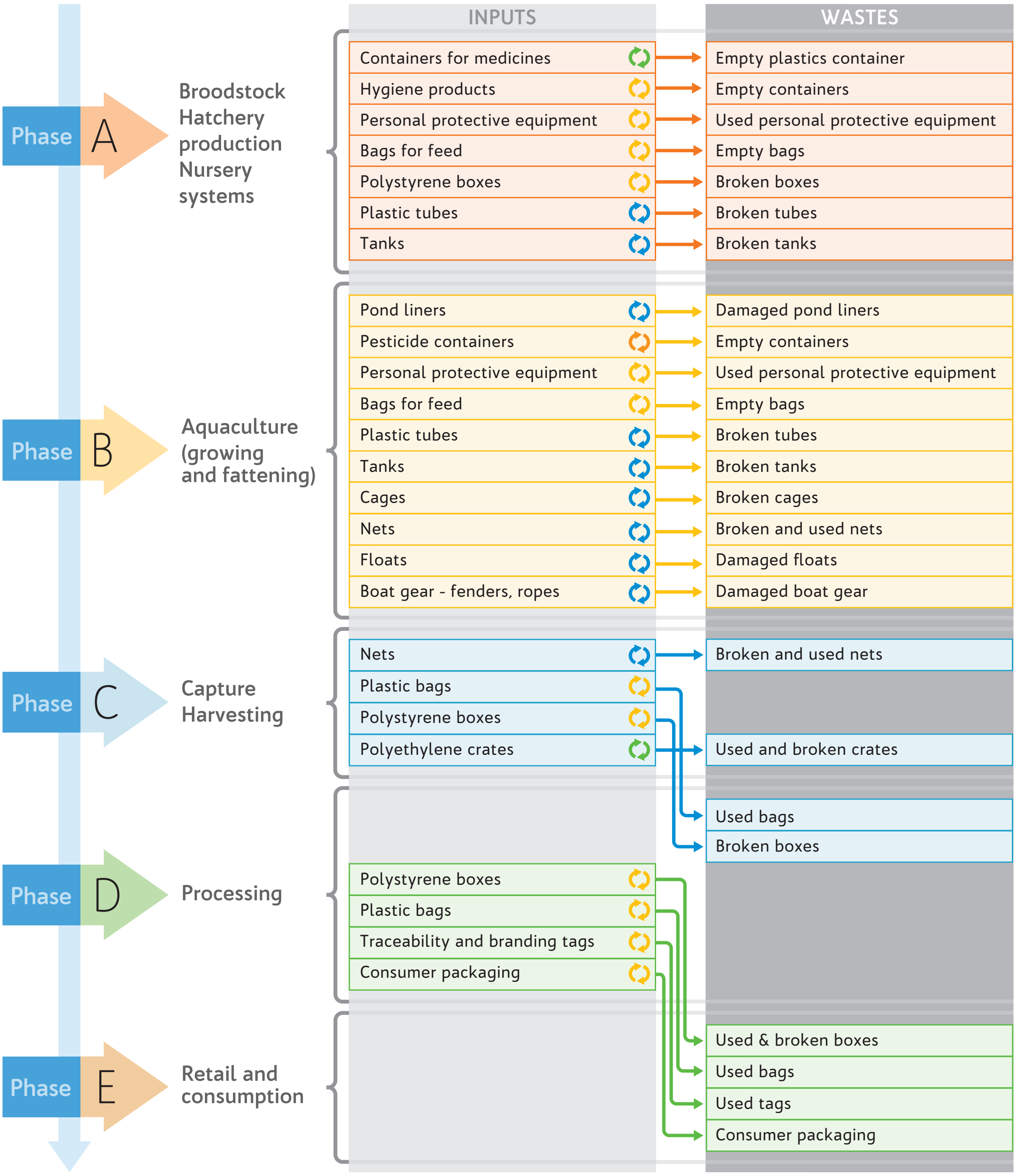
5. Marine capture fisheries

This value chain includes analysis of plastic products produced and used during marine capture fishery. It includes the capture, subsequent processing, distribution, and retail and consumption. At the end of its life, fishing gear is either abandoned, lost or discarded in the sea, or returned to port for recycling or disposal.



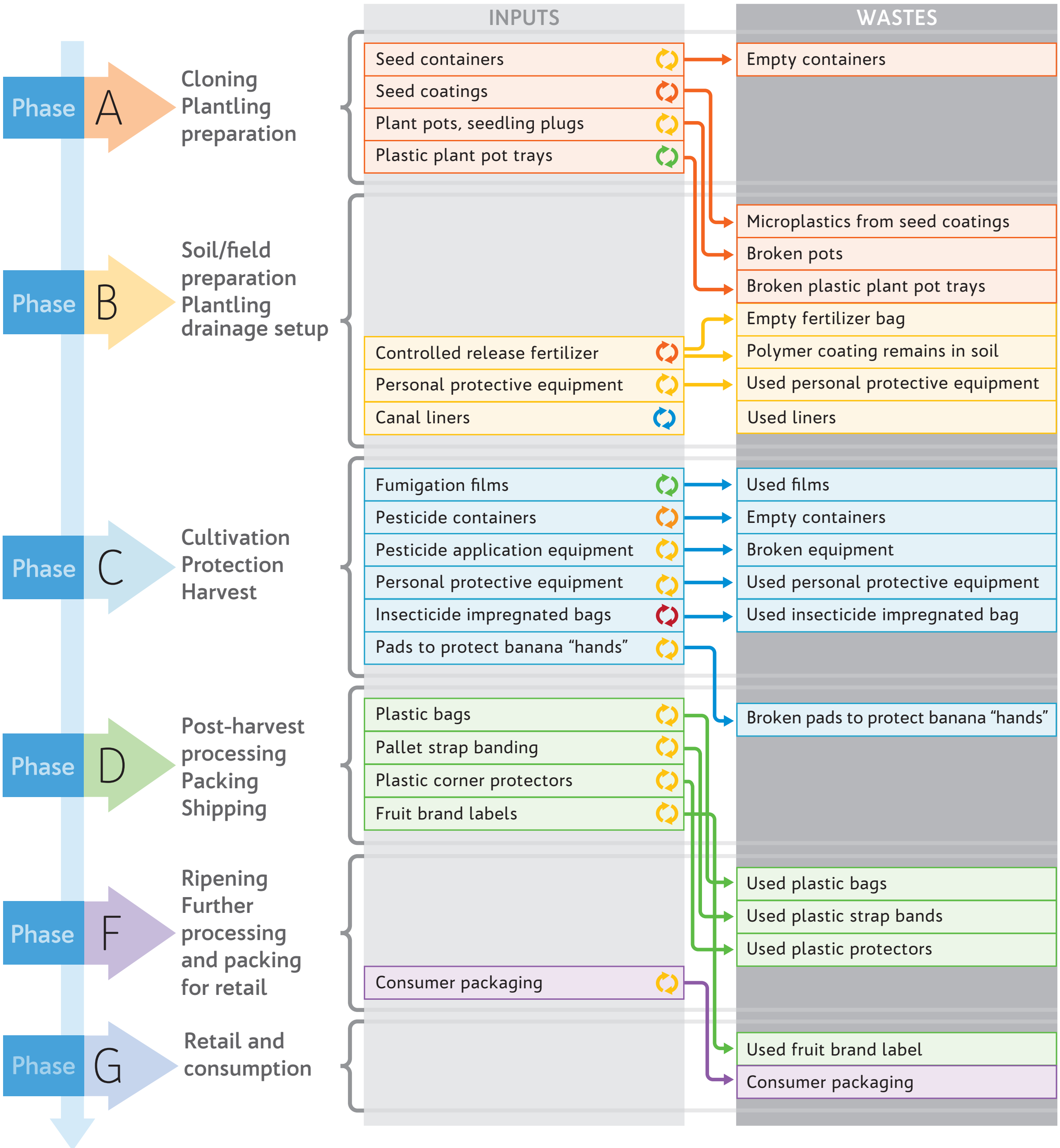
6. Aquaculture

This value chain includes analysis of the plastic products produced and used in aquaculture. It includes structure, the subsequent processing, distribution, and retail and consumption.



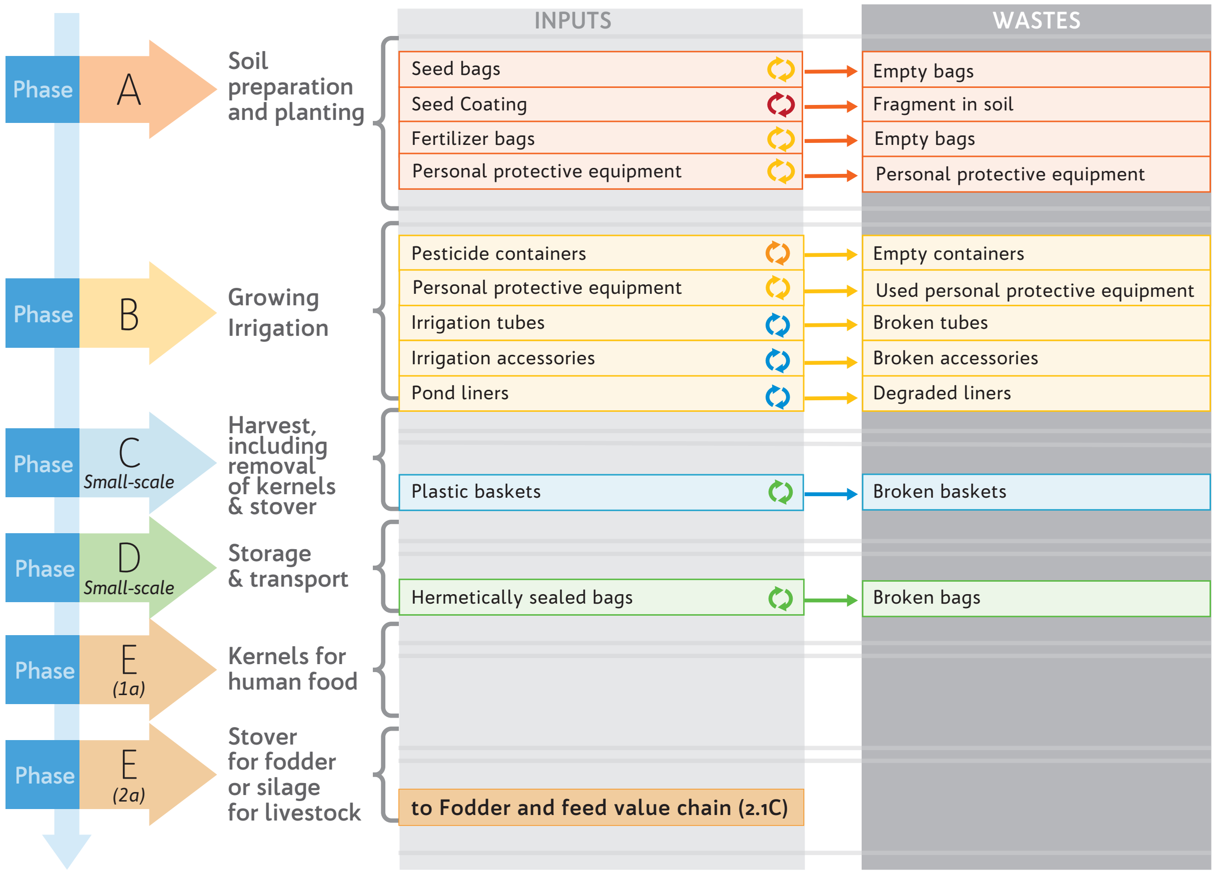
7. Banana

This value chain analyzes banana cultivation, production, processing, and transport. It was chosen as an example of a major tropical commodity with a long supply chain that uses significant amounts of plastics, especially during growth and harvest.



8. Maize

This value chain provides analysis of plastic products produced and used in small scale maize cultivation, distribution, processing, retail and consumption.



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