UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT

Plastic substitution in developing countries

Sectoral opportunities and challenges

Technical cooperation outcome

UN trade & development
UNCTAD

UNCTAD/TCS/DITC/INF/2025/

Acknowledgements

This document was prepared by Atiq Zaman, Ana Maria Caceres Ruiz, Benjamin Gazeau and Kate Ringvall from Curtin University, along with Alessandro Sanches Pereira from Instituto 17, as part of their research initiative with the Sustainable Manufacturing and Environmental Pollution (SMEP) and Ocean Economy and Fisheries Programmes at the UN Trade and Development (UNCTAD). The research was conducted under the supervision of Henrique Pacini, David Vivas and Glen Wilson (UNCTAD) and overall responsibility of Chantal Line Carpentier, Head of the Trade, Environment, Climate Change and Sustainable Development Branch of UNCTAD.

The research team gratefully acknowledges the following individuals and organizations for their support in providing information and feedback on the study: David Ongare (National Environmental Management Authority – Kenya), Emma Algotsson (Catchgreen), John Adams Carreon (Pacific Community – SPC), Anthony Talouli, Joshua Sam and Julie Pillet (South Pacific Regional Environment Programme – SPREP), Simon Derrick (Blue Skies), Suzan Yemidi (COCO360), Amin Hosseinian Far (University of Northampton), Giulia Carcasci (Food and Agriculture Organization of the United Nations – FAO), Vincent Ojijo (Council for Scientific and Industrial Research – CSIR) and Karen Raubenheimer (University of Wollongong). The report was proofread by Margaret Gollagher and Lalen Lleander.

This paper was produced under the Sustainable Manufacturing and Environmental Pollution (SMEP) Programme, funded by the Foreign, Commonwealth and Development Office (FCDO) of the United Kingdom of Great Britain and Northern Ireland and implemented in partnership with UNCTAD.

Desktop formatting was carried out by Lia Tostes and Rafe Dent.

Abbreviations

AFS	agroforestry system
ALDFG	abandoned, lost or otherwise discarded fishing gear
BDM	biodegradable mulch films
CA	conservation agriculture
CSA	climate-smart agriculture
CSIR	Council for Scientific and Industrial Research
EMF	Ellen MacArthur Foundation
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
GGGI	Global Green Growth Institute
GHGs	greenhouse gas emissions
HS	harmonized system
LDPE	low-density polyethylene
MENR	Ministry of Environment and Natural Resources
MFN	most-favoured-nation
NEMA	National Environment Management Authority, Kenya
PBAT	polybutylene adipate-co-terephthalate
PE	polyethylene
POP	persistent organic pollutant
POPRC	Persistent Organic Pollutants Review Committee
PVC	polyvinyl chloride
RCA	revealed comparative advantage
RPR	residue-to-product ratio
SMEP	Sustainable Manufacturing and Environmental Pollution Programme
SOM	soil organic matter
UNCTAD	UN Trade and Development

Table of contents

Executive summary

Executive summary

Plastic pollution poses significant threats not only to environmental health but also to human well-being and economic stability. For instance, emerging research has detected microplastics in human blood and brain tissues, raising concerns about potential long-term health effects. In marine ecosystems, plastic debris endangers wildlife and incurs substantial costs for pollution management, with global ecosystem damage estimated at approximately $2.2 trillion annually.

Despite numerous international initiatives to govern plastic materials, critical issues persist, mainly due to the expanding production of plastics, prevalent single-use packaging, and low recycling and recovery rates. These challenges underscore the urgent need for a transition to circular economy practices and the adoption of sustainable materials.

This report explores potential alternatives to conventional plastics in three sectors central to the economies of developing nations: food export packaging, fishing gear, and agricultural applications. Through case studies in Ghana, Nigeria, Fiji, and Kenya, this report identifies promising substitutes, from natural fibres to biobased polymers, possibly offering reduced environmental impact while supporting economic growth and diversification in these regions. However, the adoption of these alternatives is hindered by infrastructural limitations and the lack of standardised definitions and material standards. Recommendations emphasise sector-specific interventions to promote the shift away from plastic reliance, grounded in local resources and innovations.

Plastics in food export packaging

Plastic packaging plays a crucial role in food safety, distribution efficiency, and global trade. It protects food from contamination and spoilage, ensuring accessibility for consumers. However, sustainable packaging must prioritise material efficiency, hazard elimination, and recyclability, aligning with goals of environmental conservation and public health. In developing economies, integrating traditional and Indigenous knowledge with modern innovations can improve food protection and minimise waste. Understanding primary, secondary, and tertiary packaging— is essential for designing sustainable supply chains. Adopting a life cycle perspective ensures that packaging solutions are sustainable and do not inadvertently harm the environment.

Plastic packaging presents both opportunities and challenges in Ghana and Nigeria's cocoa market. While Ghana holds a competitive edge in cocoa production, both countries face socioeconomic challenges, such as high poverty rates and inadequate waste management infrastructure, which affect the sustainability of their cocoa export packaging. Raw cocoa beans are typically transported in jute bags lined with plastic, while processed cocoa products rely heavily on plastic packaging. In contrast, processed cocoa products like butter and powder rely heavily on plastic packaging to maintain quality during transport.

Exploring sustainable packaging alternatives such as biodegradable jute liners, compostable sacks, and seaweed-based bioplastics can reduce environmental impact. Circular economy policies, including Extended Producer Responsibility (EPR) and South-South collaborations, could drive innovation and sustainability in packaging materials.

Emerging research has detected **microplastics in human blood and brain tissues**, raising concerns about potential long-term health effects.

Fiji's economy faces ecological risks from abandoned plastic fishing gear, known as "**ghost gear**".

Plastics in fishing nets and fishing gear

The fishing industry benefits from durable plastic nets, but "ghost gear" contributes significantly to marine pollution. Regions like Fiji face severe ecological risks. The use of plastics in fishing nets and gear has substantially enhanced durability and efficiency within the fishing industry, yet it has also contributed significantly to marine pollution. Abandoned, lost, or discarded fishing gear, often termed "ghost gear," is a major source of ocean plastic debris, endangering marine ecosystems and biodiversity. For regions like Fiji, with an economy that heavily relies on fishing and tourism, the impact of plastic pollution on marine environments is particularly acute.

Recent waste audits from the South Pacific Regional Environment Programme (SPREP) and the International Union for Conservation of Nature (IUCN) reveal an urgent need for improved waste management infrastructure and robust recycling schemes in Fiji to mitigate these escalating challenges. Introducing policies that promote community waste accountability and global cooperation to reduce marine debris could play a pivotal role in curbing plastic waste in marine environments.

Establishing biodegradation standards tailored to the fishing industry would facilitate the adoption of sustainable gear materials. Furthermore, the report emphasises the importance of tracking of gear loss using a global positioning system (GPS) and systematic reporting mechanisms can reduce ocean plastic waste while fostering environmental stewardship.

Promising material innovations include biodegradable polymers and bioblends that break down safely in marine environments. Recycling abandoned fishing nets and expanding university research into bioblend materials can further support sustainable fishing while enhancing Fiji's economic resilience.

Kenya's agricultural sector, which contributes 60% of export earnings, increasingly uses plastic mulch and seedling tubes.

Plastics in agricultural mulch and seedling tubes

Plastic mulch films have become essential in agriculture for enhancing crop productivity through improved soil water retention, temperature control, and weed suppression. However, their disposal poses significant challenges. When left in fields, these films can fragment into microplastics, contributing to persistent soil pollution and potentially contaminating underground water sources. Retrieval is costly, often resulting in these films being landfilled, incinerated, or left to degrade in natural environments.

In Kenya, agriculture contributes substantially to the economy, representing a third of the GDP and 60% of export earnings. Both commercial and small-scale farmers increasingly use plastic mulch and seedling tubes, particularly in horticulture, which accelerates land degradation and threatens long-term soil health.

Potential substitutes for plastic mulches include organic mulching practices and biodegradable mulch films (BDMs). Organic mulching, utilising crop residues, is plastic-free and supports climate-smart agricultural practices, while BDMs offer a biodegradable option that removes the need for retrieval. However, BDMs come with trade-offs:

- **Advantages**: BDMs reduce labour and disposal costs by decomposing naturally, offering a lower-impact alternative to conventional plastic.
- **Drawbacks**: BDMs degrade at variable rates depending on soil, climate, and crop type, which can sometimes result in incomplete decomposition and microplastic buildup in the soil. In some cases, BDMs may also release chemicals like traditional plastics.

Kenya's abundance of crop residues provides an opportunity to transition to organic mulching, improving soil health and enhancing carbon sequestration. This approach considers crop residue availability, existing uses, and local production capacity.

While BDMs offer a secondary option to organic mulch, establishing clear agri-plastic standards is essential to ensure their safety and effectiveness in sustainable farming.

Additionally, cellulose-based products and crop residues are viable substitutes for plastic seedling tubes. These alternatives are essential for reforestation efforts and help mitigate the environmental impact of plastic seedling bags when improperly discarded.

Key findings

Packaging of food exports

The global market for plastic substitutes is maturing, valued at $388 billion in 2020. However, challenges persist, particularly in Africa, where plastic waste remains a significant issue due to weak enforcement and limited alternatives. Efforts such as plastic bag bans in Nigeria and Ghana during the mid-2010s demonstrate regional actions to reduce pollution from packaging, yet more comprehensive policies are needed. Extended Producer Responsibility (EPR) and Deposit Return Schemes (DRS) offer promising strategies, urging businesses to take greater responsibility for managing product life cycles.

In Ghana, the cocoa supply chain has the potential to utilise cocoa waste as a sustainable packaging material, aligning with global sustainability goals and potentially offering a competitive edge as markets impose stricter controls on plastic use. Such initiatives illustrate how local agricultural residues can serve as viable plastic substitutes, offering dual benefits of waste reduction and sustainable packaging innovation.

Fishing nets and fishing gear

Fiji's reliance on both fishing and tourism highlights the urgency for sustainable practices in marine industries. With Fiji's fisheries sector facing downturns due to COVID-19, including reduced fishing and tourism activities, the need for innovative, sustainable solutions is more pressing. Indirect measures like GPS tracking, gear marking, and waste collection programs could help reduce marine pollution by minimising gear loss.

Developing biodegradable fishing gear that meets local biodegradability standards can further align with Fiji's conservation goals and support economic recovery. Additionally, promoting recycling initiatives for abandoned nets and expanding seaweed culture in coastal areas could stimulate local economies. Supporting university-led research into bioblend materials and enhancing recycling facilities are key actions for transitioning toward sustainable fishing practices.

Agricultural mulch and seedling tubes

Substitutes for plastic mulch, such as organic mulching and BDMs, offer practical options for reducing plastic use in agriculture. Organic mulching, using crop residues, improves soil health and supports carbon sequestration. Kenya's abundant agricultural residues make organic mulching a viable alternative, yet improved waste management policies and infrastructure are needed to maximise their use. Examples of effective policies include incentives for crop residue collection and subsidies for composting infrastructure to promote better recovery and utilisation of these materials.

For seedling tubes, cellulose-based products and agricultural waste can serve as low-impact alternatives, reducing reliance on plastic in reforestation efforts. New business models, such as those utilising agrimats from organic waste materials, present promising pathways to meet conservation and sustainable agriculture goals in Kenya.

Key recommendations

Considering these findings, key recommendations include:

- **Promoting organic mulching practices** that leverage locally available crop residues.
- **Supporting the development of standards** for biodegradable and compostable plastics to guide sustainable agricultural practices.
- **Encouraging the adoption of EPR and DRS** for food packaging to ensure accountability in the supply chain.
- **Enhancing recycling infrastructure** and offering incentives for recovering and repurposing agricultural residues.
- **Facilitating local production** of mulch substitutes and seedling container alternatives to reduce plastic dependency.

These approaches emphasise localised solutions, regulatory support, and cross-sector collaborations, each essential for building sustainable practices that align with economic and environmental goals.

© Henrique Pacini (UNCTAD)

Chapter I

Introduction

Introduction

In the face of the triple environmental crisis, this report addresses the worsening plastic pollution crisis, which has been intensified by the COVID-19 pandemic and poses severe threats to global health, ecosystems, and the economy. This report covers three critical sectors, demonstrating the potential for replacing traditional plastics to support economic growth and reduce environmental impact. Through case studies in Ghana, Fiji, Kenya and Nigeria, it identifies sector-specific hurdles and assesses the feasibility of various material alternatives.

Annual damages to ecosystems from plastic pollution are estimated at $2.2 trillion (Forrest, et al., 2019), reflecting the enormous economic and environmental costs. The rise in single-use plastics (SUPs) during the pandemic has further compounded these challenges, especially as microplastics increasingly threaten marine ecosystems and human health.

Despite several international initiatives, significant issues persist, particularly in developing countries, emphasising the urgent need to shift toward circular economy practices. This report identifies sustainable alternatives to plastics in three critical sectors—food export packaging, fishing gear, and agricultural applications—as essential steps toward mitigating the escalating impacts of plastic pollution.

The research methodology combines qualitative and quantitative approaches, analysing plastic alternatives within the framework of international trade codes. Case studies from selected developing nations provide a deeper understanding of specific challenges and solutions, contributing to a more detailed and evidence-based narrative on sustainable material replacement.

This report distinguishes between plastic substitutes and alternatives, tailoring its recommendations to fit developing countries' unique conditions and economic frameworks. Through the lens of a circular economy, it proposes actionable strategies to decrease plastic dependency and promote a sustainable transition in these countries.

The selection of Ghana, Kenya, Nigeria, and Fiji as case study countries is based on their unique socio-economic and geographical relevance to the issue of plastic pollution. Developing nations and Small Island Developing States (SIDS) are particularly vulnerable to plastic pollution due to a combination of high plastic waste levels and limited infrastructure for effective waste management. Ghana, Kenya, and Nigeria were chosen as representative African countries facing significant challenges in addressing plastic pollution amidst rapid economic growth and urbanisation. Fiji, as an island nation in the Indo-Pacific region, exemplifies the acute impacts of plastic pollution on marine ecosystems and local communities. Both Africa and the Indo-Pacific are priority regions for the SMEP program, which funds this project, aligning the case studies with the program's strategic focus on high-impact geographical areas.

The report covers the potential material substitutions of crucial sectors in four countries: Ghana, Kenya, Nigeria, and Fiji. The following three economic sectors are explored and analysed in the context of plastic substitutes:

- **Packaging for food** exports in Ghana and Nigeria;
- **Fishing nets and fishing gear** in Fiji; and
- **Agricultural mulch and seedling tubes** used in agriculture and reforestation in Kenya.

Case studies focus on countries with **high plastic waste and limited infrastructure**: Ghana, Kenya, Nigeria, and Fiji.

The research identifies:

- The most promising materials, technologies and production methods that could allow wider substitution, lower impact in the life cycle, higher production and market scalability in a developing country context;
- Case studies that show best practices in terms of substitution, recyclability and sustainable waste disposal of the substitute options. Case studies should be constructed around a value and supply chain analysis for potential substitutes in the three areas;
- North–South partnership opportunities, especially instruments for technology transfer and investment in substitute development;
- Direct and indirect barriers to market development in substitute materials along the value chain; and conversely
- A set of positive incentives which were successfully utilized in national contexts.

These are based on case examples from sub-Saharan Africa, South Asia and the Indo-Pacific region, especially Small Island Developing States (SIDS) in the region.

Alternatives versus substitutes in plastics

Many developing nations and SIDS are struggling with the burden of mismanaged waste within their own borders and the litter that floats to their shores from elsewhere (UNCTAD, 2019). In response to this problem, UNCTAD suggested working definitions to clearly define the difference between plastic substitutes and plastic alternatives in intent and application (Figure 1). This differentiation is important in structuring pollution mitigation actions that consider local resources, innovation and the important role plastics play in the economy, especially in sectors where their replacement is difficult. UNCTAD has developed a list of 282 products and materials traded in the harmonized system (HS) that can substitute plastics in some functions (UNCTAD, 2023a).

Given the significant impact plastics have on our fragile environment, this makes clear sense – “It is estimated that there were 369 million tons of plastics traded in 2020 alone, which is $1.2 trillion in value, a significant increase from $933 billion the year before” (UNCTAD, 2022a). This report builds on this distinction and aims to find substitutes for plastics in the three identified areas.

Figure 1.
Plastic substitutes versus plastic alternatives

Plastic substitutes	vs	Plastic alternatives
Mineral, plant, marine or animal	ORIGIN	Bioplastics or Biodegradable plastics
Recyclable, reusable, biodegradable, compostable, or erodable	PROPERTIES	Recyclable, biodegradable, or compostable (end of life)
Should have lower environmental impact along their life cycle	IMPACT	Should have lower GHG lifecycle emissions when compared to plastics
Should not be harzardous for human, animal or plant life	SAFETY	Should not be harzardous for human, animal or plant life
Non-plastics		Better plastics

Source: Prepared by UNCTAD, based on presentation on plastic substitutes HS codes, Life-cycle analysis and tariffs considerations (UNCTAD, 2022).

Methodological structure and case studies

Building upon SMEP's past projects (UNCTAD, 2022a), this paper will consider a mixed method approach to analyse both quantitative and qualitative data while analysing plastics substitutes against the harmonised system codes (HS codes) developed by the World Customs Organization (WCO). In addition, the promising solutions will be further investigated through country-specific case study analysis and their Revealed Comparative Advantage (RCA) metric. RCA is used to provide countries' export strengths, and thus it indicates the advantages and disadvantages of exports of certain products and goods.

To analyse the most promising material substitution (in relation to their local sources, availability and environmental performance) in the packaging for food exports at the B2B and B2C levels, Ghana and Nigeria will be considered case study countries. As a case study country for fishing nets and fishing gear, this paper will focus on the Pacific region and Fiji. In addition, for the agricultural mulch and seedling tubes used in agriculture and reforestation, Kenya will be considered as part of a case-specific developing country context. See Table 1 for the case study countries and their selected sectors for the study.

The study uses **RCA to assess countries' strengths** in exporting alternative products.

Table 1.
Case study countries and their various sectors with the competitive advances in production and export

Sector	Country	Economic activity (RCA metric in 2022)	
Packaging for food exports	Ghana	**HS 18**	Cocoa and cocoa preparation
		HS 43	Fur skins and other skins
		HS 40	Natural rubber
		HS 12	Oil seeds
	Nigeria	**HS 27**	Mineral fuels (petroleum oil, gases)
		HS 18	Cocoa
		HS 4401	Fuel wood
Fishing nets and gear	Fiji	**HS 22**	Non-alcoholic beverage
		HS 4401	Wood waste
		HS 11	Product of milling
Agricultural mulch and seedling tubes	Kenya	**HS 0902/0903**	Tea and mate
		HS 0901	Coffee and coffee substitutes
		HS 1704	Sugar confectionary
		HS 5303	Jute and other textile bast fibres
		HS 10089	Cereals, unmilled (excluding wheat, rice, barley, maize)

Source: World Trade Organisation (2024).

Plastic substitutions through the lens of the waste hierarchy

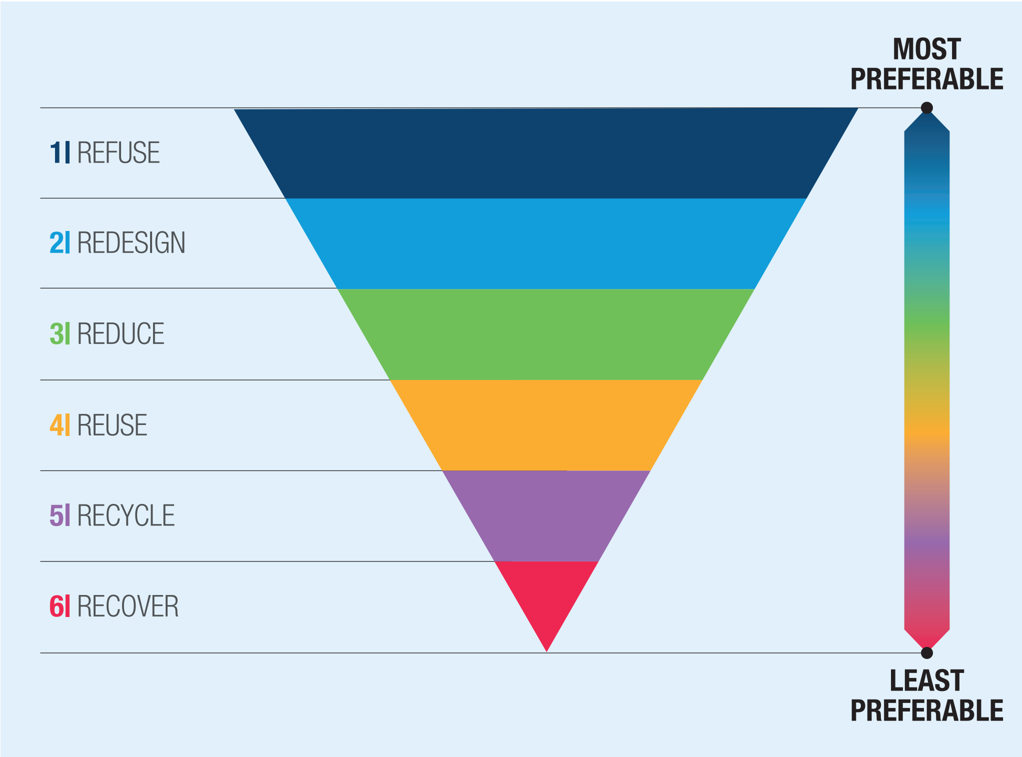
Plastic substitution options for the selected three critical sectors will be analysed through the lens of the circular economy waste hierarchy as shown in Figure 2. The focus has been divided into two aspects when analysing the case study countries.

First, the project will concentrate on plastic substitutes from alternative and nature-based sources with minimal to no pollution, tailored to the specific context of each country.

Second, plastic alternatives (biodegradable or compostable plastics with reduced conventional plastic content) will also be investigated if relevant to the local context of the critical sectors. Thus, the possible options in the case study scenario will address how the solution will involve refusing, redesigning, reducing, reusing, and recycling the products.

The 6R hierarchy encompasses the following options: "refuse" (avoiding use), "redesign" (modifying design to improve end-of-life treatment), "reduce" (minimising quantities), "reuse" (switching to more durable items), "recycle" (reprocessing plastic waste), and "recover" (obtaining energy from plastics—only if the previous 5Rs are not viable) (FAO, 2021). On the other hand, the 3D concept tackles the impacts of agricultural plastics that are not properly handled after harvest, often referred to as "leaked plastics" (FAO, 2021). This may occur by plastics becoming "damaged" in situ through mismanagement, "degraded" through biological, physical or chemical mechanisms or "discarded" by entering the environment intentionally or unintentionally.

Figure 2.
Waste hierarchy used for the case study analysis



Source: Prepared by UNCTAD based on FAO (2021).

Chapter II

Packaging for food exports


CAPRICORNIO
coffees
EXCLUSIVE
GCC
Source Global | Support Local
ROYAL BLEND
NY-2/3 SCR 16/17/18
CROP 2023/2024

Chapter highlights

- **Cocoa export** — Ghana and Nigeria are significant players in the cocoa export market, with Ghana leading in competitive advantage. Both countries face socioeconomic challenges, including poverty and plastic waste management, which impact the sustainability of their cocoa packaging.

- **Current packaging practices** — Raw cocoa beans are primarily transported in jute bags, sometimes lined with plastic for added protection. Processed cocoa products, like butter and powder, typically rely on plastic packaging to maintain quality and prevent contamination.

- **Promising circular alternatives** — Biodegradable liners for jute bags, recyclable aluminium containers, compostable sacks, and moulded pulp containers promise substitutes for plastics in cocoa packaging. These alternatives align with circular economy principles, reducing plastic waste.

- **Nature-based packaging innovations** — Alternatives like seaweed-based bioplastics, mushroom-based packaging, and biodegradable options from areca, banana leaves, hemp, and bamboo offer sustainable solutions for various packaging needs, including cocoa.

- **Policy solutions for sustainability** — Implementing circular economy policies, such as Extended Producer Responsibility (EPR) legislation, government incentives for biodegradable packaging, and single-use plastic bans, can drive sustainable practices in the cocoa export sector.

- **Collaboration and smart packaging** — South-South partnerships, especially with countries like Bangladesh, can support jute-based biopolymer development, while innovations like active and oxygen-scavenging packaging can enhance shelf life and reduce plastic dependency in cocoa exports.

Packaging for food exports

The invention of plastics and its now ubiquitous use in food packaging has had mixed impacts and outcomes worldwide. On the one hand, it has revolutionised the production, manufacturing, transportation, and import and export of food products. It has been essential in preventing food from spoiling, food waste and infection, thereby prolonging the shelf life of food products (Onyeaka, et al., 2022).

However, it is well known that plastic packaging is one of the biggest sources of environmental degradation and pollution. This is due to the predominantly linear plastic production and consumption system and an overreliance on short-lived SUP packaging (Lu, et al., 2022). Among the long list of environmental impacts of plastics in the environment include the contamination of marine and land creatures, including the proliferation of microparticles of plastics that are known to cause injury or death to marine life (Onyeaka, et al., 2022).

Packaging levels

Packaging for the whole supply chain incorporates the three levels and types of packaging: i) primary, ii) secondary and iii) tertiary (Table 2), which are integral to the overall purpose of the chosen packaging. Every level serves a particular purpose, tailored for specific packaging scenario (Cartier, 2019) and each plays a specific role in the product's journey from producer, manufacturer and consumer (Verghese, et al., 2015).

From shelf to shipment, **every layer of packaging plays a role** — but plastic dominates them all.

1. **Primary packaging** is the covering of a product in its final stage when it is about to be used. This type of packaging (e.g. cereal boxes, bottles and drink cans) is seen lining the shelves of retail stores. It protects the product inside and is sometimes called "retail or consumer" packaging as it uses marketing and design to attract customers. Sometimes, such packaging uses different technologies to extend the life of the product it is protecting (Cartier, 2019).
2. **Secondary packaging** makes it easier to store bulk quantities of a product, move them around and take stock of them in a warehouse setting. It is usually a box or sturdy container that holds an equal number of products together for easier transport and is stackable on a pallet. It is also where the brand's marketing can be most visible on a larger format.
3. **Tertiary packaging** is the final layer that ensures the products remain intact and undamaged throughout the logistics process. Whether the product comes from an online seller or a warehouse, it comes with tertiary packaging which includes peanuts,[1] dividers, die-cut foam, bubble wrap and cling wrap.

Plastic dominates packaging materials and it now has a supporting role in preserving the quality and safety of products, food in particular, increasing its shelf life and reducing food waste (Guillard, et al., 2018; Rossi and Bianchini, 2022). However, plastic overabundance and poor end-of-life mismanagement have led to plastic waste overwhelming waterways and natural systems, causing significant ecological damage (Guillard, et al., 2018).

1 "Peanuts" in tertiary packaging are used to provide secure interlocking, prevent settling, and fully surround the product for complete protection during shipping and storage. Their lightweight and reusable nature makes them an ideal choice for bulk tertiary packaging.

Table 2.
Case study countries and their various sectors with the competitive advances in production and export

Technology	Description	Potential impact on food
Multilayer barrier packaging	Packaging that contains multiple layers to provide the required barriers to moisture, gases and odour. Specific requirements can be met using a combination of polymers, aluminium foil and/or coating	Keeps out moisture and oxygen delays product degradation
Modified atmosphere packaging (MAP)	Gases are added to packaging before they are sealed to control the atmosphere within the pack, and then they are maintained by a high gas barrier film, e.g. through vacuum packaging. Carbon dioxide is added, alone or with nitrogen and sometimes oxygen, depending on the product (e.g. meat, cheese, fruit, vegetables)	Reduces respiration rates in the product and reduces growth of microorganisms
Edible coatings	Based on a range of proteins, lipids, polysaccharides and their composites, they can be used on fruit, vegetables, meat, confectionary and other products	Creates a barrier directly around food products (rather than external packaging)
Ethylene scavengers	A range of different technologies involve chemical reagents added to polymer films or sachets to absorb ethylene. Used for fruit and vegetables	Removal of ethylene delays ripening and extends the shelf life of fresh produce
Oxygen scavengers	Substances that remove oxygen from a closed package. They are often in powder form in a sachet. New technologies include oxygen scavengers in the film itself. Used for sliced processed meat, ready-to-eat meals, beer and bakery products	Oxygen accelerates the degradation of food by causing off-flavour, colour change, nutrient loss and microbial attack (bacteria and fungi). Removing oxygen slows the degradation process and extends the shelf life of the food
Moisture absorbers	Pads are made from super absorbent polymers, which absorb moisture. Used for fresh meat, poultry and fresh fish	Maintain conditions that are less favourable for the growth of microorganisms
Aseptic packaging	Packaging that has been sterilized before filling with ultra-high temperature (UHT) food. This gives a shelf life of over six months without preservatives. Formats include liquid paper board, pouches and bag-in-box	High temperatures kill microorganisms, and tight seals on the packaging prevent the entry of microorganisms, gas, or moisture that could promote degradation

Source: Cartier (2019).

The problem with plastic packaging

The food industry has been using petroleum-based plastics for food packaging since the post-World War II era. It has shown an annual growth rate of 5 per cent over the last few decades and is now the second most widely used material for food packaging, after paper-based packaging (Meikle, 1995; Sadeghizadeh-Yazdi, et al., 2019).

Between 1950 and 2015, about 8,300 million tonnes (Mt) of virgin plastics were produced across the globe, generating approximately 6,300 Mt of plastic wastes, of which around 9 per cent have been recycled, 12 per cent incinerated and 79 per cent accumulated in landfills (Babayemi, et al., 2019). UNCTAD (2023c) estimates that the flow of plastic into the ocean is likely to nearly triple by 2040 and without considerable action to address plastic pollution, 50 kg of plastic will enter the ocean for every metre of shoreline.

Ghana and Nigeria export similar crops
—but their packaging paths diverge.

Moreover, the deterioration rate of plastics varies widely depending on environmental conditions, the type of plastic, and the degradation mechanism (e.g., photodegradation, thermal degradation, biodegradation). According to Andrady (2011), typical breakdown times for different plastics in environmental conditions, though actual rates can differ:

- **Polyethylene Terephthalate (PET)** — approximately 450 years in marine environments;
- **High-Density Polyethylene (HDPE)** — more than 450 years;
- **Polyvinyl Chloride (PVC)** — can persist indefinitely in low-sunlight and low-oxygen conditions but may degrade in decades under high UV exposure;
- **Polypropylene (PP)** — approximately 20–30 years in landfills but breaks down more rapidly with UV exposure;
- **Polyethylene (PE)** — up to 500 years, but it can fragment due to UV, creating microplastics without complete mineralization.

Plastics are made from various polymers and additives tailored to their intended use, including plasticisers for flexibility, flame retardants, UV stabilisers, and pigments for colour. Common chemicals in production include solvents, unreacted monomers, processing aids, and non-intentionally added substances (NIAS), such as impurities and by-products. Of the approximately 13,000 chemicals used in plastic production, only 7,000 have been assessed for harm, with 3,200 identified as "substances of potential concern" due to their hazardous properties (UNCTAD, 2023a). Given the impact of plastics on the environment and the necessary role that packaging plays in food exports, there is a need to explore how and under what circumstances plastic substitutes could be adopted.

Case study

Ghana and Nigeria

Ghana and Nigeria were selected as case study countries to explore opportunities arising from developing plastic substitutes for their food exports using the UNCTAD list of substitutes. Their appropriateness and viability were assessed following the principles of a circular economy: i) Eliminate waste and pollution, ii) keeping materials in use at their highest value for as long as possible and iii) regenerating ecosystems.

From a purely economic trade perspective, both Ghana and Nigeria have moderately large cocoa sectors with export values of $2 billion and $455 million, respectively, with their individual RCA scores being 119 and 7.9 as shown in Table 3 (UNCTAD, 2022b). Plastics are not the main packaging material in the cocoa industry however, as jute canvas bags are predominantly used to transport cocoa before it reaches the manufacturer, where it is then processed into chocolate (UNCTAD, 2022b).

Table 3.
The comparative RCA and socioeconomic context in Nigeria and Ghana (2022)

Country	Key exports	RCA score	Population	Exports (USD)	GDP growth (%)
Ghana	Cocoa	119	32.9 million	2 billion	4.10
Nigeria	Cocoa	7.9	213.4 million	455 million	2.95

Source: UNCTAD (2022b).

The relevance of agri-food exports

The RCA is used here as a way of demonstrating economic advantage that could be used as leverage for finding a better packaging solution using circular economy principles. The main exports of Nigeria are petroleum-based products; however, cocoa is the major agricultural export with an RCA value of 7.9. Nigeria is currently the fourth largest cocoa producer, producing 250,000 metric tonnes of cocoa and is becoming a big producer of cocoa-based products. In the first quarter of 2023, the country had several agricultural exports in addition to cocoa, including:

- **Sesame seeds** — 24.20 per cent of total agricultural exports and 67.66 billion Nigerian Naira (NGN). Nigeria is one of the top producers of sesame seeds globally;
- **Soybeans** — 13.8 per cent of total agricultural exports and NGN 38.63 billion;
- **Cashews** — 12.7 per cent of total agricultural exports and NGN 34.02 billion;
- **Ginger** — accounting for 2.67 per cent and NGN 7.48 billion;
- **Cocoa beans** — the value of cocoa beans (both superior and standard quality) exported in the first quarter of 2023 was NGN 102.71 billion, accounting for 36.7 per cent of total agricultural exports (NGN 279.64 billion); and
- **Cocoa butter** — the value of cocoa butter exported between January and March 2023 was NGN 4.88 billion, accounting for 1.75 per cent of total agricultural exports.

All of the above-mentioned agri-food exports are linked to packaging, mostly plastic packaging, from the primary packaging of the agro-food products to the tertiary agro-food export. Cocoa export in Nigeria contributes its economy significantly. However, Nigeria's cocoa yields have been declining due to inconsistent production, diseases, pests and reliance on subsistence-level technology (Akiwumi & Onyekwena, 2022). Challenges include a decreasing labour force, ageing trees and a 1986 cocoa market liberalization that increased traders but did not improve efficiency, with a few companies exporting most production (Cadoni, 2013).

In contrast, Ghana's cocoa sector, which provides 30 per cent of the country's earnings, involves over six million people and supports more than 800,000 smallholder farmers (Asante-Poku, 2013; Gockowski, 2011). Ghana's top exports include cocoa beans, with most cocoa sold through Licensed Buying Companies (LBCs) to the Cocoa Marketing Company (CMC). About 80 per cent of cocoa is exported as raw beans, using jute bags, while the rest is processed domestically, primarily into semi-finished products (Monastyrnaya, et al., 2016). The type of packaging is often determined by the type of products processed and exported by other countries. For example, for raw bean exports, jute sacks, hemp or cotton bags are used, which is a better substitution for plastics and comes from renewable plants, which are carbon negative. However, plastic might be an obvious choice for exporting processed cocoa or powder.

Ghana exported $14.1B in 2021 with significant specialization in cocoa products (OEC, 2023). The country's cocoa sector faces limited domestic efforts to process cocoa by-products and inferior quality beans into various finished products (Monastyrnaya, et al., 2016).

Agricultural products exported in their raw form such as nuts, seeds and beans are generally transported in a breathable, naturally derived bag (Chen, et al., 2022). This is usually jute, hemp, or cotton because the products can continue to breathe throughout their journey to the next stage, thereby preventing bacteria or mould infestations. Plastic is not a common packaging solution when the product is raw.

> **Raw exports** like seeds and beans are usually **packaged in breathable, plant-based bags** —not plastic.

Cocoa husks offer untapped potential—from packaging to energy and soil health.

Plastics are used once the raw form of the agricultural product has been processed into butter, liquids and chocolates, and its use is growing (Babayemi, et al., 2019; Boateng, et al., 2022).

Current packaging in the cocoa export

Cocoa exports from Ghana and Nigeria encompass various products, including raw cocoa beans, cocoa butter, cocoa powder, and cocoa liquor (or paste), each with distinct processing, packaging, and transportation requirements. The primary export from both countries is raw cocoa beans, a product that undergoes careful harvesting, fermentation, drying, and packaging before export. These beans are typically shipped in large bags or bulk containers. The jute bags commonly used in Ghana and Nigeria for transporting raw cocoa are often plastic-lined, protecting against moisture and pests during transit. Jute bags can usually carry a gross weight of 60 – 65 kg, rarely of up to 100 kg cocoa (TIS, 2024). This type of packaging protects the beans' quality and aligns with sustainable practices, as jute is a biodegradable material.

In addition to raw beans, cocoa butter represents a significant export product, especially valued for its role in chocolate production and the cosmetics industry. Cocoa butter is extracted from the cocoa beans after roasting and pressing, resulting in a product that requires careful packaging to maintain purity and prevent contamination (Gilbert, 2009; TIS, 2024). Generally, cocoa butter is shipped in containers lined with plastic, offering additional protection during transit (Darmawan & Mutalib, 2024). This protective packaging is essential, as even minor contamination can compromise the quality and safety of cocoa butter, especially for food-grade applications.

The processing of cocoa beans also yields cocoa powder, derived from the cocoa mass left after the extraction of cocoa butter. Cocoa powder is widely used in baking, beverages, and chocolate production and is often exported in large sacks or bags. These are sometimes lined with plastic to control moisture, which is crucial for maintaining the quality of the powder during long shipping durations (Maguire-Rajpaul, et al., 2022).

Cocoa liquor, or paste, is another product derived from cocoa nibs after grinding. This semi-solid form of cocoa is used in chocolate production and is often exported in blocks or sealed containers to maintain its consistency and prevent moisture-related issues. Similar to cocoa butter, the packaging for cocoa liquor generally includes moisture-resistant materials, underscoring the need to preserve product integrity from production to export destination (Bates, et al., 2018).

Transportation of cocoa products requires additional packaging considerations. Plastic wraps are commonly used to secure pallets of bagged cocoa products, protecting them from external conditions, especially during transit in humid or variable climates (Laven & Fold, 2013). Furthermore, sealed plastic containers are frequently used for processed cocoa products such as cocoa butter and paste, enhancing protection against spoilage and contamination (Dand, 2010; ICCO, 2020). Each of these packaging strategies highlights the critical balance of sustainability, quality preservation, and contamination prevention in Ghana and Nigeria's cocoa export industry.

Barriers and enablers to trade and international collaboration

There has been some early research examining the viability of bioplastic production from agricultural waste in Nigeria, including the evaluation of cassava starch biodegradable plastics and their rates of degradation in soil which was found to be favourable (Qasim, et al., 2021a). However, researchers have discovered that although there is potential for bioplastics to replace petroleum-based plastics, the high production costs of biodegradable plastics and the costly process of modifying most plants used in the production make them more expensive compared to conventional plastics (Qasim, et al., 2021b). Despite having a major cocoa industry in Nigeria, the current practice of managing waste materials, particularly cocoa pod husks, is unsustainable. The cocoa husks provide various opportunities, including energy sources, nutrients from husk powder, and biochar for soil nourishment.[2]

FreshPPact and Blue Skies are supporting the research and design of plastic bottles for freshly squeezed juice sold predominantly in local markets around Ghana, which currently make up less than 5 per cent of sales (approximately 30,000 units per week). Polyethylene terephthalate (PET) bottles are filled with juice, sealed with low-density polyethylene (LDPE) caps, packed with shrink wrap in groups of 12 and then sent to local retailers (Northampton, 2023). The absence of necessary infrastructure and economies of scale make the start-up costs for bioplastic production in Nigeria (and other African nations) quite high. Moreover, there are limited capacities in the public sector to tackle the problem of plastic pollution (Moulds, et al., 2022, Nyathi, 2020 #32).

Plastic substitution and alternatives in packaging

To address the reliance on plastic packaging in the cocoa export sector of Ghana and Nigeria, alternatives that maintain quality, prevent contamination, and promote sustainability should be explored. Biodegradable and renewable materials can effectively replace traditional plastic, minimizing environmental impact and aligning with global trends toward sustainable packaging (Pinkse & Kolk, 2012). The following solutions are proposed for specific cocoa products, taking into account the unique packaging needs and environmental considerations associated with each:

- Biodegradable liners for jute bags for raw cocoa beans export — Raw cocoa beans are often shipped in plastic-lined jute bags to protect them from moisture and pests(TIS, 2024). A sustainable alternative could involve biodegradable liners made from materials such as polylactic acid (PLA) or cellulose, which decompose naturally without harming the environment (Mujtaba, et al., 2022). Studies indicate that PLA is not only moisture-resistant but also compatible with organic materials like jute, making it ideal for cocoa bean transport (Ncube, et al., 2020). By using PLA liners, exporters can maintain bean quality while reducing plastic waste.
- **Recyclable aluminium containers with natural wax coatings for cocoa butter export** — Cocoa butter requires protective packaging to prevent contamination, as it is sensitive to environmental exposure (Gilbert, 2009). Instead of plastic-lined containers, recyclable aluminium containers with natural wax or biodegradable coatings could offer a suitable alternative. Aluminium is inherently recyclable and provides an effective barrier against moisture and contaminants, which is crucial for the quality of cocoa butter. Natural wax coatings, such as those derived from carnauba or beeswax, add further protection and biodegrade over time, aligning with circular economy principles.
- **Compostable sacks with inner biofilm layer for cocoa powder export** —Cocoa powder is sensitive to moisture and is usually exported in plastic-lined bags (Maguire-Rajpaul, et al., 2022). Compostable bags made from biopolymers like polyhydroxyalkanoates (PHA) could replace conventional plastic-lined bags. PHA is durable and moisture-resistant and has been shown to perform well in humid conditions, which is critical for maintaining

Without scale or infrastructure, **bioplastics remain an expensive solution.**

2 For more information about the potential of cacao waste, see the World Resources Institute's news piece: The Hidden Benefits of Cacao Waste: How Cocoa Husks Can Drive Sustainability in Nigeria, available at: https://www.wri.org/insights/hidden-benefits-cacao-waste/.

At the origin of **cocoa exports, new packaging choices are reshaping old routines.**

cocoa powder quality during transit (Stoica, et al., 2024). An inner layer of biofilm, derived from edible plant sources, could further protect against moisture without the environmental footprint of traditional plastic.

- **Molded pulp containers with eco-friendly wax coatings for cocoa liquor export** — Cocoa liquor or paste is semi-solid and prone to moisture-related issues (TIS, 2024). Moulded pulp containers, commonly made from recycled paper fibres, are an effective alternative to plastic-lined containers. When treated with an eco-friendly wax coating, these containers can resist moisture and provide structural integrity. This solution not only reduces plastic usage but also supports recycling efforts by utilizing post-consumer waste as a raw material.

- **Biodegradable pallet wraps for transport and palletisation** — To replace conventional plastic wraps used for securing pallets of cocoa products during transport, biodegradable wraps made from PLA or starch-based polymers could be adopted. These materials offer similar durability to plastic wraps and degrade more readily after disposal, reducing plastic waste in global supply chains (Mujtaba, et al., 2022; Ncube, et al., 2020). Using biodegradable pallet wraps would address the environmental concerns associated with transit packaging, aligning with the sustainability goals of Ghana and Nigeria's cocoa industry.

Bangladesh is a leading jute bag exporter worldwide. The recent development and innovation in biopolymer production from jute plants[3] in Bangladesh provide opportunities for Ghana and Nigeria to collaborate with Bangladesh, which not only enables South-South collaboration to phase out plastics from the entire cocoa supply chain (from raw bean export by jute bags to finish product export using biopolymer from jute) but also establishes strong South-South partnerships.

3 For more on recent innovations in biopolymer production from jute in Bangladesh, see the Global Citizen article: Bangladesh Invents a Biodegradable 'Throw-Away' Bag Made From Jute, available at: https://www.globalcitizen.org/en/content/bangladesh-invents-biodegradable-throw-away-bag/.

Table 4 examines opportunities for globally available plastic substitutes that can be replicated and further developed in Africa and other developing economies. Researchers are focusing on the viability of these substitutes over bioplastics in food-contact materials (FCMs), applying the 6Rs of circularity and the Ellen MacArthur Foundation's three principles of a circular economy.

Bioplastics and biopolymers have been highlighted in many research activities as the next wave of 'green' packaging (Romão, 2022; Shlush & Davidovich-Pinhas, 2022). The work of Allan Calmont de Andrade Almeida (2021) demonstrates that a new sustainable material has been developed with a composition of 80 per cent PE and 20 per cent cocoa bean husk powder derived from the residues of the Brazilian cocoa industry. This biobased plastic was tested in terms of biodegradation with three fungi: *Colletotrichum gloeosporioides*, *Xylaria spp*. and *Fusarium graminearum*. Almeida, et al. (2021) note that incorporating polymers containing cocoa residues into bioplastic composites offers advantages from both ecological and industrial standpoints. This integration introduces novel properties to the composite and enables endophytic fungi isolated from the fruit itself to facilitate its biodegradation. Additionally, through biodegradation experiments, secondary metabolites with significant aggregate values could potentially be generated.

Ghana and Nigeria have strong cocoa export industries giving them an inherent advantage in using excess cocoa waste resources, and potentially also organic waste in creating new biopolymer packaging for food export. However, advances in bioplastics, while they address the problems associated with the production of petroleum-based plastics, do not eradicate the problems of mismanaged waste streams. Furthermore, the degree to which bioplastics are compostable and biodegradable remains questionable (Guillard, et al., 2018). Irrespective of whether a material breaks down into biodegradable, compostable materials or not, if discarded into environments that cannot deal with it in great numbers, it will still cause a problem. This partly explains UNCTAD's focus on substitutes over alternatives to plastic.

Bioplastics reduce production impacts, but not the problem of mismanaged waste.

Table 4.
Plastic substitutes in relation to three CE principles and 6Rs of circularity

Principles	Mushroom	Seaweed
CE 1 ELIMINATE WASTE/POLLUTION	No pollution in production or manufacture, use or end-of-life	No pollution in production or manufacture, depending on addtives
CE 2 CIRCULATE PRODUCTS/MATERIALS	Reusable if kept intact	Reusable depending on design
CE 3 REGENERATE NATURE	Compostable; fertilizes soil	Compostable; fertilizes soil
R 1 REFUSE	Replaces styrofoam	Replaces flexible plastics and textiles
R 2 REDESIGN	High versatility; used to produce soft or hard forms	Research indicates high versatility
R 3 REDUCE	Reduces use of noxious plastics like Styrofoam	Reduces need for flexible plastics and textiles

Source: Akiwumi and Onyekwena (2022), Aranda-Calipuy et al. (2023), Kelpi (2023), Hounsou et al. (2022), Glass Alliance Europe (2023).

Table 4. (cont.)
Plastic substitutes in relation to three CE principles and 6Rs of circularity

Principles	Mushroom	Seaweed
R 4 REUSE	Indefinitely reusable if kept intact	Reusable short- or long-term depending on design and additives
R 5 RECYCLE	Compostable	Compostable
R 6 RECOVER	Recoverable via EPR, return services, or FOGO	Recoverable via EPR or FOGO
Intended replacement for	Styrofoam, cardboard	Bioplastic, textile packaging

Principles	Areca/banana/pineapple residues	Glass
CE 1 ELIMINATE WASTE/POLLUTION	Low-pollution farming possible; manufacturing pollution depends on additives	Low-pollution manufacturing if clean energy used
CE 2 CIRCULATE PRODUCTS/MATERIALS	Reusable if design allows and kept intact	Indefinitely reusable
CE 3 REGENERATE NATURE	Compostable; fertilizes soil	Crushable and recyclable into new glass
R 1 REFUSE	Replaces flexible plastic packaging for short-term uses; made into textiles	Reusable in take-back schemes
R 2 REDESIGN	Used to produce flexible packaging and textile	Moldable to suit needs
R 3 REDUCE	Reduces use of plastic packaging and plastic-based textiles	Reduces the use of plastics
R 4 REUSE	Reusable if kept intact	Reusable if kept intact
R 5 RECYCLE	Compostable	Crushable and recyclable
R 6 RECOVER	Recoverable via FOGO	Recoverable via EPR or deposit schemes
Intended replacement for	Plastic wrap	Plastic bottles, containers

Principles	Hemp	Bamboo
CE 1 ELIMINATE WASTE/POLLUTION	No pollution in production; less water needed; no chemicals or fertilizers	Low-pollution in production, fast-growing; minimal inputs
CE 2 CIRCULATE PRODUCTS/MATERIALS	Moldable into paper, textiles, bricks, insulation; reusable	Usable in textiles, wood, food
CE 3 REGENERATE NATURE	Compostable; enriches soil	Can return to soil as wood residue

Source: Akiwumi and Onyekwena (2022), Aranda-Calipuy et al. (2023), Kelpi (2023), Hounsou et al. (2022), Glass Alliance Europe (2023).

Table 4. (cont.)
Plastic substitutes in relation to three CE principles and 6Rs of circularity

Principles	Hemp	Bamboo
R 1 REFUSE	Replaces plastics, petroleum, cotton, synthetic textiles, hardwood	Replaces hardwoods, wood-based papers, plastic packaging
R 2 REDESIGN	High versatility	Used to produce textiles or packaging
R 3 REDUCE	Reduces use of plastics and noxious chemicals; fire-retardant, antibacterial, antimicrobial	Replaces thirsty cotton or slow-growing hardwoods
R 4 REUSE	Reusable and remanufacturable	Indefinitely reusable
R 5 RECYCLE	Compostable; fertilizes soil	Mulchable
R 6 RECOVER	Recoverable via FOGO	Recoverable via EPR
Intended replacement for	Plastics, textiles, paper, food, insulation	Plastics, hardwoods, cotton, paper

Principles	Paper	Cocoa
CE 1 ELIMINATE WASTE/POLLUTION	No pollution/waste in production depending on the source of biomaterial	Some pollution with insecticide etc., used in growing could be grown regeneratively
CE 2 CIRCULATE PRODUCTS/MATERIALS	Usable in place of plastic for packaging	Reusable if design allows and kept intact
CE 3 REGENERATE NATURE	Compostable	Compostable; fertilizes soil
R 1 REFUSE	Replaces plastics	Replaces plastic or cardboard from virgin wood
R 2 REDESIGN	Used to produce harder cardboard or softer forms	Used to produce cardboard equivalent or hard forms
R 3 REDUCE	Replaces plastic packaging	Reduces plastic in products and packaging
R 4 REUSE	Reusable if kept intact	Reusable if kept intact
R 5 RECYCLE	Compostable; mulchable	Compostable if no chemical binders
R 6 RECOVER	Recoverable via EPR or FOGO	Recoverable via EPR or FOGO
Intended replacement for	Cardboard	Plastic packaging

Source: Akiwumi and Onyekwena (2022), Aranda-Calipuy et al. (2023), Kelpi (2023), Hounsou et al. (2022), Glass Alliance Europe (2023).

Biopackaging faces raw material limits, technical hurdles, and greenwashing concerns.

Other methods for food safety in transport

A raft of other methods and technologies are being actively adopted or trialled in many businesses across the globe to transport food in more sustainable ways (Guillard, et al., 2018). These businesses are predominantly located in countries with large economies and with substantial support from their governments. However, while many of these new methods and technologies are being touted as "sustainable" or "eco-friendly", these claims are disputed (Guillard, et al., 2018). Box 1 on the next page describes some of the varied packaging innovations aimed at reducing plastic in food packaging.

These innovations represent significant advances in the packaging sector but have limitations and barriers. There are still considerable technical issues associated with biopackaging related to such things as the availability of the raw material, variability in the raw material, narrow processing windows compared to plastic-based products, difficulties with scaling biosolutions and a fragmented packaging industry lacking a unity of purpose. The advancement of biopackaging faces significant challenges due to contentious issues regarding its technical, social and environmental advantages. These include unclear assertions about environmental impacts, competition between agricultural resources for food and non-food purposes, the substantial environmental cost of current "bio" solutions, problematic compostability of polylactic acid (PLA), suspicions of greenwashing and additional concerns (Guillard, et al., 2018). As Guillard, et al. (2018) suggest, there is a pressing requirement to design sustainable packaging materials that are not derived from fossil fuels, do not compete with food resources and offer a genuine advantage in addressing the persistent accumulation of plastics in our environment.

© Mark Stebnicki (Pexels)

Box 1.
Biobased, active and scavenging packaging innovation

Biopolymer and naturally derived products

Solon is a biodegradable polymer made from medium-chain-length polyhydroxyalkanoate (mclPHA) materials created by RWDC Industries as an alternative for petroleum-based plastics. PHAs are aliphatic polyesters derived naturally through the fermentation process of sugars and lipids such as glucose, sucrose and vegetable oils by diverse bacteria and serve as an intracellular carbon and energy reserve during cellular growth under stressful conditions. These polyesters have the capability to combine over 150 monomers, resulting in materials with diverse characteristics (RWDC Industries, 2023).

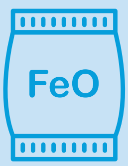
Seaweed-based packaging is another nature-based product being used to replace plastic in many situations. Companies in this area have developed seaweed-based solutions across agriculture, animal feed, organic food ingredients, bioplastics and biofuels, as well as seaweed-based packaging for a range of products, including a soft plastic alternatives.

Mushroom-based packaging is particularly innovative because mushrooms can be grown to create any shape that might be required for packaging and is a direct replacement for styrofoam. Ecovative combines mushroom mycelium with hemp hurd that naturally composts in 45 days (Ecovative, 2023).

Active packaging

This innovative packaging type incorporates diverse, active compounds such as antioxidants, antimicrobials, moisture and gas absorbers as well as ultraviolet radiation absorbers. These components interact with the packaged food or its environment to extend shelf life by preserving the quality, safety and integrity of the food (Li et al., 2022).

Vacuum packaging and modified atmosphere packaging (MAP) are engineered to enhance the shelf life and maintain the natural colour of refrigerated meat. In contrast to vacuum packaging, MAP replaces the surrounding air with a customized gas blend, specifically designed to minimize degradation while preserving desired colour characteristics. Additionally, MAP can be employed to preserve various other types of food (Li et al., 2022).



Oxygen scavenging technologies

Iron and ferrous oxide-based oxygen scavengers (provided in packets/sachets) are the most effective and commonly used scavengers. They remove residual oxygen in packaging through the reaction of iron with oxygen (Li et al., 2022).

Circular economy business opportunities for supply chains exporting food

The concept of value creation is inherent in a circular economy from a social and environmental perspective but most importantly from an economic perspective (Mura, et al., 2023). Outputs and inputs are understood as materials and services that a product or activity requires or produces as a result of operating (Christensen, 2016; Ellen MacArthur Foundation, 2015). They are seen as valuable because one business' output can be another's input, thus creating a circular economy (Ellen MacArthur Foundation, 2015; Micheaux, 2016). Innovative business models in a circular economy seek to shift the responsibility for the product's longevity, packaging and renewal back to the brand owner, as opposed to a linear economy where it sits with the consumer (Christensen, 2016; Ellen MacArthur Foundation, 2015). Examples include:

- **Take-back services** — such as for blue pallets by Chep;
- **Product as service models** — such as Philips providing lighting; and
- **Extended Producer Responsibility services** — where the packaging belongs to the brand such as in Loop by TerraCycle.

Therefore, these models reduce plastic packaging and waste by changing how the business operates.

Plastic substitutes could **reduce global plastic waste 17% by 2040.**

Key findings and policy recommendations

Undoubtedly, cocoa is an important agri-food export for both Ghana and Nigeria. Plastics are common packaging materials used in all types of packaging, including primary, secondary, and tertiary. Thus, finding plastic substitutes is difficult. On one hand, plastic use is predicted to double in 2050 from the current volume; on the other hand, plastic substitutes could cut global plastic waste by around 17 per cent by 2040 – about 63 million tonnes less or 3.5 million fewer trucks transporting plastic waste.

The study identifies several packaging opportunities as plastic substitutes, including using waste products as packaging and biodegradable packaging instead of plastic packaging and nature-based solutions for tertiary packaging in export, such as timber pallets instead of plastics pallets.

An important part of the cocoa supply chain in Ghana is exporting cocoa waste products. Presently, approximately five cocoa waste companies authorized by the Ghana Cocoa Board (COCOBOD) procure cocoa waste from farmers and processors. Representatives of these companies travel across cocoa-growing regions to acquire lower-quality cocoa from farmers. Additionally, they purchase cocoa shells, husks and cocoa skin from local cocoa processors. Prior to exportation, the cocoa waste is consolidated at the companies' warehouses for inspection by COCOBOD to ensure that no cocoa of satisfactory quality is exported through this avenue (Monastyrnaya, et al., 2016). This industry is important because it means that there is already an official collection system that could be adapted to divert the collected cocoa waste material or similar agro-waste or residue to make, if not a substitute for plastic, at least an alternative.

Biopackaging and EPR laws can cut cocoa export plastic waste in Ghana and Nigeria.

The possible plastic substitutes for the cocoa industry in Ghana and Nigeria are highly dependent on the cocoa products exported to other countries, such as raw beans, butter, processed cocoa powder, etc. The current use of jute bags should be encouraged, with the improvement of replacing plastic liners with biodegradable liners made from PLA or cellulose. Findings on more sustainable substitution of plastic materials are also important. Recyclable aluminium containers with natural wax coatings for cocoa butter export could offer a suitable alternative. For cocoa powder products, biopolymers like polyhydroxyalkanoates (PHA) which are composable, could replace conventional plastic-lined bags. The study identified moulded pulp containers, commonly made from recycled paper fibres, are an effective alternative to plastic-lined containers for exporting liquid cocoa products. In addition, biodegradable wraps made from PLA or starch-based polymers are also identified as substitution options to replace conventional plastic wraps used for securing pallets of cocoa products during transport.

In addition to these identified plastic substitutes, regulatory policies and mechanisms are important, particularly in countries where there is an absence of waste infrastructure and education and design consideration of packaging. Several policy and legislature examples developing countries have adopted that aim to deal with both the problem of litter and shifting the responsibility for packaging design to producers rather than consumers. The extended producer responsibility (EPR) legislation makes producers responsible for the entire life cycle of their products, including packaging waste management. Such laws incentivise producers to design packaging that is more recyclable or compostable and invest in recycling infrastructure. Developed economies such as Australia, Germany, Japan and the Republic of Korea have implemented successful EPR programs for various materials, including plastics. Moreover, the EPR legislation for plastic waste management is a critical tool in addressing the environmental challenges posed by the increasing volume of plastic waste. Countries have adopted various approaches to EPR schemes aimed at improving the management of product end-of-life cycles and reducing the environmental impact of plastics (Allen-Taylor, 2022; Diggle, 2020; Harris, 2021; Lodhia, 2017; Mayers, 2007; Mazhandu, 2020; Miezah, et al., 2015; Røine, 2006; Tudor, 2021).

Other policy and legislative actions that can be adopted to address plastic packaging include container deposit schemes (CDS). This involves legislating a deposit on beverage (or other plastic) containers which is refunded when the container is returned for recycling at a registered receiving location (Allen-Taylor, 2022; Huertas, 2011; Millette, 2023).

Other policies can include packaging taxes or levies:

- **Implementing taxes or levies** on plastic packaging can encourage producers to reduce packaging waste and invest in sustainable alternatives. The Plastic Packaging Tax in the United Kingdom, introduced in 2022, is an example of this approach (Herberz, 2020), the revenue generated can be used to fund recycling infrastructure or environmental initiatives;
- **Governments can incentivise the use of biodegradable** and compostable packaging materials through subsidies, tax breaks or procurement preferences; and
- **Standards and certification programs** can ensure the environmental integrity of these materials and agreements such as the Basel Convention and the Stockholm Convention address the transboundary movement and management of hazardous wastes, including plastics (Bharadwaj, 2019).

Organic waste in Africa holds untapped potential for producing plastic alternatives.

Several African countries have implemented bans or restrictions on single-use plastic bags to reduce plastic pollution and encourage reusable alternatives. Rwanda, for example, implemented a nationwide ban on plastic bags in 2008 and has been successful in reducing plastic waste (Herberz, 2020). Developing economies can implement EPR legislation to hold producers responsible for managing the entire life cycle of their products, including packaging waste. These programs can incentivize producers to design more sustainable packaging and invest in recycling infrastructure. Countries such as South Africa have started to explore EPR frameworks for various materials, including plastics. Governments can launch public awareness campaigns to educate consumers, businesses and policymakers on the environmental impact of plastic packaging and the importance of waste reduction and recycling (Lau, 2020). Such campaigns can promote behaviour change and support the implementation of other policy measures. Examples include the "Ban Plastic Bags" campaign in Kenya and various educational initiatives by non-government organizations across the continent (Godfrey, 2019).

The effectiveness of bans on plastics, particularly in developing economies, is a multifaceted issue that has garnered significant attention due to the global challenge of plastic pollution. The research on this topic suggests that while bans can have positive effects, they are not a panacea and must be part of a broader strategy to address the issue effectively (Wang, 2021). Developing economies can invest in innovative technologies for plastic recycling and waste management, including collection systems, sorting facilities and recycling infrastructure, while governments can provide incentives or support for the adoption of these technologies through grants, subsidies or tax breaks (Wang, et al., 2021). Initiatives such as the African Circular Economy Alliance and the Africa Plastics Pact aim to bring stakeholders together to develop solutions for plastic waste management, promote sustainable packaging practices and promote innovation and collaboration in circular economy solutions across the continent. African countries can collaborate with international organizations, donor agencies and other governments to access funding, technical expertise and best practices in addressing plastic pollution. Initiatives such as the UN Environment Programme's Clean Seas campaign and partnerships with organizations such as the World Bank and the European Union can provide support for policy development and implementation (Benson, 2018; Qu, 2019).

There is a significant opportunity to develop a circular economy-focused supply chain with substitutes for plastics in the exportation of food in developing economies. Traditional containers are still in use in some parts of Africa. A significant amount of organic matter is currently being wasted that could be transformed into plastics for keeping food unspoiled (if a plastic-like material is still necessary) and there are opportunities for developing service business models that eliminate the need for some types of packaging for manufacturers (Adejumo, 2023; Babarinsa, et al., 2022; Boateng, et al., 2022; Doe, et al., 2023; Ezung, 2020). The study also identified opportunities for establishing strong South-South partnerships to address plastic substitutions in food packaging in the entire supply chain.

Chapter III

Fishing nets and fishing gear

© lahiru iddamalgoda (Unsplash)

Chapter highlights

- **Accountability for lost gear** — Lost or discarded fishing gear becomes the responsibility of local communities and governments to collect and dispose of, as there is currently no tracking system to hold fishing vessels or manufacturers accountable. In addition, it contributes to marine pollution and "ghost fishing," where abandoned gear continues to catch and kill marine life.
- **Long lifespan, short use** — Traditional fishing gear materials can take up to 2,500 years to decompose, yet they are typically only used for about three years before being discarded as waste.
- **Biodegradables for static gear** — A biodegradable solution is required that can endure mechanical stress in marine environments for three years before beginning to decompose, especially suitable for static fishing gear like traps.
- **Limitations for dynamic gear** — While biodegradable alternatives may work for static gear, they are less feasible for dynamic fishing gear, such as nets and lines.
- **Urgency for island nations** — Countries like Fiji, which rely on marine resources for their economy and tourism, face significant challenges in managing fishing gear waste. Due to limited space and resources constraints sustainable fishing gear alternatives are essential to protect Exclusive Economic Zones of small island nations.

Fishing nets and fishing gear

Given the prevalence of conventional plastics such as PA and PE in fishing gear worldwide, this section examines material alternatives and substitutes for fishing nets and gear, including promising materials, technologies and production methods based on maturity levels. It presents an analysis of selected case studies based on current practices and identifies key challenges of material substitutions. Further, the report analyzes and presents the key barriers and enablers to trade.

Abandoned, lost or otherwise discarded fishing gear (ALDFG) is responsible for substantial amounts of persistent and biodiversity-damaging ocean pollution. There are few practical alternatives to conventional fossil-based nylon gear and these are being explored under the SMEP Programme. This is of critical relevance for countries with large marine economic zones, such as many SIDS in the Pacific region, many of which do not have adequate downstream management capacities to cope with current levels of plastic litter.

Marine plastic pollution

Key problems

Traditionally, fishing equipment relied upon natural fibres such as sisal, cotton, hemp and materials such as wood and cork (Laist, 1987). The invention of plastic industrial fishing gear represented a milestone for maritime technology and fisheries management, signifying a transformative shift from traditional natural fibre-based materials to synthetic polymers (Jambeck, et al., 2015). This innovation emerged against the backdrop of a rapidly evolving fishing industry marked by a growing global demand for seafood, a pressing need for more efficient and durable fishing equipment, the imperative to address the ecological consequences of overfishing and the persistence of lost or discarded fishing gear in marine ecosystems (Watson, et al., 2006). Plastic fishing gear not only revolutionized the durability and longevity of fishing equipment but also introduced a range of design possibilities, enabling the customization of gear to suit specific fishing methods and target species, thus enhancing catch efficiency. Furthermore, the scalability and cost-effectiveness of plastic gear production facilitated its widespread adoption among fishing communities worldwide, bolstering the industry's economic viability. However, lost or discarded fishing gear became a significant component of marine debris.

An estimated **29% of fishing lines, 8.6% of traps, and 5.7% of nets are lost to the ocean** every year.
(Richardson et al., 2019)

There is limited quantitative data which can reflect the marine pollution created by fishing gear to demonstrate an accurate overview of the problem. The result from a survey study showed that 2 per cent of all fishing gear, comprising 2,963 km2 of gillnets, 75,049 km2 of purse seine nets, 218 km2 of trawl nets, 739,583 km2 of longline mainlines and more than 25 million pots and traps are lost to the ocean annually (Richardson, et al., 2022).

Richardson, et al. (2019) undertook a literature review and meta-analysis of 68 publications (1975 to 2017) on ALDFG and estimated that 5.7 per cent of all fishing nets, 8.6 per cent of all traps and 29 per cent of all lines are lost to the world's oceans annually. The variance in the reported concentration of lost fishing gear annually across these studies can be attributed to several factors, including the geographic area of the study, the specific

Table 5.
Material used per application

Fishing net & line	Fishing traps	Ropes	Aquaculture
Nylon-6	HDPE	Nylon	PP (oyster cup)
HDPE	PP	Natural fibres	
ABS (net float)	Wood (bamboo)	PE	
PLA	Metal (wire)	PP	
	Natural fibres		

Source: Adapted from FAO (2018) and Macfadyen, et al., (2009).

year in which the study was conducted and the methodologies employed for data collection. The available academic research data on lost fishing gear needs to be more comprehensive in assessing and quantifying the actual realities underlying this pollution. Despite the growing recognition of the issue, there is a significant need for in-depth empirical investigation to fully grasp the intricate complexities and nuanced dimensions that characterize this concern.

Using the Arafura Sea as a case study, Butler, et al. (2013) tried to identify the value chain and stakeholders involved in lost fishing nets. The authors followed the net value chain through its manufacturing site in the Republic of Korea, its use by fishing vessels in Indonesia and its retrieval as a ghost net in Australia. This exercise demonstrates that responsibility for such pollution belongs not to one entity but to an entire supply chain. The upstream stakeholders incur economic benefits while the downstream stakeholders are left with environmental and economic costs — fisherpersons, tourism sites and biodiversity are all affected. Recycling and retrieving fishing gear may create social and economic benefits for local communities. However, it is highly dependent on local infrastructure and market accessibility by those communities involved in this practice. Just as there are limitations on quantifying marine pollution, statistics around recycling ratios from end-of-life fishing gear are still scarce.

Following the comprehensive analysis of available literature and the extensive compilation of information from polymeric material databases, it is evident that the materials utilized to manufacture fishing gear show considerable differences, delineated across a spectrum of distinct material grades and nature as shown in Table 5.

Lifespan

The projected duration of usability for fishing gear manufactured from plastic materials is approximately 30 to 35 months, after which it inevitably decays into a state of waste (Chamas, et al., 2020). When these materials are inadvertently lost within the marine environment, they undergo a lengthy decomposition process taking many years, ultimately creating a hazardous medium for aquatic life because of the presence of microplastics. A comprehensive study has underscored that products originating from petroleum-based sources possess the potential to undergo degradation in marine settings for a duration of up to 2,500 years (Chamas, et al., 2020).

The journey and deposition of waste, whether it be materials that have been diligently collected through formal waste management processes or those that have been illicitly deposited, remains an area characterised by a noticeable lack of available data. A similar lack of information prevails in waste management accountability for fishing gear practices and recycling

Fishing gear made from petroleum-based plastics can take up to **2,500 years to degrade in the ocean.**

(Chamas et al., 2020)

Biodegradable fishing gear must last up to 35 months before degrading —matching the lifespan of nylon gear.

initiatives, rendering waste materials' precise trajectory and destination unknown. This critical information void hampers efforts to comprehensively understand and assess the efficiency, sustainability and ecological implications of contemporary waste management systems. There is a pressing need for further empirical investigations and data acquisition to elucidate the intricate dynamics governing waste disposal and processing mechanisms.

Material development within bioplastics, biodegradable plastics and fibre-oriented solutions are explored through innovative strategies and advancements in these material categories. Beyond plastics, an additional dimension of plastic substitutes involves utilising non-plastic materials. Often characterised by their diverse compositional nature, these substitutes within the fishing gear spectrum are fibre-based solutions. Alternative materials, including bioplastics, are also explored when substitutions are impossible.

Status of current specification guidelines

Plastic biodegradation is the extensive conversion of polymer carbon to carbon dioxide (CO_2) (under aerobic conditions) or CO_2 and methane (CH_4) (under anaerobic conditions) and new microbial biomass over a specific timeframe. Every standard related to biodegradation sets a target for a specific (varies by standard) number of days (usually less than one year) but in fishing gear applications, products cannot start to degrade within this timeframe because of the high cost of procurement or replacement compared with existing fossil-based materials. Also, current solutions (e.g. nylon) have a life expectancy of 35 months, which should be the basis for the lifespan of biodegradation in fishing gear applications. Thus, there is a need to include new requirements in biodegradation standards for this specific industry-focused application.

The term "composted solution" cannot be applied to this context because composting standards have well-defined guidelines (ISO, 2021). While the material eventually degrades in a compost environment (land-based operation), the degradation process is prolonged compared to what is typically expected. This extended degradation period is a likely reason why composting standards do not consider a prolonged lifespan in the case of bioplastics. Therefore, a novel categorization or label must be established for materials falling into this unique category, where decomposition rates are rigorously measured and disclosed, considering specific environmental conditions, including freshwater and seawater environments. Moreover, there is a compelling need for enhanced public awareness and community education concerning lost fishing gear. Even though bioblend materials exhibit a substantially accelerated rate of degradation compared to conventional materials, the lifespan of bioblend products can extend up to 35 months, with only marginal integrity loss during this period. This implies that bioblend materials may cause just as much damage to biodiversity as conventional materials if they are lost during their product life cycle, recovered at sea with wildlife entangled in them or retrieved as litter on beaches. This underscores the critical importance of implementing more effective tracking mechanisms for known lost gear which can be seamlessly integrated into a comprehensive recovery scheme to minimize environmental damage.

Additionally, the quantification of lost and damaged fishing gear can be significantly aided by measuring the volume collected within waste management facilities and tracking the trade of such gear from shops and factories to individuals and fishing companies. This approach aligns with the broader objective of reinstating responsibility upon users to actively collect and manage their waste, thus contributing to reducing the ecological footprint associated with lost or discarded fishing gear.

Promising materials

Biodegradable polymers in the marine environment

This section aims to gain insights into the degradation process of materials focusing on biopolymers within the marine environment. As indicated by the Nova-Institute (2024),[4] the polymers that demonstrate the capacity to biodegrade effectively within a marine environment include the following:

- **Cellulose acetate** (proven under certain conditions or for certain grades);
- **Cellulose** (lignin concentration <5%);
- **Lignin, wood** (proven under certain conditions or for certain grades);
- **Polyhydroxybutyrate** (PHB); and
- **Starch**.

However, this assessment does not account for the results related to bioblends and the ratios of materials employed. Other biomaterials can be specifically tailored to suit the demands of fishing applications encompassing a wide range of options that extend beyond polybutylene succinate (PBS) blends yet are not limited to them. Blend possibility: poly (butylene adipic) PBAT and PBS and its authorized blends for application purposes and marine environment biodegradation characteristics.

Biodegradation in the water environment of various biopolymers

Deroiné, et al. (2014) studied the degradation of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) in distilled water at various temperatures, finding that higher temperatures accelerated water absorption due to hydrolysis, causing polymer chain scission. After 12 months of immersion, the tensile properties showed a significant decline. Building on this, a similar study investigated PLA in both fresh and seawater environments (Table 6), revealing a similar pattern of temperature-dependent water absorption, though to a lesser degree. As with PHBV, PLA's mechanical properties were impacted by temperature, with increased crystallinity enhancing strength over time. Molecular weight analyses further confirmed temperature-driven degradation. These results highlight the common degradation behaviours of PHB and PLA in aqueous environments, emphasizing temperature's role in their degradation kinetics and mechanical changes (Deroiné, et al., 2014).

As explained in the research conducted by Kasuya, et al. (1998), the degradation process in freshwater environments exhibits a more accelerated rate when compared with seawater conditions. This variance in degradation rates is attributed to the inhibitory effect of salt activity in seawater which retards the penetration of water molecules into the polymer matrix. However, this phenomenon may not be universally applicable, as specific freshwater environments characterized by elevated mineral content may exhibit comparable behaviour, potentially following a similar mechanism.

> **PHB, PLA, and cellulose can biodegrade in marine environments**, but degradation depends on temperature and water type.

4 Nova Institute, 2024. Biodegradable Polymer in various environments. Available at https://www.biocycle.net/wp-content/uploads/2024/10/poster_l.jpg.

Table 6.
Degradation rate of biopolymers in different aquatic environments

Material	Freshwater (river)	Freshwater (lake)	Seawater (bay)	Seawater (ocean)
P(3HB)	100	93	41	23
P(3HB-co-14%3HV)	100	100	100	100
P(3HB-co-14%3HB)	100	74	70	59
Poly(E-caprolactone)	100	100	100	67
Polyethylene succinate	100	100	2	5
Polyethylene adipate	100	95	100	57
Polybutylene succinate	2	22	2	2
Polybutylene adipate	24	80	34	11

Source: Kasuya et al. (1998).
Note: Values represent film weight loss (%) as a measure of degradation after 28 days of immersion at 25 °C in the respective aquatic environments.

Trap application

Araya Schmidt and Queirolo (2019) evaluated the feasibility of incorporating natural fibres into the construction of traps, specifically emphasizing their application in netting. The evaluated materials included various iterations of cotton and jute twine experiments characterized by differing constructions (Table 7). These twines underwent a rigorous examination process through submersion in seawater over 56 days, carried out under meticulously controlled laboratory conditions. The average projected duration for twine breakage stands at 188 days for jute, 125 days for twisted cotton and 144 days for braided cotton.

Mitigating the phenomenon of ghost fishing involves not only achieving rapid degradation but also considering the ecological implications of sourcing the necessary materials from natural resources. Notably, natural fibres exhibit a swifter decomposition rate than petroleum-based plastics when employed for identical purposes. The life cycle assessments (LCAs) of cotton and jute are important in the choice of materials. Resource accessibility must also be considered as natural fibres may face competing uses in some countries. Furthermore, exploring alternative sources, such as recycled cotton derived from textile recycling schemes presents an intriguing avenue for testing and procuring materials suited to fishing applications.

Table 7.
Degradation rate of natural fibre in the marine environment

Material	Breaking strength loss rate (kgf/day)		Estimated twine broke time (days)	
Twisted Jute	0.47	MIN. 0.08 – MAX 1.16	188	MIN 113 – MAX 230
Twisted Cotton	0.46	MIN 0.13 – MAX 0.89	125	MIN 68 – MAX 234
Braided Cotton	0.17	MIN 0.13 – MAX 0.22	144	MIN 108 – MAX 205

Source: Kasuya et al. (1998).
Note: values represent the average, minimum, and maximum performance across three different constructions of each fibre type.

Kim, et al. (2014) assessed a biodegradable blend of PBS and PBAT processed through injection moulding to fabricate traps. This biomaterial amalgamation was subjected to a comparative analysis against commercially available recycled HDPE (r-HDPE). The experimentation encompassed two distinct locations, with the traps deployed at the first site nine times, revealing a marginal 3 per cent decrease in Conger Eel catch efficiency compared to the r-HDPE traps. Conversely, at the second experimental site deployed eight times, the biomaterial traps exhibited a slightly enhanced catch efficiency of 3 per cent compared to the r-HDPE traps. The findings of this study underscored that, in this trap design, the biomaterial blend delivered comparable catch efficiency to that of petroleum-based plastics. However, it is essential to acknowledge that the scope of the study was confined to assessing the catch efficiency and did not encompass an evaluation of the biomaterial blend's lifespan or its generation potential of microplastics. Notwithstanding this limitation, the existing practice of replacing commercial traps within two years potentially provides an avenue for the biomaterial blend to penetrate the market. The cost of the biomaterial blend is higher than the present fossil-based solution, potentially influencing its commercial viability in the absence of regulations or subsidies.

Net and line application

Deroine, et al. (2019) demonstrated that PBS exhibits mechanical properties akin to polyolefin polymers. Furthermore, the research has substantiated that PBS undergoes a degradation process when subjected to marine environments, albeit at a relatively gradual pace. This property makes PBS blends a viable prospect for utilization in fishing gear applications, where qualities such as abrasion resistance and resistance to knots are essential. PBS has demonstrated attributes in these domains, particularly when subjected to a specific draw ratio and temperature during the monofilament drawing process. Additionally, the resistance of PBS to ultraviolet (UV) radiation is crucial for its suitability in such applications. To bolster its UV resistance, PBS necessitates the incorporation of appropriate additives into the material matrix, ensuring its durability and performance under the rigours of marine exposure.

In the study by Liu, et al. (2022), marine biodegradation experiments were conducted utilizing sediment and marine organisms as a substrate to assess the biodegradability of materials, specifically focusing on PBS and PBAT. The experimentation involved the analysis of multiple grades of these materials to comprehensively evaluate their degradation characteristics in a marine environment (Table 9).

PBS–PBAT traps matched or slightly outperformed recycled plastic traps in eel catch efficiency.

Table 8.
Summary of bioplastic trial for fishing trap application

Material	Water environment	Duration	Relative efficiency
PBS-PBAT blend	Coastal seawater	9 times during 1 month EXPERIMENT #1 8 times during 1 month EXPERIMENT #2	±3% OVER CONVENTIONAL PE

Source: Kim, et al. (2014).

Table 9.
Molecular weight evolution

Molecular weight evolution (kDA)	PBAT (%)	PBS (%)
60 days immersion over initial sample	-2.5	-6.36
90 days immersion over initial sample	-5.8	-16.36

Source: Liu, et al. (2022).

Catch efficiency & loss rate

Petrol-based lines/nets versus biodegradable alternatives

Cerbule, et al. (2022) compared PA and polybutylene succinate co-adipate-co-terephthalate (PBSAT) for the snood line application. When evaluating the risk of loss following five fishing trips, where an item is considered lost if it is either missing or broken from the mainline, the following observations were made:

- For PA with a diameter of 1 mm, the risk of loss was calculated to be approximately 4.66 per cent, ranging from a minimum of 3.84 per cent to a maximum of 5.46 per cent;
- The risk of loss was slightly higher for PBSATs with a 1 mm diameter at 6.1 per cent, with values ranging from a minimum of 4.59 per cent to a maximum of 7.96 per cent; and
- PBSAT, with a slightly larger diameter of 1.1 mm, exhibited a risk of loss of approximately 5.59 per cent, with a minimum value of 3.99 per cent and a maximum value of 7.38 per cent.

Notably, no significant differences were observed between the two materials when assessing the catch efficiency, indicating comparable performance.

The study involved Grimaldo, et al. (2019) Grimaldo, et al. (2019) evaluating two materials, PBSAT and PA, in the context of gillnet performance. Throughout the entire winter fishing season in a Norwegian location, it was observed that the PA gillnet outperformed the biodegradable PBSAT gillnet by capturing 21 per cent more fish. Furthermore, the study examined the impact of the number of deployments on the relative catch efficiency of the gillnets, revealing that the biodegradable PBSAT gillnet exhibited a diminishing efficiency trend compared to the consistent performance of the PA gillnet. Mechanical property assessments indicated that the biomaterial (PBSAT) experienced a 10 per cent reduction in mechanical properties between its pre-use and post-use states, whereas the PA material remained unaffected. Both materials displayed signs of net damage after use, with the biogillnets exhibiting 66 per cent slightly damaged knots and 19 per cent badly damaged knots, while the PA gillnets showed 74.5 per cent and 16 per cent, respectively. Additionally, the biodegradable gillnets suffered from 8.6 per cent of broken knots, whereas the PA gillnets exhibited a lower rate of 3.3 per cent. These findings collectively provide valuable insights into the comparative performance and durability of PBSAT and PA gillnets in real-world fishing conditions.

Biodegradable gillnets captured up to 50% fewer cod and 41% fewer saithe than PA gillnets, prompting resistance from fishers.

A separate study conducted by Grimaldo, Herrmann, Tveit, et al. (2018a) revealed a notable 30 per cent decrease in the efficiency of the biomaterial gillnet compared to PA. These experiments occurred in a distinct geographical location and during a different seasonal period. Notably, the diminished efficiency was particularly pronounced when dealing with fish of larger dimensions, specifically those measuring 65 cm or more in length. This reduced performance can be attributed to disparities in the elasticity and tensile stress properties between the biomaterial fishing net and its PA counterpart.

In another comprehensive study undertaken by Grimaldo, Herrmann, Vollstad, et al. (2018b) spanning a two-year fishing season, an assessment was conducted on the same materials. It was observed that the biogillnets, compared with the PA gillnets, exhibited a decrease in performance, capturing 50.0 per cent fewer cod and 41.0 per cent fewer saithe in 2016 and 26.6 per cent fewer cod and 22.5 per cent fewer saithe in 2017 when compared to their PA counterparts. These significant discrepancies in catch efficiency prompted negative feedback from the fishermen involved in the study, indicating a notable resistance to adopting biomaterial nets. Overcoming this resistance to change poses a substantial challenge that warrants careful consideration. The assessment included an analysis of the proportion of knots falling into distinct categories, including those without damage, slightly damaged, badly damaged and broken knots for gillnets utilized in 2016 and 2017.

Grimaldo, et al. (2020) conducted an extensive evaluation using the same materials over three distinct fishing seasons, spanning 63 deployments. The findings revealed a progressive loss of catch efficiency in the biodegradable gillnets as they successively captured 18.4 per cent, 40.2 per cent and 47.4 per cent fewer fish than their PA counterparts during the first, second and third seasons, respectively. Furthermore, a dedicated 1,000-hour ageing test exposed the propensity of both materials to commence degradation after a mere 200 hours, with the biodegradable gillnets exhibiting a notably accelerated degradation rate when juxtaposed with the PA gillnets.

Throughout a four-year testing period from 2010 to 2013, Kim, et al. (2016) observed that the degradation rate was more pronounced during summer, coinciding with elevated water temperatures. A comprehensive analysis utilizing scanning electron microscopy (SEM) for visual inspection revealed that degradation initiation occurred approximately 24 months after the material's immersion in seawater. Regarding performance, the bionet demonstrated a slightly reduced catch efficiency, capturing 0.7 per cent fewer fish than the conventional PA-based net.

Table 10.
Review of fishing gear performance using biodegradable materials in coastal seawater

Source	Type	Variable	Exposure	Species	Efficiency (%)	Loss(%)	Damage (%)	
Cerbule, et al., 2022	**Longline**	Ø 1 mm	n/a	Cod	-14.63	-6.91	-1	REPLACED
				Haddock	-10.56			
		Ø 1.1 mm	n/a	Cod	-2.47	-4.5	-0.04	REPLACED
				Haddock	-15.57			
Grimaldo, et al., 2018a	**Gillnet**	n/a	27 days	Halibut (GRL)	-9.46	n/a	n/a	
Grimaldo, et al., 2018b	**Gillnet**	Year 1	2 years	Cod	-33.34	n/a	-2.86 2.14 1.42 0	ZERO SLIGHT SEVERE BROKEN
				Saithe	-25.78			
		Year 2	2 years	Cod	-15.32	n/a	-33.57 33.33 -0.71 0	ZERO SLIGHT SEVERE BROKEN
				Saithe	-12.68			
Grimaldo, et al., 2019	**Gillnet**	Zone 1	43 days	Cod	-14.28	n/a	0.4 -8.5 2.6 5.3	ZERO SLIGHT SEVERE BROKEN
		Zone 2			-9.42			
Grimaldo, et al., 2020	**Gillnet**	Year 1	3 years	n/a	-10.18	n/a	n/a	
		Year 2			-25.14			
		Year 3			-31.04			
Kim, et al., 2016	**Driftnet**	n/a	n/a	n/a	-0.7	n/a	n/a	

Note: Materials tested are PBSAT bioblend (PBS-PBAT) versus conventional nylon. Positive values in the Efficiency % column indicate that the bioblend achieved higher catch efficiency than the conventional material; Variable refers to the test condition, which may include monofilament thickness (Ø), exposure period (e.g., Year 1/2), or trial area (e.g., Zone 1/2) depending on the study; n/a = not applicable or not available in the source.

Biodegradable fishing gear must match catch efficiency and fully degrade at sea within five years —a major challenge.

Projects developing alternative solutions

The strategies of circular economy and advanced biobased solutions to keep our lands and seas alive from plastics contamination (SEALIVE) is a European innovation project that addresses the intricate challenges of plastic pollution. The project strategically focuses on fostering the adoption of biomaterials and actively contributing to the circular economy through comprehensive strategies. The consortium comprises 24 entities, including the notable inclusion of ICCI Seabird (France).

Another noteworthy project in this domain is the Kuwait test site initiated by a Republic of Korea producer focusing on biodegradable fishing nets since 2013. Spain has also been involved in developing oxo-degradable fishing nets since 2014. Additionally, the INovative fIshing Gear for Ocean (INdIGO) project, a European initiative supported by the European Regional Development Fund (ERDF) within the framework of the Interreg France (Channel) England programme, has been actively working on biodegradable fishing nets from 2019 to 2023 and NaturePlast (France) has played a pivotal role in this project.

The European Union-funded Glaukos project, initiated on 1 June 2020 is dedicated to developing biobased textile fibres and coatings. Collaborating with B4Plastics (Belgium), a Polymer Architecture technology company, Glaukos leverages advanced molecular design tools in creating environmentally friendly, yet robust materials tailored for specific end applications.

Based in South Africa, Gaia BioMaterials is supported by UNCTAD through the SMEP Programme. It aims at introducing bioblend materials into the fishing gear industry. The company is engaged in experimental phases for their materials focusing on marine rope applications in aquafarming, seaweed farming and coral restoration. Furthermore, they have developed a solution for lines and gillnets currently undergoing trial phases.

It is difficult to develop superior alternative materials for the fishing gear industry, which demands products that uphold an efficient catch ratio akin to existing fossil-based materials while ensuring complete degradation within a five-year period when lost at sea. Innovative bioproducts may not be more sustainable than fossil fuel-based materials because of the nature and limitations of the industry.

These projects are dedicated to innovative material development and use coded name tags instead of disclosing the specific formulation blend. This approach is likely adopted to safeguard the intellectual property associated with material development. But how can we be sure that any solution is an effective alternative to the conventional materials used? Either a data sharing system on material composition needs to be created or mandated at the global level or third-party certification would be essential to ascertain the percentage of organic or natural materials. This would ensure continuous advancements in substitutive solutions rather than mere improvements.

Case study

Fiji

The socioeconomic context of small island countries is a complex interplay of various factors encompassing their geographical constraints, economic activities, governance structures, cultural dynamics and external influences. Small island countries, often characterised by their limited landmass and isolation, face unique challenges and opportunities that shape their socioeconomic landscape. The proximity to the ocean can both bless and burden these countries; it offers access to marine resources but exposes them to the risks of marine pollution. Tourism often plays a pivotal role, serving as a significant source of income and employment. Agriculture, especially subsistence farming, may be prevalent, but its contribution to the national economy can be limited due to land scarcity. External influences play a crucial role in the socioeconomic context of small island countries. Global economic trends, international trade agreements, foreign aid and geopolitical dynamics can all impact these nations' economies.

For instance, Fiji comprises approximately 330 islands, of which only about one-third are inhabited. It covers about 1.3 million square kilometres of the South Pacific Ocean.

Implementing policies aimed at waste tracking represents a strategic initiative to instil a sense of responsibility among users, compelling them to diligently collect their waste and assume financial accountability when their gear is found along shores or retrieved by third parties. The effectiveness of such policies is contingent upon global implementation, recognising that marine waste transcends geographical boundaries due to ocean currents. For this policy-driven approach to yield maximum benefit, waste management systems must be able to recycle the collected waste into new products.

Conversely, developing innovative materials presents an alternative that sidesteps the necessity for extensive recycling infrastructure to address waste concerns. While composting facilities designed for organic waste could be leveraged, their usefulness hinges on the bioblend having spent a specific duration in the marine environment, thereby undergoing substantial degradation. This precondition ensures that the material requires less than 180 days to disintegrate upon entering a composting facility.

In a broader context, the proposed solutions promise to bolster the economies of countries such as Fiji. A healthier marine environment is anticipated to have a positive ripple effect on tourism activities. Additionally, adopting bioblends offers the prospect of reducing reliance on fossil-based feedstocks. Applying the LCA methodology is an intriguing avenue to comprehensively assess the overall impact, promising insights into the quantifiable benefits of these proposed measures.

Plastics account for 18% of total waste in Fiji, yet detailed data on waste management capacity remains lacking.

In the most recent waste audit report conducted in Fiji under the leadership of SPREP (2023) plastics accounted for 18 per cent of the total waste. The current waste management capacity needs comprehensive data collection, necessitating further investigation into the existing infrastructure and practices. It is imperative to obtain more detailed information regarding the capacity of waste management facilities and the processes involved in handling waste. Additionally, there is a need to establish the types of items included in recycling schemes to ensure a comprehensive understanding of waste management practices for fishing gear products.

According to the report from IUCN (2023) the projected plastic waste generation for 2023 is 21,897 tonnes, with 15,177 tonnes being managed, 1,571 tonnes recycled, 5,148 tonnes mismanaged and likely to enter the marine environment and 1,287 tonnes of waste expected to leak into the marine environment. Furthermore, the report by IUCN (2022) indicated that the fishing industry disposed of 9.3 tonnes of plastic waste in 2019, with 60 per cent comprising PET and 22 per cent PP. The sector was found to leak 2.9 tonnes per year of consumer-based plastics such as water bottles and 19.9 tonnes per year of fishing gear. Additionally, 65 tonnes of plastic-related fishing items were imported in 2019. Future need to invest in infrastructure such as waste transfer stations and material recovery facilities will be critical to support the recycling sector and source separation (IUCN, 2022).

© Plastic Odyssey

Table 11.
Fiji's economic contribution from fishing, aquaculture, and fisheries (2020–2021)

Economic indicator	2020	2021	Annual change	
	FDJ million	FDJ million	FDJ million	%
Fishing & aquaculture GDP	49.8	11.3	-38.5	-77.3
Fishing & aquaculture manufacturing	7.016	7.1	+0.84	+1.2%
Fisheries sector to real GDP	—	56.9 **0.7% OF GDP**	—	—
Fisheries sector exports	187	149.8	-37.2	-19.9%
Fisheries sector imports	95.8	66.7	-29.1	-30.4%

Source: Fisheries (2022).

RCA & the import of fishing gear

The aggregate value of fishing gear imports in Fiji, measured in 1,000 United States dollars, experienced a notable decline of 27.9 per cent from 2017 to 2022. However, in 2021, the reduction compared to 2017 was only 3.57 per cent, suggesting a potential gap in the reporting for 2022. Preceding the onset of the COVID-19 pandemic, the decrease in import value stood at 15 per cent.

Official statistics released by the Fiji Bureau of Statistics (FBOS) detailed the economic contributions of the fishing and aquaculture sectors to Fiji's gross domestic product (Real GDP). In 2021, this sector contributed 49.8 million Fijian Dollars (FJD), reflecting a decline of FJD 11.3 million (-18.5 per cent) from its 2020 contribution of FJD 61.1 million. Moreover, the sector fostered growth within the manufacturing industry, contributing FJD 7.1 million to real GDP growth in 2021, marking an increase of FJD 83,596 (1.2 per cent). The cumulative impact of fisheries-related activities within the broader fisheries sector amounted to FJD 56.9 million (0.7 per cent) towards the national real GDP in 2021.

Furthermore, the fisheries sector constituted a substantial portion of Fiji's national export earnings, contributing FJD 149.8 million (8 per cent) in 2021. However, this figure represented a significant decline of FJD 37.2 million (-19.9 per cent), which was attributed to the adverse effects of the COVID-19 pandemic compared to the 2020 export earnings of FJD 187 million. Noteworthy changes in consumer preferences, particularly a shift towards prepared and preserved fish and crustaceans during the pandemic and the government's economic recovery targets of import substitution, contributed to a substantial reduction in fisheries sector imports, amounting to FJD 66.7 million in 2020. This reflected a substantial decrease of FJD 29.1 million (30.4 per cent) as shown in Table 11.

The FBOS 2019 Annual Employment Survey findings revealed that 1,048 individuals were directly employed in the fishing sector, indicating a notable reduction of 22.31 per cent from the 2018 employment figures (Fisheries, 2022).

Fiji's fishing gear imports fell by 27.9% between 2017 and 2022.

Avenues to explore further

Several strategies and mechanisms have been employed within the domain of fisheries management in addressing the issue of fishing gear loss and its associated environmental consequences:

GPS tracking on vessels

Strategically utilizing GPS tracking systems aboard fishing vessels plays a pivotal role in identifying areas where fishing gear is susceptible to loss. This approach is often harmonized with comprehensive marine studies to delineate oceanic currents and patterns.

Gear marking

A noteworthy initiative involves the unequivocal marking of fishing gear, affording the means to ascertain its ownership or origin. Such marking serves a dual purpose by facilitating the traceability of lost gear back to its source and acting as a potent deterrent against the illicit dumping of gear. Notably, specific regions, including the European Union, since 2009 following Regulation (EC) 1224/2009 and Eastern Canada according to the Government of Canada in 2021, have mandated gear marking as an integral facet of their fisheries management regulations. Marking fishing gear becomes challenging when the equipment originates from countries that do not adhere to such regulations.

In Nigeria, 523 fishers removed 700 kg of lost fishing gear.

Free waste collection at ports

A commendable practice involves providing cost-free waste collection services for out-of-use fishing gear at port facilities. This proactive measure serves as a disincentive for intentional gear disposal at sea. However, it is imperative to concurrently develop a robust recycling infrastructure and an efficient accountability system complete with a traceability process that explains the final destination of the collected material. The "Fishing Net Gains Africa" initiative is engaged in an ALDFG retrieval program in the coastal regions of Nigeria. Although a relatively modest undertaking, the program has successfully removed 700 kg of ALDFG with the involvement of 523 fishermen who are incentivized to bring nets ashore, contributing to a reduction in ghost fishing and benefiting the local fishing community (Drinkwin, 2022).

Establishing mandatory EPR schemes for collecting and recycling waste fishing gear

A vital step in managing waste fishing gear is implementing mandatory EPR schemes. These schemes mandate the systematic collection and recycling of waste fishing gear, curtailing its adverse environmental impact.

Bioplastic alternatives development

Exploring bioplastics as an alternative material for manufacturing fishing gear presents a promising avenue for mitigating the enduring ecological repercussions of lost or abandoned fishing gear. These biodegradable materials hold the potential to alleviate the persistent presence of such gear in the marine environment, fostering enhanced sustainability within the fishing industry. The new materials still need improvement to match the performance of fossil-based materials (nylon and others). Still, the number of research programs and businesses involved in this area will provide better solutions for the future.

Recommendations and limitations

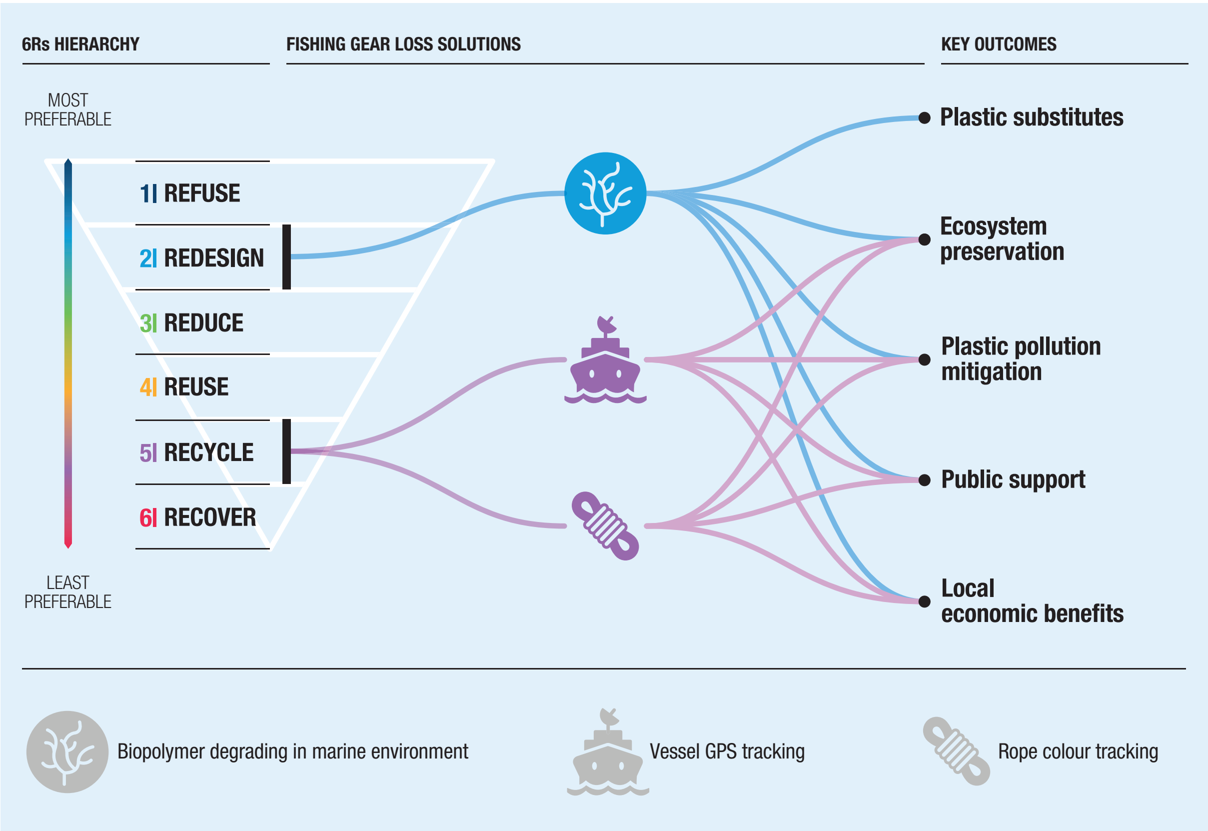
Emerging opportunities exist in recycling marine macro debris into alternative products through a systematic process surrounding collection, washing, sorting and subsequent conversion. Coastal communities can benefit from engaging in seaweed culture and conversion processes into biopolymer and other end-applications, where the bioplastic could be used in various areas such as food packaging and mulch film.

Harnessing local resources to transition towards substitution for fishing gear is critical and needs continual experimentation. University laboratories are leading in designing blends utilizing locally mapped material fibres, for example. Additionally, there is a focus on recycling waste collected from marine environments, reinforcing the imperative of sustainable practices in managing and repurposing materials sourced from the oceans (Figure 3).

Exploring and creating bioblends that incorporate natural fibres with biopolymer blends derived from organic sources would be essential in reducing the ratio of fossil-based origin currently used within alternatives. The degradation mechanism of biobased fishing nets and lines is also crucial. Active degradation facilitated by the bottom sea microbiome would be optimal for expediting the process. It raises the question of whether certain types of fishing gear, excluding traps, are designed to reside on the seabed.

Seaweed-based bioplastics offer new opportunities for coastal communities.

Figure 3.
Mapping fishing gear loss solutions across the 6R hierarchy



Source: Prepared by UNCTAD based on FAO (2021).

Bioblend materials from small-scale setups can be **costly and produced in limited volumes.**

Limitations

The first focal point involves addressing the challenge of securing access to advanced material solutions aligned with sustainable practices within the fishing gear industry. Development of innovative materials often takes place in small capacity set-ups, which translate into high prices and low volumes.

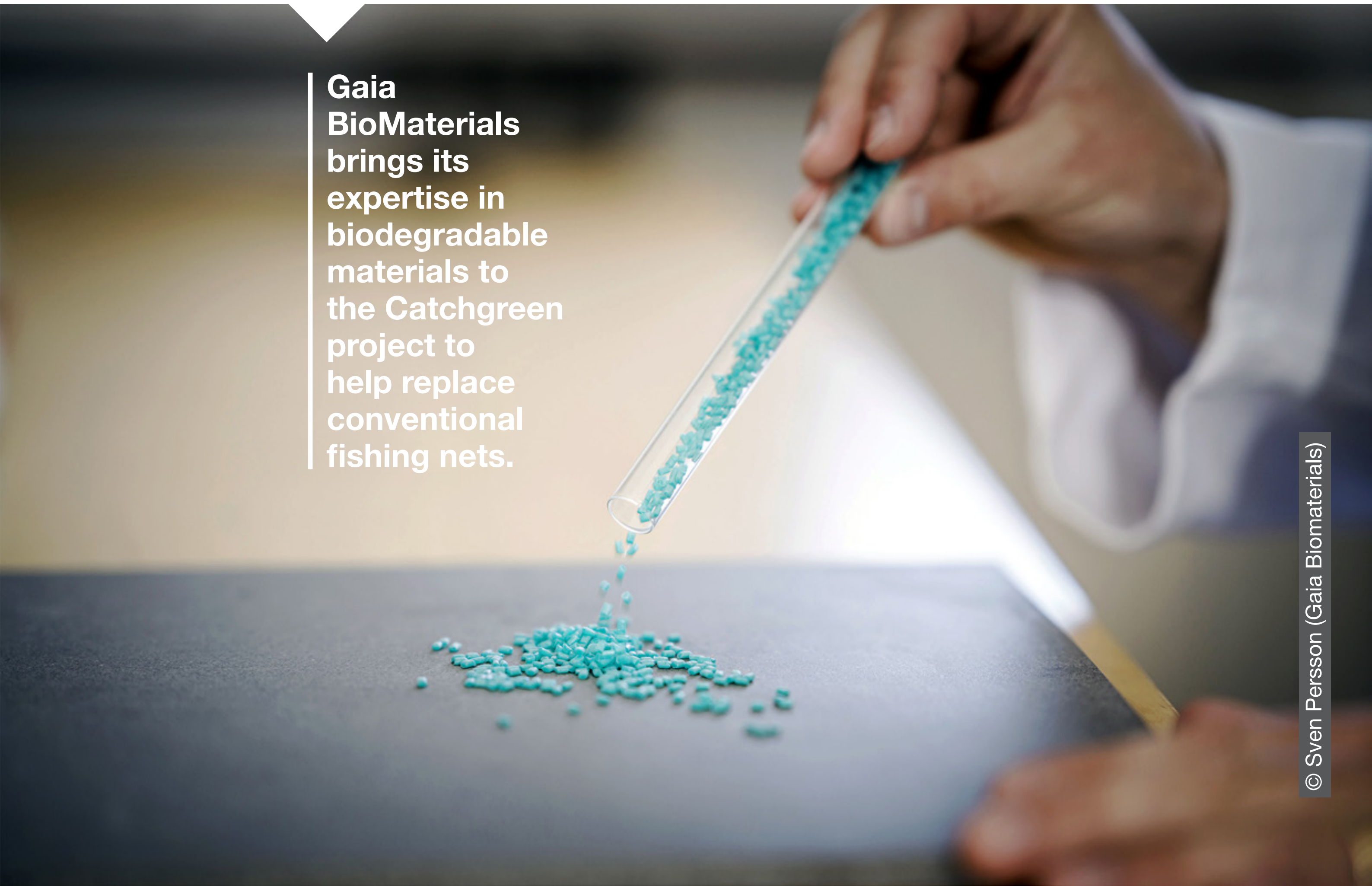
A second critical consideration is the complexities associated with intellectual property (IP) rights concerning bioblend materials. The discussion acknowledges potential hurdles in transferring knowledge and technology to emerging materials. However, it proposes a solution through partnerships wherein suppliers could be responsible for producing and shipping materials or products to designated countries. This could be facilitated through secure programs, covering costs if subsidized.

The third facet centres on the management and control of maintenance procedures for bioblend fishing gear, contemplating effective strategies for both maintenance and remedial actions.

Additionally, the discussion addresses the reporting mechanisms for fishing gear transactions, particularly in replacing lost gear. Various solutions are proposed such as tagging items with radio frequency identification (RFID) or similar technologies to account for their movement when leaving a shop. The consideration extends to implementing a registry for lost gear which could be operated voluntarily. Other possibilities include assigning RFID tags with unique user codes to fishing gear and establishing a digital platform for registering users and equipment providers, thereby enhancing traceability.

In cases where quantifying the volume of gear proves challenging, an alternative approach involving measuring the value of transactions as gear moves from one party to another is suggested. This could be integrated into a platform for streamlined monitoring and reporting.

Gaia BioMaterials brings its expertise in biodegradable materials to the Catchgreen project to help replace conventional fishing nets.



© Sven Persson (Gaia Biomaterials)

Chapter IV

Agriculture mulch and seedling tubes

Chapter highlights

- **Plastic mulch challenges** — While agricultural plastic mulch is widely used and well-established, its end-of-life management is highly challenging, polluting soils and hindering their carbon sequestration capacity and health.
- **Kenya case study** — This section analyses the case of Kenya, where land degradation has resulted from the use of agricultural mulch films and seedling tubes.
- **Sustainable alternatives** — Organic mulching practices and Biodegradable Mulch Films (BDM) are more sustainable options over conventional plastic mulch.
- **Benefits of organic mulching** — Organic mulching, such as crop residues and natural fibres, contributes to soil health and carbon sequestration.
- **BDM considerations** — BDM eliminates the need for retrieval and end-of-life management; however, the long-term effects must be considered and studied.
- **Kenya's local potential** — Kenya could leverage their vast supply of crop residues to promote local production of plastic mulch and seedlings substitutes.
- **Policy framework needed** — The transition to sustainable agricultural practices calls for standardised regulatory frameworks for biodegradable and compostable plastics.

Agriculture mulch and seedling tubes

The use of plastic mulch in agriculture is a widespread practice that increases crop yields, extends the growing season and reduces the need for irrigation, fertilizers and herbicides (FAO, 2021). This is achieved as plastic mulching films enable soil moisture retention, reduce nutrient leaching and control weed growth in the crop row (FAO, 2021). While there are evident benefits to using plastic mulches in agriculture, these materials leach into the soils and ultimately contribute to land degradation. This, in turn, has long-term and devastating consequences for the environment and the livelihoods of local communities.

The case of mulch and seedling tubes, and potential substitutes

There are several reasons why agricultural mulch plastic films have a detrimental effect on ecosystems and soil health. To begin with, it has been demonstrated that plastic mulching is a major source of microplastics (1 μm < size < 5 mm) in agricultural settings (Huang, et al., 2020). Over time, there is more accumulation of microplastic particles where agricultural plastic mulching has been continuously implemented (Huang, et al., 2020). Plastic fragmentation is widely attributed to a combination of physicochemical processes (Mateos-Cárdenas, et al., 2020) initiated by environmental stressors involving sunlight, water and air exposure (Sorasan, et al., 2022). Moreover, there is evidence suggesting that plastic degradation continues even after the generation of microparticles (Sorasan, et al., 2022).

Microplastic formation resulting from the degradation of mulching films has a dual impact. Firstly, this degradation process releases substances that disrupt the delicate balance of the soil microbiome, hindering its ability to sequester carbon from the atmosphere and transform it into bioavailable nutrients. Consequently, impaired soil functionality adversely affects plant growth, reducing crop yields. Notably, experiments have revealed that these effects are more pronounced after a decade of plastic exposure (Graf, et al., 2023). This is particularly significant considering that farm soils have endured constant exposure to plastic over the past five decades (Graf, et al., 2023).

Plastic mulch films fragment into microplastics, harming soil and ecosystems.

Secondly, microparticles from agricultural mulch plastic films can attach pesticide residues and chemicals on their surface and within their structure and act as vectors or carriers of these substances in the environment. This phenomenon could potentially lead to higher levels of these contaminants into nearby agricultural soils, where they may be reabsorbed by microplastics in the soil or reach the roots of crops. This underscores the need for proper agricultural mulch retrieval from the fields after application (Sahai, et al., 2023).

Proper disposal of plastic mulching films used in agriculture is challenging. Despite the importance of removing agricultural plastic mulch films, they are often left in croplands because of the time-consuming and labour-intensive nature of their removal (Huang, et al., 2020). This contributes to the build-up of microplastics in farmlands, affecting not only soil health, as previously discussed, but also terrestrial biodiversity and food security (Huang, et al., 2020). Another key factor determining the retrievability of these films is whether they have been adequately specified, especially in terms of their thickness. This parameter affects the films' structural integrity, or fragmentation degree, both during and after use (FAO, 2021).

Moreover, inadequate retrieval practices can lead to high contamination levels of the plastics with soil and plant residues, making recycling efforts difficult and costly. Contamination to plastic film ratios can be as high as 2:1 (FAO, 2021). As a result, mulching films are usually landfilled and, in some cases, burned. More importantly, if the film contains PVC, the second most common material in these products, its incineration releases gases classed as POPs under the Stockholm Convention (FAO, 2021).

Plastic mulch beds can also lead to soil erosion in the uncovered areas, especially when the soil between the beds has been cleared and left bare (Tarrant, et al., 2020). After rain events, run-off is induced on the bare soil, increasing the risk of nutrients and pesticides leaching away. In fact, there is evidence showing that plastic mulch used in agriculture may serve as a pesticide vector (Salama & Geyer, 2023). Pesticide residues can attach to the non-crystalline regions of the films thus enabling the spread of pesticides in the soil matrix (Salama & Geyer, 2023). Studies have shown that mulch microplastics strengthen the adsorption of pesticides into the soil, an effect that is further heightened over time as seen in ageing treatment experiments (Wu, et al., 2022). Mulches that have been exposed to pesticides must not be landfilled, as there is a risk of pesticide residues leaching out (Salama & Geyer, 2023).

Recent reports by FAO (FAO, 2021) and the FCDO-UNCTAD SMEP Programme have all signalled the importance of more work in plastic mulch films (UNCTAD, 2023b). Agricultural plastic mulch is one of the five main contributors that overburdens both ocean environments as well as nations' waste management systems, along with SUPs, packaging products, textiles and ALDFG (UNCTAD, 2023b). Plastic mulching was ranked the second highest environmental risk among all agricultural plastics by FAO, only second to slow-release fertilizers (FAO, 2021). Such ranking was based on the following criteria (FAO, 2021):

- Amount of plastic products used yearly;
- Leakage potential where the product is used, based on the 3D concept;
- Type of ecosystem where the plastic may leak (e.g. soil); and
- Potential adverse effects on plants, animals and humans, including the product's capacity to generate microplastics.

This study provides recommendations on plastic mulching substitutes tailored for the specific context in Kenya. As a regional leader and one of the more stable economies in East Africa, Kenya's agriculture remains its largest sector, accounting for around 25-30% of GDP (Maurer, et al. 2023). By conducting a literature review that includes academic literature (e.g. journals, books) and grey literature (e.g. government and industry reports). More importantly, the research draws from the list and HS codes of plastic mulch substitutes identified by UNCTAD in the 2023 report on plastic pollution (UNCTAD, 2023b). Substitutes are assessed regarding their properties, potential for creating new business models, impact on the current food system model, negative externalities and manufacturing capacity. Local availability and economic indicators, including RCA and recovery/recycling rate of potential substitutes are analysed to assess their economic viability.

FAO ranks plastic mulch among **the top agricultural plastic risks.**

Small-scale farmers produce 75% of Kenya's crops, supporting over 80% of the population.

Case study

Kenya

Kenya is a country highly reliant on the agricultural sector (MENR, 2016), which plays a key role in its economy. Agriculture accounts for 70 per cent of rural jobs (40 per cent of the nation's workforce) (ITA, 2022). The agricultural sector directly makes up a third of the country's GDP, and indirectly accounts for 27 per cent of GDP due to its deep linkages with other sectors serving as the main driver of the non-agricultural economy (FAO, 2023a). In addition, 60 per cent of export earnings come from agriculture products. The sector also provides livelihood for millions of Kenyans (over 80 per cent) in the form of employment, income and food security. Small-scale farmers account for 75 per cent of the country's total agricultural output (Harvest, 2020).

Small-scale farming in rural Kenya heavily relies on rain-fed agriculture and is extremely vulnerable to the adverse effects of climate change, including unpredictable rainfall patterns and frequent droughts (GGGI, 2021). The vast array of social and economic benefits that agriculture delivers is greatly threatened by land degradation, whose impacts are even worse in the most productive areas in the country (Ministry of Environment and Natural Resources, MENR, 2016). The National Environmental Management Authority (NEMA) has highlighted that land degradation, along with climate change, also results from the use of agricultural mulch films and seedling tubes made from plastics materials. This is particularly prominent in agriculture and forestry soils where there is extensive plastic pollution on land.

The agricultural sector also faces several challenges. Diseases, pests and weeds affect food crops, reducing their yield and quality. It has been estimated that these food crop offenders have caused losses of 40 per cent (KALRO, 2023). The government has shown interest in addressing these losses while working on the protection and conservation of the environment (Food Crops, 2023), demonstrating its commitment to promote sustainable development.

Another obstacle is its food crop production is not enough to meet domestic food demand (Food Crops, 2023). Agriculture in Kenya, akin to the situation across the African continent (Mayowa Kuyoro, 2023), contends with being among the lowest-productivity sectors. As a result, Kenya is forced to import large quantities of foods to account for local consumption (Food Crops, 2023).

© Henrique Pacini (UNCTAD)

Trade dynamics of plastic mulch

The information obtained first-hand from NEMA indicates a growing acceptance of plastic mulch for its durability and effectiveness in pest reduction. The local distribution is roughly 50-50 between domestically produced and imported plastic mulch. The two major consumers, Kakuzi Ltd and Del Monte Ltd, utilize plastic mulch to cultivate various crops, including blueberries, tea, commercial forestry, avocados and pineapples. Individual farmers also adopt plastic mulch for growing tomatoes, cabbage, capsicum, strawberries, spinach and kale. However, precise figures regarding the quantities of plastic mulch introduced to the Kenyan market still need to be clarified by the primary local plastic mulch manufacturers. Government officers have expressed support for plastic mulch, arguing that it is not a labour-intensive practice and can cut production costs by up to 80 per cent (Waweru, 2023).

Plastic mulch is traded under the HS code 3920 with the description of 'Other plates, sheets, film, foil and strip, of plastics, non-cellular and not reinforced, laminated, supported or similarly combined with other materials (Flexport, 2023). Given that the main type of polymer used in plastic mulch films is PE (FAO, 2021), the HS code can be narrowed down to HS 392010 with the description of 'Plastics; plates, sheets, film, foil and strip (not self-adhesive), of polymers of ethylene, non-cellular and not reinforced, laminated, supported or similarly combined with other materials' (United Nations, 2022). The top three world exporters of HS 392010 are, in this order, China, Germany and the United States (United Nations, 2022). There is no data on exports since Kenya does not export products under HS 392010, it only imports them.

The horticultural sector stands as a prominent subsector within Kenya's agriculture, playing a significant role in the nation's GDP (FAO, 2023c). Horticultural products rank as the second, third and fourth top exported products from Kenya (COMTRADE, 2021). Some of the horticultural crop groups grown in Kenya include fruit trees, medicinal and aromatic plants and flowers and ornamental plants (FAO, 2023c). Plastic mulch is a mainstay on most horticultural crop cultivation with holes often created in the mulch for planting vegetable seedlings.

Sustainable interventions for plastic mulching films

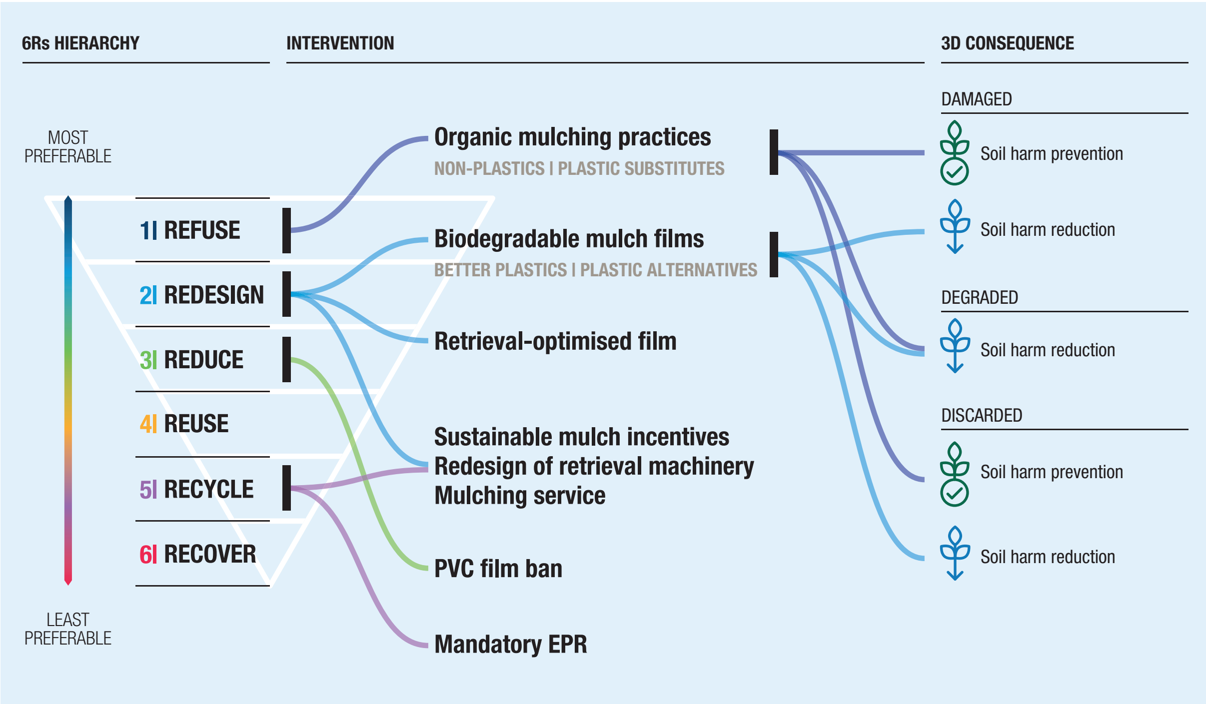
An analysis of the 6R hierarchy and the 3D concept

Several possible alternative solutions in reducing the adverse impacts of plastic mulching films while maintaining or enhancing their current benefits have been put forward by FAO (FAO, 2021). Figure 4 shows how these interventions stack against two main criteria: the 6R hierarchy based on zero waste and circular economy principles and the 3D concept, which applies to mismanaged and leaked plastics. This study focuses on the top two interventions seen encircled in the dotted line, organic mulching practices and BDMs (Figure 4).

Overall, the two types of interventions that are at the top of the 6R hierarchy are organic mulching practices and BDMs. The former includes adopting plastic substitutes (non-plastics) such as crop residues, cover crops, natural fibres and other biomass forms (FAO, 2021). These practices are at the top of the hierarchy because they avoid using plastic mulches. Moreover, if the substitute used gets damaged or is inappropriately disposed of, it will not harm the soil. If it degrades, the harm to the soil is reduced compared to its plastic counterpart. On the other hand, redesigning to switch to using plastic alternatives (bioplastics or biodegradable plastics) is the second-best strategy according to the 6R hierarchy because these plastic alternatives would eliminate the need for retrieval, hence the need for end-of-life management. However, the long-term effects of these materials are yet to be determined and need further research.

Plastic mulch can reduce production costs by up to 80%, according to Kenyan government officers.

Figure 4.
Interventions that deliver similar benefits of agricultural plastic mulch while reducing its adverse impacts



Source: Prepared by UNCTAD based on FAO (2021).

Organic mulching practices

Organic mulching practices are at the top of the 6R hierarchy because of their deliberate avoidance of plastics and promotion of the use of organic materials or cover crops (forms of biomass) (FAO, 2021). These practices not only eliminate the use of plastics and their associated greenhouse gas emissions (GHGs) but also offer a significant advantage: they enhance the soil's capacity to capture carbon (FAO, 2021). Incorporating biomass into the soil increases soil organic matter (SOM) (FAO, 2005), which plays a crucial role in driving the diversity and activity of soil fauna and microorganisms, thereby profoundly influencing the physicochemical properties of soils and ultimately, soil health (FAO, 2001). Consequently, SOM serves as a key determinant in both agricultural production and environmental functions, encompassing carbon sequestration and enhancement of air quality (FAO, 2001). Organic mulching practices, in essence, allow nature to rebuild soils and increase biodiversity, thus regenerating nature.

According to EMF, given that "regenerate nature" stands as the third principle of a circular economy (Ellen MacArthur Foundation, n.d.), adopting organic materials or cover crops as mulch contributes to the transition towards a circular, regenerative approach to agriculture.

As further described below, Kenya has an overabundance of organic materials in the form of crop residues, namely maize stubble and coffee husks (UNCTAD, 2023b). While this represents a clear advantage in terms of local availability, it is also crucial to identify the current uses or applications when assessing their potential as substitutes for plastic mulch. The report fully addresses this in the following sections.

Organic mulching enhances soil health and carbon capture while avoiding plastic use.

Framing criteria for plastic mulch substitutes

Plastic mulch substitutes, like plastic substitutes, should ideally be competitive (with good productive capacities) and effective in managing waste downstream in the areas where it is implemented. The existing productive capacities of a country to supply alternative materials can be assessed through the RCA (UNCTAD, 2023b), a proxy or an indicator of a country's comparative advantage in producing certain goods or materials compared to other countries. When the RCA is greater than one, it means a comparatively advantageous competitive productive capacity exists. Regarding the efficiency of downstream management of alternative material wastes, the recovery/recycle rates can serve as an indicator. The ideal substitute for plastics should have an RCA over 1 and recovery/recycle rates above 60 per cent (UNCTAD, 2023b). The combination of these two indicators, RCA and recovery/recycling rate, can infer the economic viability of material substitutes (UNCTAD, 2023b).

Other key factors to consider when assessing plastic mulch substitutes are their availability within the local environment, potential limitations and the perspectives of consumers regarding their adoption (UNCTAD, 2023b). In addition, determining the introduction of a substitute should be guided by several elements: their physical properties, potential impacts on food systems (including trade-offs from current uses) and on ecosystems (including negative externalities) and new business models that may ramp up manufacturing capacities (UNCTAD, 2023b).

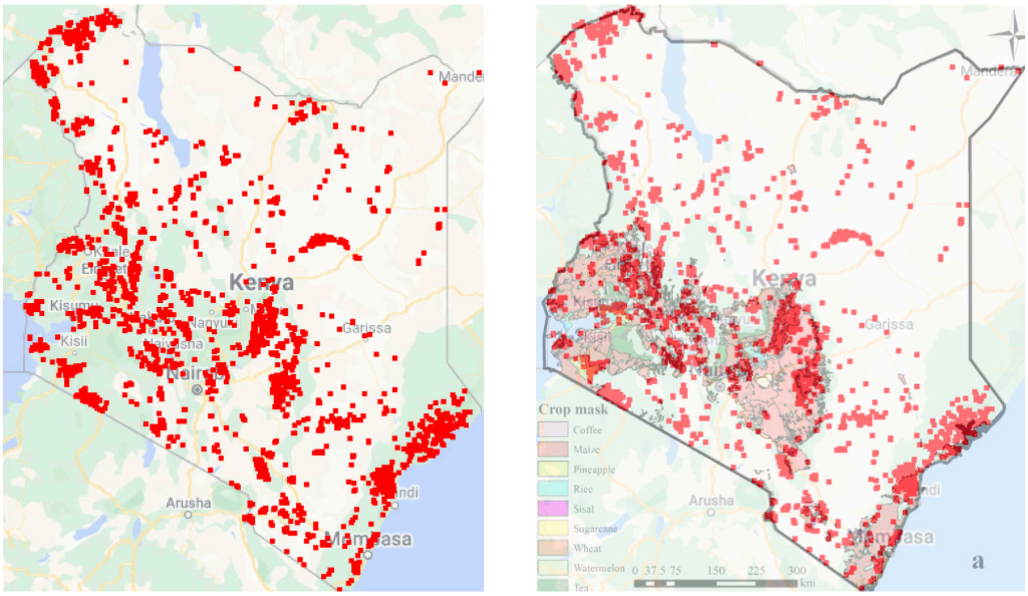
Properties

Crop residues such as straws, stovers and other non-edible parts play a crucial role in the recycling of nutrients, improving soil fertility (FAO, 2015). Using crop residues such as mulch is instrumental in mitigating soil erosion (FAO, 2015). As crop residues decompose, they increase SOM, thus improving soil structure and reducing erosion risk caused by water run-off. Furthermore, crop residues can be an effective means to control weeds and pests (FAO, 2015). Studies have shown that they offer similar benefits when assessing how these residues stack up against plastic mulch (UNCTAD, 2023b). However, it is important to highlight that because the choice of mulch depends on the specific crop or plant, crop residues may not be considered a one-size-fits-all mulching solution (UNCTAD, 2023b).

Some studies have delved into using crop residues as agricultural mulch in Kenya, particularly maize stubble. After conducting several experiments, Tuure, et al. (2021) suggested maize residue mulching as an accessible and feasible method for conserving soil moisture in the effective root zone in semi-arid smallholder systems in East Africa. The experiment was run with 1 cm of mulch thickness, and further calculations showed that increasing it from 1 to 3 cm or 3 to 5 cm would have fostered the soil moisture content even further. While the capacity to retain moisture increases with mulch thickness, crop residue availability sets the limits on application rates (Tuure, et al., 2021).

Crop residues like maize stubble can improve soil moisture and fertility, offering **a viable alternative to plastic mulch** in Kenya.

Figure 5.
Crop residue burning in Kenya and its overlap with farmland areas



Source: Adapted from Ni et al. (2022).

Food system and current uses of crop residues

Crop residues in Kenya constitute a significant share of the total annual biomass production in the country (Kimutai, 2014). These agricultural residues serve as an energy source in both industrial and domestic settings. There is no evidence suggesting that agricultural residues in Kenya are used for human consumption. Despite this, the utilization of crop residues as fuel is limited and, instead, they are predominantly burned and dumped in crop fields (Kimutai, 2014). The graph above [5]gives an overview of the fires that occurred in Kenya over the period January 2020 to October 2023 (Figure 5). During this period, a significant percentage, approximately 85 to 90 per cent, of the fires were concentrated in croplands across the country (Ni, et al., 2022).

Most fires in Kenya (2020–2023) occurred in croplands where residues are burned or fed to cattle.

Other studies suggest that the use of crop residues as animal fodder is a commonplace practice amongst smallholders. Castellanos-Navarrete, et al. (2015) showed that although keeping crop residues was the cheapest source of nutrient inputs for the next crop, especially when compared with manure, farmers prioritized its use for cattle feeding. In fact, most farmers (73 per cent) focus on cattle feeding, overlooking soil fertility, given its crucial role in their livelihoods. Overall, the demands for cattle feed and the limited availability of organic resources, especially in poor farms, make crop residue mulching particularly challenging (Castellanos-Navarrete, et al., 2015). Duncan (2016) conducted a study that supports this strong preference among Kenyan farmers for allocating crop residues to livestock feeding. This is particularly true amongst smallholder farmers. However, there is a shift in allocation practices along a productivity gradient. As productivity increases, farmers tend to allocate a larger portion of crop residues to soil fertility management.

5 The fire data was sourced from NASA's VIIRS fire detection database and mapped using Google Maps' latitude/longitude coordinates, with an accuracy of 375 meters. A total of 3,574 high-confidence records are visualized. The graph in Figure 5 was generated using a custom website built with the Google Maps JavaScript API: https://map.websoft.space/. Farmland data for Kenya was obtained from Ni, et al. (2022), Effectiveness of Common Preprocessing Methods of Time Series for Monitoring Crop Distribution in Kenya, Agriculture, 12(1), 79. https://www.mdpi.com/2077-0472/12/1/79.

The information gathered first-hand from NEMA in Kenya has provided additional insights into the various applications of crop residues that exist in the country, including but not limited to animal feed, organic manure (often considered the cost-effective choice), briquette production, direct burning and more recently, the cultivation of black soldier flies (a current trend in Kenya). When proposing a novel application for crop residues, it is essential to consider the multitude of uses outlined here. The success of integrating a new potential use of crop residues depends on how seamlessly it can align with existing day-to-day applications. On the same note, FAO advocates that decisions regarding the utilization and distribution of biomass resources such as crop residues, should always be grounded in well-founded evidence and take into account local context and needs (FAO, 2023b).

Negative externalities

Using crop residues as potential plastic mulch substitute is a nature-based approach that can lead to enhancing crop yields while reducing negative externalities (UNCTAD, 2023b). Although there are limited data in LCAs regarding the use of crop residues as agricultural mulch (FAO, 2021), it is reasonable to anticipate that they have fewer environmental impacts compared to plastic mulches. This is primarily because crop residues do not generate additional GHGs from film manufacturing industries or waste disposal processes.

However, it is crucial to test this hypothesis before introducing crop residues as a plastic mulch substitute for horticultural crops in Kenya. Such assessments would not only provide valuable support for policymaking and the development of national and regional strategies (FAO, 2021) but could also align with the country's Environmental Management and Coordination Act which mandates a comprehensive environmental impact assessment, identified as one of the key achievements of Kenya's public governance (Instituto 17, 2022).

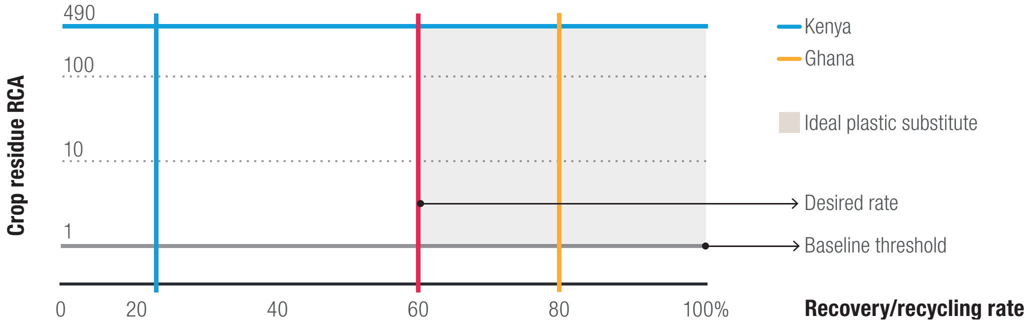
Economic viability

Figure 6 shows the RCA and the recovery/recycling rate for crop residues in Kenya. Additionally, the graph illustrates the optimal area for finding suitable plastic substitutes. Kenya enjoys a significant advantage in producing crop residues, with an RCA of approximately 490, well above the baseline threshold of 1 (UNCTAD, 2023b). To provide context, Kenya's most exported crop, tea, has an RCA of 413.1 (UNCTAD, n.d.). However, the recovery/recycling rate is only at around 23 per cent, significantly lower than the desired 60 per cent (UNCTAD, 2023b). This disparity can be attributed to the common practice of open-burning crop residues.

Although crop residues are not the optimal plastic substitute, substantive policies and interventions can be suggested to achieve recovery/recycling rates, albeit the results may take some time to materialize (UNCTAD, 2023b). The following section also considers data in Figure 6 below from Ghana for comparison.

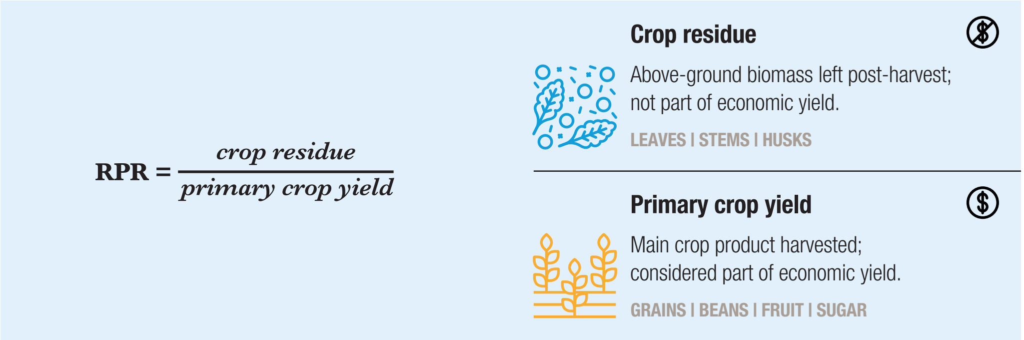
Kenya has a high comparative advantage in crop residues but recycles only 23%, mainly due to open burning.

Figure 6.
RCA and recovery/recycling rate in Kenya and Ghana



Source: Prepared by UNCTAD, based on UNCTAD data (UNCTAD, 2023b).

Figure 7.
Mathematical representation of the Residue-to-Product Ratio (RPR)



Source: Prepared by UNCTAD, based on Garcia, et al. (2019).

Residue-to-product ratio (RPR)

The residue-to-product ratio (RPR) expresses the relationship between the amount of crop residue and the primary product (yield) obtained from a crop (Karan & Hamelin, 2021). Specifically, it is the proportion of the total above-ground biomass of a crop that is allocated to the primary product such as cereals and the proportion that remains as residue after harvest (Karan & Hamelin, 2021) (Figure 7).

While the RPR approach facilitates residue calculation in multi-cropping systems where multiple crops may be cultivated in a designated area within a year, it has limitations (Koppejan, 1998). One drawback is the potential variability in RPR values among different crop varieties, influenced by factors such as weather, crop type, water availability, soil fertility and farming practices (Koppejan, 1998). Additionally, moisture content, which is rarely included in RPR reports, can significantly differ between fresh and air-dry biomass, meaning that estimating residue amounts using RPR may lead to inaccuracies. Therefore, caution is advised when relying on RPR values.

Literature shows that the estimation of the primary cereal straw resources in Kenya utilizes RPR, which signifies the amount of residue available after harvest. Table 12 provides an overview of crop residues in Kenya corresponding to HS code 121300 (cereal straw and husks, unprepared, whether or not chopped, ground, pressed, or in the form of pellets) along with their associated RPR.

Table 12.
Residue-to-product ratios (RPR) of major crop residue cereals produced in Kenya

Crop	Residue type	RPR		
Cane	Bagasse	0.29		
Coconut	Husks	0.42		
	Husks & shells	0.12		
Coffee	Husks	2.10		
Maize	Cob	0.29	0.40	0.273
	Husks	0.20	0.27	
	Stalk	1.59	1.79	2.00

Source: Seglah, et al. (2019), Tolessa (2023), Kimutai (2014), Koppejan (1998).

Table 12. (cont.) Residue-to-product ratios (RPR) of major crop residue cereals produced in Kenya

Crop	Residue type	RPR		
Millet	Straw	1.83	1.75	
Pineapple	Not specified	0.40–0.60* CONTESTED GDP		
Rice	Husks	0.26	0.27	0.30
	Straw	1.66	1.46	1.75
Sorghum	Straw	1.99	1.75	
Wheat	Husks	0.27		
	Straw	1.30	1.75	

Source: Seglah, et al. (2019), Tolessa (2023), Kimutai (2014), Koppejan (1998).
Note: The RPR value for pineapple (marked with *) is based only on estimated ratios from Eliasson & Carlsson (2020) and Singh, et al. (2018).

New business models and manufacturing capacity

Whilst many substitutes for plastics show potential, custom approaches may be necessary in promoting their widespread adoption, meeting national and international demands, increasing manufacturing capacity and advancing circular agriculture (UNCTAD, 2023b). This holds true for the utilization of crop residues in Kenya, where tailored approaches can be valuable. An illustrative example is provided by Ghana, another sub-Saharan African nation, which has achieved an impressive 80 per cent recovery/recycling rate for crop residues. Even though there is still room for improvement (Seglah, et al., 2019), Ghana's experience offers valuable insights for Kenya, serving as a potential roadmap and source of best practices. By expanding the application of crop residues, Ghana not only boosted its recovery/recycling rates but also fostered the emergence of new business models primarily in rural settings. As opposed to more advanced economies where crop residues have mostly industrial uses, Ghana's crop residue utilization is significantly more traditional (Seglah, et al., 2019). In Ghana, crop residues, particularly cereal straw find diverse agricultural uses such as mulching, composting, animal feed and bedding for mushroom production (Seglah, et al., 2019). Non-agricultural purposes include using crop residues as cooking fuel, fencing, mat and basket weaving as well as construction and roofing materials.

In addition, straw is seen as a major feedstock for the biobased economy, which shifts away from fossil fuel-based products and relies on renewable sources. Currently, the combustion of straw is the most common application (Bakker, et al., 2013). Crop residues such as straw are generally not in competition with other uses due to their low-to-zero economic value. Still, there are exceptions when straw has competing uses (Bakker, et al., 2013). Although collection and logistical costs may be high, the use of straw in Kenya's energy sector (especially in rural areas) or even trading opportunities may be considered. In Europe, for instance, wheat straw, along with other types of straw, is considered a primary feedstock for the biobased economy due to the substantial annual production volumes (Bakker, et al., 2013).

Ghana recovers 80% of its crop residues, offering a model for Kenya's circular agriculture.

Agrimats

Another innovative business model centred on crop residues is mulch matting. Agrimats are crafted from cost-effective or readily available organic waste materials such as grass or weed biomass, municipal sewage sludge, algae residues, bagasse and forestry waste (thinned logs, wood chips, sawdust, etc.) (Mgolozeli, et al., 2020).

In a study by Onwona, et al. (2012), pressurized steam and compression technology were employed to create stable 2 cm thick mulching materials known as agrimats from forestry residues. The main raw material used was wood chips. The agrimats were placed on both gentle and steep slopes in the field and exhibited a significant reduction in soil erosion by 94.4 per cent and 92.3 per cent on steep (30°) and gentle (5°) slopes, respectively. Moreover, agrimats demonstrated impressive moisture absorption and retention capabilities, ranging from 67 to 77 per cent for up to two days (Onwona, et al., 2012). The outcomes of the experiment revealed that the moisture retention capacities of biomass boards (agrimats) are relatively high and could be used to reduce soil moisture losses. Furthermore, the incorporation of urea enhances the durability and moisture retention capacity of agrimats. These benefits indicate that the transformation of forestry residue into agrimats for use as ground covers or mulch on farms could yield additional advantages, including enhanced yields, soil moisture preservation, reduction in the need for weeding or herbicide application, erosion control, hill slope stabilization and an overall enhancement in ecological services (Onwona, et al., 2012). Mgolozeli, et al. (2023) also demonstrated that adding algae in the production of agrimats could further enhance the functionality, increasing agrimats' water-holding capacity while minimizing run-off.

Forestry-residue agrimats reduced erosion by over 90% and retained up to 77% moisture for two days.

Agrimats offer a cost-effective solution in addressing crop residue competition in mixed crop-livestock systems (Mgolozeli, et al., 2020) allowing farmers to profit further by selling crop residues as livestock feed or fuel after harvest (Mgolozeli, 2021). They also help alleviate the challenges associated with weed control and herbicide use in no-tillage practices (Mgolozeli, et al., 2020). Additionally, they contribute to cost savings on irrigation, especially in semi-arid regions with limited rainfall (Mgolozeli, et al., 2020). This is particularly relevant for Kenya as almost 80 per cent of the country is classified as either arid or semi-arid. Agrimats can last on the field for up to two years or more, depending on rainfall and temperature patterns, soil type and quality of the organic material used during the fabrication process before they completely decompose (Onwona, et al., 2012)

Another study involved a comparison between agrimat, algae, grass and lime ammonium nitrate when it comes to the movement of minerals from the soil to the crop (Mgolozeli, 2021). There were two types of agrimats (biomulch) used in the experiment: one fabricated with 100 per cent bagasse and the other agrimat with 90 per cent bagasse and 10 per cent algae (Mgolozeli, 2021). The trial results indicated that 100 per cent agrimat cover held a much greater stabilizing ability compared with the other materials used in the study (Mgolozeli, 2021).

Some other studies have followed the same lines and have experimented with other crop residue types to produce agrimats. One study showed that transforming crop residue into mulch sheets offers possibilities for weed control, increased yield and quality in fruit trees and vegetable crops (Sandeep Bains, 2021). The experiments were carried out by developing non-woven mulch mats with 100 per cent rice straw using paper-making techniques; cotton yarn was used as warp and rice straw as weft (Sandeep Bains, 2021). This initiative was suggested to prevent open burning of rice straw after harvest, as is the case in Kenya (Kimutai, 2014).

Table 13.
Conservation tillage methods and description

Method	Description
Zero-Till NO-TILL	No soil disturbance, crop residues are typically left on the surface or placed into slits or holes created for planting seeds. Used in large-scale agricultural crops due to large machines, although small-scale farmers could do so by hand.
Strip-Till	Minimum tillage; limited to strips where crops will be planted; the rest of the field is untilled.
Ridge-Till	Planting is done on raised ridges. The previous crop residue is removed from the ridge tops into adjacent furrows to leave space for planting new crops. This method requires specialized machinery due to ridge-maintenance.
Mulch-Till	Crop residues are partially integrated into the soil (at least one-third) using tools such as chisels, sweeps, field cultivators or similar farming equipment.

Source: Prepared by UNCTAD, based on GGGI (2021).

Organic waste opportunities

Organic waste opportunities are at the forefront of sustainable agricultural practices. New developments in substitutes can enable innovative methods for utilizing and disposing of organic inputs in farming. These innovations are particularly relevant in the context of conservation tillage (GGGI, 2021). Conservation tillage encompasses any soil cultivation method that leaves the previous year's crop residue such as maize or wheat straw on fields before and after planting the next crop. It reduces soil erosion and run-off as well as provides other benefits such as carbon sequestration (GGGI, 2021). This technique covers at least 30 per cent of the soil surface with crop or organic residue after planting. Conservation tillage methods include zero-till, strip-till, ridge-till and mulch-till; more information in Table 13.

It is worth pointing out that while new methods in treating organic waste, in this case crop residues, often start locally, their global adoption is promising. For instance, the European Union and FAO offer training on producing and disposing of organic mulch (UNCTAD, 2023b).

In a broader context, conservation tillage is one of the recommended soil management strategies of climate-smart agriculture (CSA), a concept launched by FAO in 2010 (GGGI, 2021). CSA aims to move from conventional, pollutant agricultural methods into sustainable agricultural approaches that ensure food security in a changing climate (GGGI, 2021). Other soil management strategies which are part of CSA include intercropping, crop rotation and fallow management (GGGI, 2021).

It is within this context that sustainable land management practices take more prevalence, contributing to the further introduction of conservation agriculture (CA) (GGGI, 2021). FAO promotes the adoption of CA principles that not only prevents the loss of arable land but also regenerates degraded lands (FAO, 2022b), which is in line with the "regenerate nature" principle of the circular economy according to EMF. Conservation agriculture requires 20 to 50 per cent less labour, thereby reducing GHGs by lowering energy inputs and enhancing nutrient use efficiency (FAO, 2022b). Simultaneously, it plays a role in stabilizing and safeguarding the soil, preventing it from deteriorating and releasing carbon into the atmosphere (FAO, 2022b). The CA principles are (FAO, 2022a):

Conservation agriculture reduces labour by up to 50% and lowers GHG emissions.

- Minimum mechanical soil disturbance through direct seed and fertilizer application;
- Permanent organic soil cover: maintaining a protective layer of crop residues or covering crops that cover at least 30 per cent of the soil; and
- Species diversification: through crop rotation and intercropping.

Table 14 below presents an overview of implementing crop residues as mulch in agricultural settings with CSA approaches and applicable CA principles.

Table 14. Crop residue mulching as a practice in climate-smart agriculture (CSA) and conservation agriculture (CA)

Practice	Climate-smart agriculture	Conservation agriculture
Biomass as agricultural mulch E.G. CROP RESIDUES	ZERO-TILL Crop residues are evenly distributed and left on the soil surface.	MINIMUM DISTURBANCE Soil is disturbed as little as possible.
	MULCH-TILL Crop residues are incorporated into at least 30% of the soil surface.	PERMANENT COVER Soil remains covered with crop residues or live mulch.

Source: Prepared by UNCTAD, based on GGGI (2021), FAO (2022a), and FAO (2022b).

Potential organic substitutes

UNCTAD has identified an initial set of plastic mulch substitutes: hay, leather, ray, straw, seaweed film and fibres, white clover, wood bark, woodchip and wool and has also laid out an illustrative set of corresponding HS codes for these substitutes. Chapter 12 of the HS system, titled 'Oil seeds and oleaginous fruits, industrial or medicinal plants; straw and fodder,' appears to be the most suitable classification for substitutes involving organic materials and clover crops, particularly for the 'straw and fodder' component. While agricultural commodities incorporating waste and by-products can fall under HS Chapters 4 to 23, Chapter 12 seems the best-suited for accommodating organic substitutes. Additionally, Chapter 9 includes coffee husks and skin.

Manufacturing activities based on plastic substitute feedstocks is in its early stages of development in Kenya (UNCTAD, 2022c). Therefore, a viable economic development strategy is to incentivize uptake by the domestic market and enhance manufacturing capacity. Importing raw material feedstock to build robust domestic sectors can promote regional trade integration even more since the region already has a thriving informal trade, especially in sub-Saharan Africa (UNCTAD, 2022c) (UNCTAD, 2018). This holds true for cover crops, as they are not locally available. However, it is crucial to emphasize the utilization of locally available feedstocks when expanding manufacturing capacity.

In Kenya, organic materials, categorized under HS codes 121300 and 090190, closely align with the characteristics of crop residues. Table 15 shows HS codes identified for organic materials and cover crops that could be used as mulch in horticultural crops where plastic mulch is mostly used. The photo on the next page shows a practical application of coconut coir-based mulch between plant rows at the SMEP Programme site at Blue Skies fruit factory near Accra, Ghana. This example illustrates how locally available organic materials, such as coconut residues, can be used in place of plastic mulch in horticultural production.

Table 15.
Related HS codes and overview analysis of potential mulching substitute for horticultural crops in Kenya

Potential substitute		Description	Availability in Kenya
Cover crops	HS 120925	Forage plant seeds intended for sowing, such as ryegrass (*Lolium multiflorum* Lamarck and *Lolium perenne* Linnaeus).	No
	HS 121490	Forage products, such as swedes, mangolds, fodder roots, hay, sainfoin, clover, forage kale, lupines, vetches, etc. PELLETISED | OTHER FORMS	No
Organic material	HS 121300	Cereal straw and husks UNPREPARED | CHOPPED | GROUND | PRESSED | PELLETISED	Yes
	HS 090190	Coffee husks and skins; or coffee substitutes containing coffee in any proportion.	Yes
	HS 230320	Beet pulp and bagasse; or sugar manufacture waste. PELLETISED | OTHER FORMS	Yes

Source: Prepared by UNCTAD, based on UNCTAD (2023b), and FAO (2021).

© Max MacGillivray (Blue Skies)

Biodegradable mulch films (BDMs)

Biodegradable mulch films (BDMs) have been available in the European Union for many years. These products have gained popularity among fruit and vegetable farmers because they offer not only similar benefits to non-biodegradable plastic mulch films, including improving crop yield and quality but also provide post-harvest advantages (European Bioplastics e.V., 2018).

Biodegradable films do not require retrieval from the field and can be ploughed into the soil. Since these films can be left on the field, they must only be strong enough to be laid out on the farmland. This means that they can have a lower thickness specification than non-BDM (European Bioplastics e.V., 2018). Conventional mulch films must have a minimum thickness of 25 µm to improve their resistance to damage during the after-use removal process (FAO, 2021).

Requirements and test methods

In 2018, a new product standard for BDM for agriculture and horticulture was released under the standard number EN17033 (European Bioplastics e.V., 2018), which outlines the criteria for biodegradable films made from thermoplastic materials designed for application as mulch in agriculture and horticulture (Accuris, 2018). Mulching films can claim to be biodegradable if there is 90 per cent of CO_2 conversion in less than two years during a controlled test (European Bioplastics e.V., 2018).

The scope covers films intended to undergo biodegradation in soil without causing any negative environmental effects (Accuris, 2018). Additionally, it defines the testing procedures to evaluate these criteria and outlines requirements for the packaging, identification and marking of such films (Accuris, 2018).

There are also other tests required such as ecotoxicity and assessment schemes that consider soil biome or ecosystem such as plants, microorganisms, organic matter and the interaction between them (European Bioplastics e.V., 2018).

Key additional considerations on biodegradable mulch films (BDMs)

Notwithstanding the tests and standards that biodegradable films must meet, there are some factors worth mentioning:

- Biodegradable films are more unstable than PE mulch films and have biodegradation rates that are highly variable and dependent on various factors, including the type of soil, rain patterns, soil pH, and climate (FAO, 2021; Huang, et al., 2023);
- Crop cycles have also shown to affect biodegradation rates. In some cases, where crops are sown and harvested yearly (annual crops), accumulation of partially BDM may take place. Formulation of such films, therefore, must consider the various crop cycles that may occur in the same farmland area(FAO, 2021);
- High degradation rates variability of biodegradable films leads to high uncertainty of their environmental impact (Huang, et al., 2023);
- Not every BDM can fully degrade under natural conditions. Instead, some may undergo degradation into microplastics at a faster rate than traditional plastic mulch films, presenting an additional risk to the soil environment (Fan, et al., 2022);
- Before reaching full degradation, BDM microplastics preserve the attributes of their PE mulch counterparts, namely the absorption of organic/inorganic nutrients and working as biocarriers (Huang, et al., 2023). There is also potential for BDM microplastics to transport and release potentially harmful chemicals, including organic contaminants and heavy metals as they degrade or migrate. Such contaminant's carrying capacity is higher than microplastics generated by conventional plastic mulch films (Fan, et al., 2022; Shi, et al., 2022); and
- When BDMs are under the soil surface, their degradation rate is substantially slowed due to low light and anaerobic conditions, which may result in significant build-up (Huang, et al., 2023).

To sum up, in considering BDMs as a sustainable solution to conventional mulch film pollution, it is imperative to have a more profound understanding of the impact of BDM residues on the agroecosystem's biological, geological and chemical processes (Huang, et al., 2023). These films' aftermath and long-term use must also be assessed as this remains poorly understood (FAO, 2021).

Need for agri-plastic standards to inform regulations

Biobased, biodegradable and compostable plastics are increasingly emerging as alternatives to conventional, non-biodegradable plastics (European Commission, 2022). In Kenya, several companies assert that their agri-plastic products are biodegradable and compostable, relying on tests performed in Europe or Asia. Nevertheless, local authorities such as NEMA lack the resources to independently validate these assertions. Similarly, the Kenyan Standards Bureau faces a challenge as it lacks specific standards to assess these claims, a predicament shared by various East African countries and other regions worldwide.

In the European Union, a technical proposal has been introduced to enhance understanding of these materials (biodegradable/compostable/biobased) and clarify where these plastics can genuinely bring environmental benefits—under what conditions and in which applications (European Commission, 2022). The proposal aims to guide citizens, public authorities and economic operators in making decisions on policy, purchasing or investment. A shared understanding across the European Union on the production and use of these plastics will also prevent differences at the national level and fragmentation of the market.

The European Union proposal clarifies biobased, biodegradable and compostable plastics and sets out conditions to ensure the positive environmental impact of their production and consumption. For this, a product labelled as 'biobased,' 'biodegradable,' or 'compostable' needs to satisfy key conditions (European Commission, 2022):

- **Biobased** — The term should be used only if the product's exact and measurable share of biobased plastic content is specified, allowing consumers to know the actual biomass used in the product. The biomass used must be sustainably sourced without harming the environment. The sourcing of these plastics should comply with sustainability criteria, prioritizing organic waste and residues. Applicable standards for biobased products include ISO 16620-1 to ISO 16620-4.
- **Biodegradable** — It should be made clear that such products should not be littered, and specifications on how long the product needs to biodegrade, under which circumstances and in what environment (such as soil, water, etc.) should be provided. Products likely to be littered, including those covered by the Single-use Plastics Directive, cannot be claimed or labelled as biodegradable. Applicable standards for biodegradable products include ISO 5430:2023 and ISO 5148:2022.
- **Compostable** — Only industrially compostable plastics complying with relevant standards should be labelled as 'compostable'. Industrially compostable items should display how the items should be disposed of. Applicable standards for compostable products include ISO 17088:2021 and ISO 5412:2022.

Although the effectiveness of managing end-of-life bioplastics, biobased or biodegradable products relies heavily on local infrastructure, Kenya and other countries in East Africa could draw on proposals such as the European Union's and the internationally recognized standards (ISO) outlined herein to initiate conversations about creating policy frameworks based on relevant and reliable standards. This will assist regulators in granting authorizations to trustworthy and verifiable products.

The AgriMulchFilm project

The African mulch film market is projected to have an annual growth of 3.6 per cent (SMEP, 2022a). This growth is driven by the need to ramp up crop productivity to meet the food demands of the expanding population (SMEP, 2022a). Along with this, the agricultural sector is beginning to shift into more sustainable practices that reduce adverse environmental impacts and foster social and economic benefits (SMEP, 2022a).

AgriMulchFilm developed biodegradable mulch films tailored to local soils and climate.

These factors have facilitated the implementation of the AgriMulchFilm project, a collaboration between the Elizade University in Nigeria and the Council for Scientific and Industrial Research (CSIR) in South Africa, supported by the SMEP Programme (SMEP, 2023). The project seeks to develop fully BDM films that replace the conventional non-biodegradable PE mulch films by tapping into locally accessible natural materials (e.g. starch, seaweed) along with other additives (SMEP, 2023). The BDM is comprised of 60 per cent of petroleum-based PBAT and 40 per cent of starch-based materials. Notably, once used, BDM films can be left on farmlands and subsequently ploughed into the soil, which allows for biogenic recycling (SMEP, 2023).

The uniqueness of these BDMs lies in their customized biodegradation rates, tailored to subtropical climate crop cycles and natural soil conditions (SMEP, 2023). This innovation holds the potential to be extended and adopted across numerous nations in both Africa and South Asia (SMEP, 2023). Expected outcomes aim at contributing to the enhancement of both human and ecological well-being. The project was completed in 2024 (SMEP, 2023).

The FreshPPact Impact Hub

© Vincent Ojijo (CSIR/SA)

Blue Skies has introduced the FreshPPact Impact Hub to foster research and development addressing environmental challenges in the fresh produce industry, particularly in supply chains linked to developing economies (SMEP, 2022b). The Hub welcomes membership from retailers, manufacturers and agribusinesses, aiming to tackle SUP packaging, GHGs, environmental pollution and habitat loss. Aligned with the SMEP Plastics Pollution Mitigation initiative, the Hub's initial focus is on developing alternatives for plastic agricultural mulch, workwear and packaging used in the fresh produce industry in Ghana, where Blue Skies is a leading producer of fresh-cut fruit products for the European market. The objectives of the FreshPPact Impact Hub are (Northampton, 2023):

- **Material substitution** — Exploration of alternative materials such as organic or living mulch derived from residues such as coconut coir, pineapple crowns or plant chippings;
- **Accelerated biodegradation** — Utilization of biodegradable materials that do not produce contaminants in the manufacturing process and exhibit efficient biodegradation during and after use;
- **Improved manufacturing** — Modification of products to enhance recyclability, facilitate remanufacture or the establishment of local manufacturing capabilities using recycled materials;
- **Remanufacturing** — Recovery and reconstruction of used products to restore them to their original performance;
- **Recycling** — Development of solutions that enable the recycling of waste materials for alternative purposes such as roads and chairs; and
- **New working practices or protocols** — Implementation of innovative agricultural techniques through training to enhance soil structure or facilitate the effective removal and recycling of plastic mulch.

In assessing the performance of various plastic alternative mulching materials used in pineapple farms in sub-Saharan Africa, particularly in Ghana, a design of experiment was conducted by the research team leading the experimentation phase of this project. The experimental treatments included a BDM film, biomaterial film, biocompostable fibre-based mulch and the practice of no mulch, which involved a structured weeding process.

The BDM film came from the AgriMulchFilm project described in the section above. The biomaterial film came from the coconut husks processed into coconut coir-based mulch which employed a binding agent from rubber trees (see image below). For the biocompostable fibre-based mulch, Biodolomer produced by Gaia was used. Although the product is already developed, the use of test mulch may have different variants in terms of the amount of black UV and stabilizer.

The experiment aims to establish a scientific comparison among these alternatives to plastic mulching concerning key measures such as fruit yield, fruit quality, weed biomass weight and ease of removal for targeted composting using a customized mechanical mulch lifter. Potential benefits include reduced microplastic pollution and improved human and ecological well-being. Concurrently, a lifting machine to remove plastic mulch film from fields is being tested.

The project started in the first half of 2024 and is expected to last one year. The findings could provide practical guidance for farmers, organizations and policymakers, not only in Ghana but also in the wider region and beyond. Moreover, Kenya could also benefit from this project significantly as opportunities for technology transfer may arise.

FreshPPact is testing biodegradable mulches on pineapple farms in Ghana to reduce plastic use and improve soil health.

Kenya needs 15 billion biodegradable seedling tubes by 2032.

Plastics in agriculture

The case of seedling tubes and potential substitutes

There is a pressing need to replace SUP-based potting tubes in Kenya. With a goal of growing 15 billion trees by 2032, the country requires an equivalent number of potting seedling bags (Mwangi, 2023). In light of this, the government has a policy mandating that only 100 per cent biodegradable (compostable) plastics shall be used for seedling planting. It also sets biodegradability as a preferred packaging characteristic because compostable packaging has drawbacks, including limited availability and shelf life (Mwangi, 2023). Moreover, the lack of infrastructure to manage compostable products at the end of their life is a key challenge (Mwangi, 2023). The government has also determined that other challenges of compostable packaging for potting seedling use are related to vulnerability to environmental conditions and pests, and higher production costs (Mwangi, 2023). (Mwangi, 2023)In 2023, a tender notice for the supply and delivery of biodegradable potting tubes for tree seedlings was released by the Ministry of Environment, Climate Change and Forestry, State Department for Forestry in Kenya (Ministry of Environment, 2023). While the bidding process closed in May 2023, there has been no information on any decision, leaving a gap in the market for biodegradable seedling tubes. In tackling this gap, this section outlines some biodegradable alternatives to SUP potting, which may be of interest to Kenya or other parties.

Relevant start-up initiatives

In general, identified alternatives to plastic seedlings are cellulose based. While some use recycled materials, others use materials from forests. The table below shows key features of some material alternatives to plastic seedlings.

Table 16.
Crop residue mulching as a practice in climate-smart agriculture (CSA) and conservation agriculture (CA)

Feature	Ellepot	Fertilpot	Cocoon
Material	Wood fibres with undisclosed polymer	Forest waste materials	Recycled cardboard
Additives	Undisclosed polymer	None	Fungi and nutrients
Degradation time	2 months – 12+ months VARIOUS OPTIONS	3 months	3 months
Benefits	Promotes root growth, faster planting, minimizes transplant shock	100% degradation, becomes humus, releases nutrients	Increased survival rate, reduced water irrigation, ideal for harsh environments
Raw material source	Certified forests	Forestry by-products THINNING, FELLING	Recycled materials
Production location	Global INCLUDING NAIVASHA, KENYA	France VOSGES FORESTS	Not specified
Additional information	Wide range of degradation times	Chemical-free	Uses drones and satellites for planting plans and tracking

Source: Prepared by UNCTAD, based on Ellepot (n.d.), FERTIL (n.d.).

Current research and future prospects

PlantVillage

PlantVillage in Kenya creates sustainable villages and communities by planting and growing trees to adapt to and mitigate impacts of climate change. The agroforestry team produces biodegradable potting tubes for high-value fruit trees in the country (PlantVillage, 2023). The pots are crafted from recycled cardboard and discarded newspapers and fortified with biochar and mycorrhizal fungi to facilitate better plant growth (PlantVillage, 2023). While biochar enriches soil fertility, mycorrhizal fungi nurtures tree development by supplying essential nutrients to the roots (PlantVillage, 2023).

The project collaborates with local farmers across the four counties of Baringo, Bungoma, Busia and Kilifi. In Bungoma County, for instance, two farmers are involved in raising 1,000 tree seedlings, which they will repay with the first harvest earnings (PlantVillage, 2023). Trial results will be disclosed in due course.

Crop residue-based seedling tubes

Scientists at the National Agriculture Research Institute in Uganda are developing biodegradable pot seedlings called "eco-plastic potting bags" using agricultural waste (e.g. crop residues from banana, cassava or cereal) as an alternative to plastic wrappings (World Business Journal, n.d.). In Uganda, about 1.4 million tonnes of agricultural waste is generated each year and much of it is underutilized (World Business Journal, n.d.). This project is expected to significantly benefit farmers as they will be able to sell their crop residues for processing (World Business Journal, n.d.).

The core process involves several key steps: i) the farm waste is dried and shredded into powder (Africanews, 2023; World Business Journal, n.d.), ii) the powder form is mixed with products such as starch to generate a paste, iii) drying is required once again and iv) the paste is rolled out into sheets that serve as biodegradable pots (Africanews, 2023) (World Business Journal, n.d.).

In addition to the study on crop residue-based biodegradable pots, researchers are working on plant-based repellent (Africanews, 2023) (World Business Journal, n.d.) to prevent pests from attacking the eco-plastic potting bags, a common challenge faced by these products (Africanews, 2023). Field trials have been conducted in Eastern Uganda, specifically in the Mount Elgon region, engaging local farmers (World Business Journal, n.d.).

While insufficient information is available regarding trial results or other viability factors of this new product, the roll out in mass production is scheduled for this year. Support from the University of Bangor in the United Kingdom has been secured for this purpose (Africanews, 2023) (World Business Journal, n.d.).

This project represents a significant opportunity for Kenya, as like Uganda, it has an overabundance of organic agricultural waste.

Performance edge in using biodegradable seedling tubes

Another significant advantage of using biodegradable seedling pots is that they perform better than their plastic counterparts. Controlled studies have shown that seedlings raised in composable potting tubes, including those made from banana sheaths fibres and cellulose, outperformed those grown in plastic pots when examining growth after transplanting (Mwangi, et al., 2021). Although seedlings raised in plastic pots showed considerably faster growth while still in nursery beds, this trend changes after the seedlings are transplanted. Assessments made after two, four and six months showed that seedlings grown in biodegradable pots had outperformed their counterparts in growth and vigour (Mwangi, et al., 2021). Hence,

Biodegradable pots outperform plastic ones in seedling growth after transplanting.

Plastic mulch harms soil health by reducing carbon capture and nutrient availability.

seedlings raised in biodegradable pots compensated for poor early performance by outgrowing those nursed in plastic pots once they were transplanted into the field. Muriuki, et al. (2013) also demonstrated this trend by using other types of organic pots, namely biodegradable fibre baskets when testing biodegradable seedling containers as an alternative to fossil-based tubes.

While this is a promising outcome when using biodegradable seedling pots, the long-term effects of their use must also be considered. As stated previously in this report, FAO has underscored that the implications of the long-term use of biodegradable products require further research due to existing gaps in understanding (FAO, 2021).

Key findings

Kenya has an economy highly reliant on agriculture. The use of plastic mulch in agriculture is more commonly adopted in horticultural cultivations, one of the top three export crops, where farmers create holes in the mulch to grow horticultural product seedlings. Plastic mulch has many benefits, and horticultural farmers seem to greatly value this product due to its capacity to stave off pests and weeds and increase crop yields. However, plastic mulch is a major source of nano, micro and macro-plastics, releasing substances that have deleterious effects on soil health and functionality. These effects include the decrease of soil carbon sequestration and the hindering of nutrient availability. This report explored plastic mulch substitutes - products are not fossil-fuel-based at any level - used in agriculture based on the HS codes.

Organic mulching practices

Organic mulching practices such as using crop residues, cover crops and natural fibres are at the top of the 6R hierarchy. These practices not only reduce plastic use but also enhance soil health and carbon capture. Crop residues such as straws and husks are abundant in Kenya and can serve as potential substitutes for plastic mulch.

Crop residues had been initially assessed based on five main criteria: properties, organic waste opportunities, manufacturing capacity, negative externalities and economic viability. In terms of their properties, studies have shown that their benefits are the same as plastic mulch films, erosion control and weed and pest management, with the addition of better soil health.

The economic viability showed that even though the RCA is extremely high, at around 490, the recycling and recovery rate is only 20 per cent. We outline some possible actions that could increase this low rate.

We also offer insights into new ways to repurpose crop residues in Kenya. These efforts primarily involve conservation tillage methods, where approximately 30 per cent of the residues are left on the fields. There are several types of these tillage methods, with two requiring specialized equipment and the other two being suitable for manual implementation. This manual approach could be particularly advantageous in an agricultural sector where smallholders are the primary contributors to crop cultivation.

In terms of business models, lessons from Ghana's experience with crop residue utilization, including mulch matting and various agricultural and non-agricultural uses, provide insights for Kenya in not only fostering new business models centred on crop residues, but also improve their waste treatment.

Kenya could create economies of scale and foster its manufacturing capacity through value-added manufacturing. This may help mitigate the food insecurity issues while creating economic growth. To do so, Kenya could first import raw materials, in this case cover crops such as ryegrass and clover, to establish a strong domestic sector. However, Kenya imposes a high most-favoured-nation (MNF) tariff rate on many natural feedstocks, which could represent a barrier. Secondly, Kenya could tap into locally available raw feedstock materials to develop domestic markets. As such, Kenya could leverage the exceptionally high production of crop residues to improve the country's manufacturing capacity. While there is value in prioritizing the utilization of locally available feedstocks, some countries may opt to develop a robust domestic sector by importing raw material feedstock.

The increasing use of biobased, biodegradable and compostable plastics as alternatives to conventional non-biodegradable plastics prompts the need for agri-plastic standards to guide regulations. In Kenya, companies rely on European or Asian's test for the biodegradability and compostability of their agri-plastic products, lacking local validation resources. The Kenyan Standards Bureau faces a common challenge with East African countries and other regions in lacking specific standards for the assessment of these plastic alternatives. The technical proposal of the European Union outlines the conditions for labelling products as 'biobased', 'biodegradable' or 'compostable', emphasizing precise biobased content, proper disposal guidelines and compliance with relevant standards. While local infrastructure plays a crucial role, Kenya and East African countries can leverage proposals such as the European Union's and international standards (e.g., ISO) in initiating policy frameworks, ensuring regulators authorize trustworthy and verifiable products.

Biodegradable mulch films (BDMs)

BDMs are considered a viable option as they offer similar benefits to non-biodegradable plastic mulch films and do not require post-harvest removal. They are becoming popular among fruit and vegetable farmers in Europe. However, the rate of biodegradation of these films can exhibit substantial variation based on soil and climatic conditions and careful assessment must be undertaken before implementation. FAO also points out that the long-term impact on soils from the use of BDM needs to be thoroughly assessed.

The AgriMulchFilm project is an initiative supported by the SMEP Programme driven by two main factors:

- The African mulch film market is growing at an annual rate of 3.6 per cent to increase crop productivity to meet the demands of a growing population; and
- the agricultural sector is also shifting towards more sustainable practices.

The project aims to develop fully BDM films using locally available natural materials and additives. While 60 per cent of these films are petroleum-based (PBAT), 40 per cent are starch-based. These BDM films can be left on farmlands and ploughed into the soil. The innovation customizes biodegradation rates to suit sub-Saharan climate crop cycles and soil conditions, making it adaptable for adoption in various African and South Asian nations. The project is in its final phase and is expected to conclude in May 2024, with potential benefits including reduced microplastic pollution and improved human and ecological well-being.

The FreshPPact Impact Hub, established in collaboration with Waitrose by Blue Skies, aims to address environmental challenges in the fresh produce industry, especially within developing economies' supply chains. Targeting issues such as SUP packaging, GHGs, pollution and habitat loss, the Hub invites membership from retailers, manufacturers and agribusinesses. Initially focusing on the fresh produce industry in Ghana, the Hub aims to develop alternatives for plastic agricultural mulch, workwear and packaging. Objectives include exploring alternative materials, accelerating biodegradation, improving manufacturing for recyclability, remanufacturing, recycling waste materials and implementing innovative agricultural techniques. The team plans to conduct research in pineapple farms in Ghana, assessing the performance of various plastic alternative mulching materials, including the BDM from the AgriMulchFilm project. This project, which started in early 2024, aims to provide practical guidance for stakeholders and potentially reduce microplastic pollution, benefiting human and ecological well-being. The initiative could also offer significant opportunities for technology transfer in Kenya.

Biodegradable mulch films offer benefits without requiring removal after harvest.

Some **biodegradable mulch films may degrade into microplastics** faster than traditional films.

Key recommendations

Biodegradable mulch films

Key additional considerations for BDMs extend beyond fulfilling tests and complying with standards. Firstly, BDMs exhibit higher instability compared to PE mulch films, with variable degradation rates influenced by soil type, rain patterns, pH and climate. Secondly, crop cycles, especially with annual crops, can lead to the accumulation of partially degraded BDMs, emphasizing the need to account for various crop cycles in the formulation. Thirdly, the variability in degradation rates raises uncertainty about the environmental impact of BDMs. It is also worth pointing out that some BDMs may degrade into microplastics faster than traditional plastic mulch films, posing additional risks to the soil environment. Before complete degradation, BDM microplastics retain attributes similar to PE mulch, acting as biocarriers for nutrients and potentially releasing harmful chemicals. The degradation rate of BDMs is substantially slowed under the soil surface, contributing to significant build-up. To consider BDMs as a sustainable solution, a deeper understanding of their impact on biological, geological and chemical processes in the agroecosystem is crucial. FAO has underscored that the aftermath and long-term implications of BDM use require further assessment due to current gaps in understanding.

Agrimats from crop **residues can reduce** herbicide use and erosion.

Agrimats

The various studies conducted on agrimats, particularly those utilizing crop residues, represent a great opportunity for Kenya. With an abundance of crop residues and a pressing need for sustainable agricultural practices, the adoption of agrimats could not only address challenges related to weed control, herbicide use and erosion but also instigate new business avenues. The cost-effective production of agrimats from locally available organic waste materials, including crop residues, aligns with Kenya's agricultural landscape. Potential benefits include enhanced yields, soil moisture conservation, reduced dependency on herbicides and erosion control. Implementing agrimats could help to move away from the dependency on plastic mulch in horticultural crops in Kenya.

Considering Kenya's predominant arid and semi-arid regions, where irrigation is a crucial factor, agrimats offer a promising solution for cost savings in water usage. Furthermore, agrimats are durable, lasting up to two years or more, ensuring prolonged effectiveness in the field. These findings echo the results of studies that demonstrate significant reductions in soil erosion on both gentle and steep slopes, along with impressive moisture absorption and retention capabilities.

The successful experimentation with various crop residue types such as bagasse and rice straw further underscores the adaptability of agrimats to different agricultural contexts. With this evidence, there is a strong case for promoting the use of crop residues, readily available in Kenya, to produce agrimats. Such a move not only supports sustainable farming practices (conservation agriculture) but also holds the potential for business opportunities, regional trade and addressing environmental concerns, particularly the issue of open burning of crop residues. In conclusion, leveraging the findings from these studies can inform policy decisions, encourage local adoption and stimulate economic activities centred around the production and utilization of agrimats in Kenya's agricultural landscape.

Further research could assess the various types of crop residues produced in Kenya as feedstock for agrimats to determine which types of biomass would be most suitable to replace the already widespread practice of using plastic mulching in horticulture.

Social and political contexts matter. Current applications and uses as well as the preferences and traditions of smallholders in Kenya must be considered. How could the government help biomass-based agrimats gain acceptance among potential end-users (farmers)? What would the transition away from petroleum-based mulches look like?

Lastly, agrimats could represent a significant economic opportunity for Kenya but the current imports and local production of plastic mulch must be considered as there may be sectors in society that could push back against their introduction to Kenyan agriculture.

Seedling tubes

While there are a handful of novel developments as an alternative to plastic potting bags, it may be worth looking into local resource availability if developing a local economic sector is of interest. Specifically, research shows crop residues could be material input to produce biodegradable seedling tubes. We recommend investigating local resource availability to facilitate the development of sustainable and economically beneficial solutions for seedling tubes.

Local **feedstocks can support** sustainable **seedling tube** production.

© Vincent Ojijo (CSIR/SA)

References

Accuris. (2018). DIN EN 17033: Plastics - Biodegradable mulch films for use in agriculture and horticulture - Requirements and test methods. Available at: https://global.ihs.com/doc_detail.cfm?document_name=DIN%20EN%2017033&item_s_key=00755423.

Adejumo, B. (2023). The appraisal of local food packaging materials in Nigeria

Africanews. (2023). Uganda: Turning farm waste into biodegradable seedling pots. Available at: https://www.africanews.com/2023/05/07/uganda-turning-farm-waste-into-biodegradable-seedling-pots/.

Africa Harvest. (2020). Enhancing the lives of african small scale farmers. [No longer available online].

Akiwumi, P., & Onyekwena, C. (2022). Building socio-economic resilience in Nigeria by fostering productive capacities. Available at: https://unctad.org/news/blog-building-socio-economic-resilience-nigeria-fostering-productive-capacities.

Allan Calmont de Andrade Almeidaa, J. G. d. M. P., Gabriel Rodrigues Alvarengaa, Henrique Finocchio and Taicia Pacheco Fill; . (2021). The sustainable cycle of a new cacao-based bioplastic: from manufacturing to exploitable biodegradation products. The Royal Society of Chemistry, 11 29976-29985.

Allen-Taylor, K. (2022). A study of the extended producer responsbility (EPR) scheme for plastic waste management in Germany. Journal of Global Ecology and Environment. Available at: https://doi.org/https://doi.org/10.56557/jogee/2022/v16i47723.

Almeida, A. C. d. A., Pontes, J. G. d. M., Alvarenga, G. R., Finocchio, H., & Fill, T. P. (2021). The sustainable cycle of a new cacao-based bioplastic: from manufacturing to exploitable biodegradation products [10.1039/D1RA04432J]. RSC Advances, 11(48), 29976-29985. Available at: https://doi.org/10.1039/D1RA04432J.

Andrady, A. L. (2011). Microplastics in the marine environment. Marine Pollution Bulletin, 62(8), 1596-1605. Available at: https://doi.org/10.1016/j.marpolbul.2011.05.030.

Aranda-Calipuy, M. M., Roncal-Lázaro, A., Quezada-Alvarez, M. A., Siche, R., Cabanillas-Chirinos, L., Rojas-Villacorta, W., Benites, S. M., & Rojas-Flores, S. (2023). Pleurotus ostreatus Mycelium and Sugarcane Bagasse as Substitute Environment-Friendly Material for Polystyrene Foam. Sustainability (Basel, Switzerland), 15(12), 9157. Available at: https://doi.org/10.3390/su15129157.

Araya Schmidt, T., & Queirolo, D. (2019). Breaking strength evaluation of biodegradable twines to reduce ghost fishing in the pot and trap fisheries of Chile. Latin American Journal of Aquatic Research, 47(1), 201-205. Available at: https://doi.org/10.3856/vol47-issue1-fulltext-24.

Asante-Poku, A., & Angelucci, F. (2013). Analysis of Incentives and Disincentives for Cocoa in Ghana. Technical notes series, Issue.

Babarinsa, O. A., Okoruwa, A. E., & Babarinsa, F. A. (2022). Potential socio-economic impact of replacing traditional woven baskets with reusable plastic crates on livelihoods of basket makers in Southeast Nigeria. African journal of food, agriculture, nutrition, and development : Ajfand, 22(6), 20581-20595. Available at: https://doi.org/10.18697/ajfand.111.22035.

Babayemi, J. O., INnorom, n. C., & Osibanjo, O. W. (2019). Ensuring sustainability in plastics use in Africa: consumption, waste generation, and projections. Environmental Sciences Europe, 31(1), 1-20. Available at: https://doi.org/10.1186/s12302-019-0254-5.

Bakker, R., Elbersen, H. W., Poppens, R. P., & Lesschen, J. P. (2013). Rice Straw and Wheat Straw - Potential feedstocks for the Biobased Economy.

Benson, P. (2018). China's plastic waste import ban. Science. No longer available online.

Bharadwaj, B., Baland, J., & Nepal, M. (2019). What makes a ban on plastic bags effective? The case of Nepal. Environment and Development Economics,, 25, 95 - 114. Available at: https://doi.org/https://doi.org/10.1017/S1355770X19000329.

Boateng, J. K., Attiogbe, E. J. K., Stahl, A., Apoh, W., Boadi, C., & Frimpong, W. O. (2022). Using Africa's past to promote change toward safer alternatives for food packaging in Accra. Cogent Social Sciences, 8(1). Available at: https://doi.org/10.1080/23311886.2022.2137962.

Butler, J. R. A., Gunn, R., Berry, H. L., Wagey, G. A., Hardesty, B. D., & Wilcox, C. (2013). A Value Chain Analysis of ghost nets in the Arafura Sea: Identifying trans-boundary stakeholders, intervention points and livelihood trade-offs. Journal Of Environmental Management, 123, 14-25. Available at: https://doi.org/10.1016/j.jenvman.2013.03.008.

Cadoni, P. (2013). Analysis of incentives and disincentives for cocoa in Nigeria Technical notes series, Issue.

Cartier, E. (2019). Primary, Secondary and Tertiary Packaging: What's the Difference? Available at: https://www.emballagecartier.com/en/article/primary-secondary-and-tertiary-packaging-whats-the-difference/.

Castellanos-Navarrete, A., Tittonell, P., Rufino, M. C., & Giller, K. E. (2015). Feeding, crop residue and manure management for integrated soil fertility management – A case study from Kenya. Agricultural Systems, 134, 24-35. Available at: https://doi.org/https://doi.org/10.1016/j.agsy.2014.03.001.

Cerbule, K., Grimaldo, E., Herrmann, B., Larsen, R. B., Brcic, J., & Vollstad, J. (2022). Can biodegradable materials reduce plastic pollution without decreasing catch efficiency in longline fishery? Marine Pollution Bulletin, 178, Article 113577. Available at: https://doi.org/10.1016/j.marpolbul.2022.113577.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation Rates of Plastics in the Environment. ACS Sustainable Chemistry & Engineering, 8(9), 3494-3511. Available at: https://doi.org/10.1021/acssuschemeng.9b06635.

Chen, C., Abong, G., Hartwig, S., & Keding, G. (2022). Sustainable Packaging Materials for Processed Fruits and Vegetables in East Africa: a case study of Nairobi, Kenya. Journal of Consumer Sciences, 49, 2021.

Christensen, C. M., Bartman, T., & van Bever, D. (2016). The hard truth about business model innovation. MIT Sloan Management Review, 58(1), 31-40.

COMTRADE, U. (2021). International Trade Database Intelligence. Available at: https://frsabido.shinyapps.io/COMTRADE/.

Darmawan, D., & Mutalib, A. (2024). Evaluation of environmental impact on cocoa production and processing under life cycle assessment method: From beans to liquor. Environmental advances, 15, 100481. Available at: https://doi.org/10.1016/j.envadv.2023.100481.

Deroiné, M., Le Duigou, A., Corre, Y.-M., Le Gac, P.-Y., Davies, P., César, G., & Bruzaud, S. (2014). Accelerated ageing and lifetime prediction of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) in distilled water. Polymer Testing, 39, 70-78. Available at: https://doi.org/10.1016/j.polymertesting.2014.07.018.

Deroine, M., Pillin, I., Le Maguer, G., Chauvel, M., & Grohens, Y. (2019). Development of new generation fishing gear: A resistant and biodegradable monofilament. Polymer Testing, 74, 163-169. Available at: https://doi.org/10.1016/j.polymertesting.2018.11.039.

Diggle, A., & Walker, T. . (2020). Implementation of harmonized Extended Producer Responsibility strategies to incentivize recovery of single-use plastic packaging waste in Canada. Waste Management, 110, 20-23 Available at: https://doi.org/10.1016/j.wasman.2020.05.013.

Doe, B., Aboagye, P. D., Osei-Owusu, P. K., Amoah, T., Aidoo, A., & Amponsah, N. Y. (2023). Towards Circular Economy and Local Economic Development in Ghana: Insights from the Coconut Waste Value Chain. Circular economy and sustainability (Online), 3(1), 347-372. Available at: https://doi.org/10.1007/s43615-022-00182-w.

Duncan, A. J., Bachewe, F., Mekonnen, K., Valbuena, D., Rachier, G., Lule, D., Bahta, M. and Erenstein, O. (2016). Crop residue allocation to livestock feed, soil improvement and other uses along a productivity gradient in Eastern Africa. Agriculture, Ecosystems and Environment. (Agriculture, Ecosystems & Environment, 228), 101-110. Available at: https://doi.org/10.1016/j.agee.2016.05.011.

Ecovative. (2023). Mushroom Packaging. Available at: https://mushroompackaging.com/.

Elena Monastyrnaya, Jonas Joerin, Evans Dawoe, & Six, J. (2016). Assessing the resilience of the cocoa value chain in Ghana. Case study report. E. Swiss Federal Institute of Technology Zurich.

Ellen MacArthur Foundation. (2015). Towards a circular economy: business rationale for an accelerated transition. Available at: https://ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition.

Ellen MacArthur Foundation. (n.d.). Regenerate nature. Ellen MacArthur Foundation.Available at: https://ellenmacarthurfoundation.org/regenerate-nature.

Ellepot. (n.d.). FP 12+ Ellepot Paper. Available at: https://www.ellepot.com/ellepot-products/paper/paper-programme/fp/.

European Bioplastics e.V. (2018). New EU standard for biodegradable mulch films in agriculture published. Available at: https://www.european-bioplastics.org/new-eu-standard-for-biodegradable-mulch-films-in-agriculture-published/.

European Commission. (2022). Questions and Answers – communication on a policy framework for biobased, biodegradable and compostable plastics. Available at: https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_7158.

Ezung, T. S., & Wokha, K.V.K. (2020). Traditional Packaing Materials, in focus. The Morung Express. Available at: https://morungexpress.com/traditional-packaging-materials.

Fan, P., Yu, H., Xi, B., & Tan, W. (2022). A review on the occurrence and influence of biodegradable microplastics in soil ecosystems: Are biodegradable plastics substitute or threat? Environment International, 163, 107244. Available at: https://doi.org/10.1016/j.envint.2022.107244.

FAO. (2001). Soil carbon sequestration for improved land management. Available at https://www.fao.org/3/bl001e/bl001e.pdf.

FAO. (2005). Chapter 4. Practices that influence the amount of organic matter. In The importance of soil organic matter. Key to drought-resistant soil and sustained food production. Available at: https://www.fao.org/3/a0100e/a0100e07.htm.

FAO. (2015). Training manual for organic agriculture. Available at: https://www.fao.org/fileadmin/templates/nr/sustainability_pathways/docs/Compilation_techniques_organic_agriculture_rev.pdf.

FAO. (2018). Abandoned, lost and discarded gillnets and trammel nets – Methods to estimate ghost fishing mortality, and the status of regional monitoring and management. Available at: https://openknowledge.fao.org/server/api/core/bitstreams/420301ff-2fb2-473c-98f5-a28ff6106861/content/.

FAO. (2021). Assessment of Agricultural Plastics and Their Sustainability—A Call for Action. Rome.

FAO. (2022a). The 3 principles of conservation agriculture. Available at: https://www.fao.org/3/cb8663en/cb8663en.pdf.

FAO. (2022b). Conservation Agriculture. Available at: https://www.fao.org/3/cb8350en/cb8350en.pdf.

FAO. (2023a). The agriculture sector in Kenya. Available at: https://www.fao.org/kenya/fao-in-kenya/kenya-at-a-glance/en/.

FAO. (2023b). Bioeconomy Talks: Sustainable bioenergy with Manas Puri. Available at: https://www.fao.org/in-action/sustainable-and-circular-bioeconomy/resources/news/details/en/c/1637435/.

FAO. (2023c). Overview of Horticultural Crops Directorate. [No longer available online].

FERTIL. (n.d.). Biodegradable pots of fertil. Available at: https://www.fertilpot.com/.

Fisheries, M. o. (2022). Ministry-of-Fisheries-Annual-Report-2021–2022.

Flexport. (2023). Harmonized System Code (HS) Lookup & Finder. Available at: https://www.flexport.com/data/hs-code/3920-other-plates-sheets-film-foil-and-strip-of-plastics-noncellular-and-not-reinforced-laminated-supported-or-similarly-combined-with-other-materials/.

Food Crops. (2023). Overview. [No longer available online].

Forrest, A., Giacovazzi, L., Dunlop, S., Reisser, J., Tickler, D., Jamieson, A., & Meeuwig, J. J. (2019). Eliminating plastic pollution: how a voluntary contribution from industry will drive the circular plastics economy. Frontiers in marine science, 6, 627.

Garcia, S., Lopez-Lozano, R., Panarello, L., Cerrani, I., Nisini, L., Zucchini, A., Velde, M., & Baruth, B. (2019). Assessing lignocellulosic biomass production from crop residues in the European Union: Modelling, analysis of the current scenario and drivers of interannual variability. GCB Bioenergy, 11. Available at: https://doi.org/10.1111/gcbb.12604.

GGGI. (2021). Compendium of Practices in Climate-Smart Agriculture and Solar Irrigation. Available at: https://gggi.org/wp-content/uploads/2021/03/Compendium-of-Practices-in-Climate-Smart-Agriculture-Web_Final.pdf.

Gilbert, C. (2009). Cocoa Market Liberalization in Retrospect. Review of Business and Economics, LIV, 294-312.

Glass Alliance Europe. (2023). What is glass? Available at: https://glassallianceeurope.eu/the-world-of-glass/.

Gockowski, J., Afari-Sefa, V., Sarpong, D. B., Osei-Asare, Y. B., & Dziwornu, A. K. (2011). Increasing income of Ghanaian cocoa farmers: Is introduction of fine flavour cocoa a viable alternative. Quarterly Journal of International Agriculture, 50 (2), 175-200.

Godfrey, L. (2019). Waste Plastic, the Challenge Facing Developing Countries—Ban It, Change It, Collect It? RECYCLING. Available at: https://doi.org/10.3390/RECYCLING4010003.

Graf, M., Greenfield, L. M., Reay, M. K., Bargiela, R., Williams, G. B., Onyije, C., Lloyd, C. E. M., Bull, I. D., Evershed, R. P., Golyshin, P. N., Chadwick, D. R., & Jones, D. L. (2023). Increasing concentration of pure micro- and macro-LDPE and PP plastic negatively affect crop biomass, nutrient cycling, and microbial biomass. Journal of Hazardous Materials, 458, 131932. Available at: https://doi.org/10.1016/j.jhazmat.2023.131932.

Grimaldo, E., Herrmann, B., Jacques, N., Kubowicz, S., Cerbule, K., Su, B., Larsen, R., & Vollstad, J. (2020). The effect of long-term use on the catch efficiency of biodegradable gillnets. Marine Pollution BULLETIN, 161, Article 111823. Available at: https://doi.org/10.1016/j.marpolbul.2020.111823.

Grimaldo, E., Herrmann, B., Su, B., Føre, H. M., Vollstad, J., Olsen, L., Larsen, R. B., & Tatone, I. (2019). Comparison of fishing efficiency between biodegradable gillnets and conventional nylon gillnets. FISHERIES RESEARCH, 213, 67-74. https://doi.org/10.1016/j.fishres.2019.01.003.

Grimaldo, E., Herrmann, B., Tveit, G. M., Vollstad, J., & Schei, M. (2018). Effect of Using Biodegradable Gill Nets on the Catch Efficiency of Greenland Halibut. Marine and coastal fisheries, 10(6), 619-629. Available at: https://doi.org/10.1002/mcf2.10058.

Grimaldo, E., Herrmann, B., Vollstad, J., Su, B., Moe Føre, H., Larsen, R. B., & Tatone, I. (2018). Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (Gadus morhua) and saithe (Pollachius virens) fisheries. ICES Journal of Marine Science, 75(6), 2245-2256. Available at: https://doi.org/10.1093/icesjms/fsy108.

Guillard, V., Gaucel, S., Fornaciari, C., Angellier-Coussy, H., Buche, P., & Gontard, N. (2018). The Next Generation of Sustainable Food Packaging to Preserve Our Environment in a Circular Economy Context. Frontiers in nutrition (Lausanne), 5, 121-121. Available at: https://doi.org/10.3389/fnut.2018.00121.

Harris, L., Liboiron, M., Charron, L., & Mather, C. . (2021). Using citizen science to evaluate extended producer responsibility policy to reduce marine plastic debris shows no reduction in pollution levels. . Marine Policy, 123, 104319. Available at: https://oi.org/10.1016/j.marpol.2020.104319.

Herberz, T., Barlow, C., & Finkbeiner, M. . (2020). Sustainability Assessment of a Single-Use Plastics Ban. Sustainability. Available at: https://doi.org/ https://doi.org/10.3390/su12093746.

Hounsou, M., Dabadé, D. S., Götz, B., Hounhouigan, M., Honfo, F., Albrecht, A., Correa Dresch, L., Kreyenschmidt, J., & Hounhouigan, D. (2022). Development and use of food packaging from plant leaves in developing countries. Journal für Verbraucherschutz und Lebensmittelsicherheit, 17 Available at:. https://doi.org/10.1007/s00003-022-01390-0.

Huang, F., Zhang, Q., Wang, L., Zhang, C., & Zhang, Y. (2023). Are biodegradable mulch films a sustainable solution to microplastic mulch film pollution? A biogeochemical perspective. Journal of Hazardous Materials, 459, 132024. Available at: https://doi.org/10.1016/j.jhazmat.2023.132024.

Huang, Y., Liu, Q., Jia, W., Yan, C., & Wang, J. (2020). Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environmental Pollution, 260, 114096. Available at: https://oi.org/10.1016/j.envpol.2020.114096.

Huertas, T. F. (2011). Better Deposit Guarantee Schemes. In T. F. Huertas (Ed.), Crisis: Cause, Containment and Cure (pp. 145-156). Palgrave Macmillan UK. Available at: https://doi.org/10.1057/9780230321359_9.

Instituto 17. (2022). Kenya factsheet. Available at https://i17documentos.blob.core.windows.net/documentos/SMEP/Factsheet-Kenya.pdf.

International Trade Administration (ITA). (2022). Kenya - Country Commercial Guide. Available at: https://www.trade.gov/country-commercial-guides/kenya-agribusiness.

ISO. (2021). ISO 17088 - Plastics — Organic recycling.

IUCN. (2022). Plastic waste Profile. International Union for Conservation of Nature.

IUCN. (2023). The economic impact of plastic pollution and the benefits of reducing mismanaged waste in Fiji. International Union for Conservation of Nature.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Marine pollution. Plastic waste inputs from land into the ocean. Science (American Association for the Advancement of Science), 347(6223), 768-771. Available at: https://doi.org/10.1126/science.1260352.

Journal, W. B. (n.d.). Ugandan scientists introduce eco-friendly solution to plastic waste in agriculture. Available at: https://worldbusinessjournal.com/ugandan-scientists-introduce-eco-friendly-solution-to-plastic-waste-in-agriculture/.

KALRO. (2023). Crops. Available at https://www.kalro.org/divisions/crops/.

Karan, S. K., & Hamelin, L. (2021). Crop residues may be a key feedstock to bioeconomy but how reliable are current estimation methods? Resources, Conservation and Recycling, 164, 105211. Available at: https://doi.org/10.1016/j.resconrec.2020.105211.

Kasuya, K.-i., Takagi, K.-i., Ishiwatari, S.-i., Yoshida, Y., & Doi, Y. (1998). Biodegradabilities of various aliphatic polyesters in natural waters. Polymer Degradation and Stability, 59(1), 327-332. Available at: https://doi.org/10.1016/S0141-3910(97)00155-9.

Kelpi. (2023). Turning the tide on plastic packaging. Kelpi, UK. Available at: https://www.kelpi.net/.

Kim, S., Kim, P., Lim, J., An, H., & Suuronen, P. (2016). Use of biodegradable driftnets to prevent ghost fishing: physical properties and fishing performance for yellow croaker. Animal Conservation, 19(4), 309-319. Available at: https://doi.org/10.1111/acv.12256.

Kim, S., Park, S.-w., & Lee, K. (2014). Fishing performance of environmentally friendly tubular pots made of biodegradable resin (PBS/PBAT) for catching the conger eel Conger myriaster. Fisheries Science, 80(5), 887-895. Available at: https://doi.org/10.1007/s12562-014-0785-z.

Kimutai, S. (2014). A study on agricultural residues as a substitute to fire wood in Kenya: a Review on Major Crops. Available at: https://iiste.org/Journals/index.php/JETP/article/view/15497/15905.

Koppejan, A. K. a. J. (1998). Agricultural And Forest Residues – generation, utilization and availability. Available at: https://www.fao.org/3/AD576E/ad576e00.pdf.

Laist, D. W. (1987). Overview of the biological effects of lost and discarded plastic debris in the marine environment. MARINE POLLUTION BULLETIN, 18(6), 319-326. Available at: https://doi.org/10.1016/S0025-326X(87)80019-X.

Lau, W., Shiran, Y., Bailey, R., Cook, E., Stuchtey, M., Koskella, J., Velis, C., Godfrey, L., Boucher, J., Murphy, M., Thompson, R., Jankowska, E., Castillo, A., Pilditch, T., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M., Fischer, D., He, K., Petit, M., Sumaila, U., Neil, E., Bernhofen, M., Lawrence, K., & Palardy, J. . (2020). Evaluating scenarios toward zero plastic pollution. SCIENCE ADVANCES, 369, 1455 - 1461. Available at: https://doi.org/https://doi.org/10.1126/science.aba9475.

Li, X., Zhang, R., Hassan, M. M., Cheng, Z., Mills, J., Hou, C., Realini, C. E., Chen, L., Day, L., Zheng, X., Zhang, D., & Hicks, T. M. (2022). Active Packaging for the Extended Shelf-Life of Meat: Perspectives from Consumption Habits, Market Requirements and Packaging Practices in China and New Zealand. Foods, 11(18), 2903. Available at: https://doi.org/10.3390/foods11182903.

Liu, B., Guan, T., Wu, G., Fu, Y., & Weng, Y. (2022). Biodegradation Behavior of Degradable Mulch with Poly (Butylene Adipate-co-Terephthalate) (PBAT) and Poly (Butylene Succinate) (PBS) in Simulation Marine Environment. POLYMERS, 14(8), 1515. Available at: https://doi.org/10.3390/polym14081515.

Lodhia, S., Martin, N., & Rice, J. (2017). Extended Producer Responsibility for waste televisions and computers: A regulatory evaluation of the Australian experience. Journal of Cleaner Production, 164, 927-938. Available at: https://doi.org/10.1016/J.JCLEPRO.2017.07.020.

Lu, Z., Hasselström, L., Finnveden, G., & Johansson, N. (2022). Cost-benefit analysis of two possible deposit-refund systems for reuse and recycling of plastic packaging in Sweden. Cleaner Waste Systems, 3, 100048. Available at: https://doi.org/10.1016/j.clwas.2022.100048.

Macfadyen, G., Huntington, T., & Cappell, R. (2009). Abandoned, lost or otherwise discarded fishing gear. UNEP Regional Seas Reports and Studies, No. 185FAO Fisheries and Aquaculture Technical Paper, No. 523. Available at: https://openknowledge.fao.org/server/api/core/bitstreams/0c49669a-bc33-4792-ae8c-b24d985c79ad/content/.

Maguire-Rajpaul, V. A., Sandbrook, C., McDermott, C., & Hirons, M. A. (2022). Climate-smart cocoa governance risks entrenching old hegemonies in Côte d'Ivoire and Ghana: a multiple environmentality analysis. Geoforum, 130, 78-91. Available at: https://doi.org/10.1016/j.geoforum.2021.09.015.

Mateos-Cárdenas, A., O'Halloran, J., van Pelt, F. N. A. M., & Jansen, M. A. K. (2020). Rapid fragmentation of microplastics by the freshwater amphipod Gammarus duebeni (Lillj.). Scientific Reports, 10(1), 12799. Available at: https://doi.org/10.1038/s41598-020-69635-2.

Mayers, K. (2007). Strategic, Financial, and Design Implications of Extended Producer Responsibility in Europe: A Producer Case Study. Journal of Industrial Ecology. Available at: https://doi.org/10.1162/jiec.2007.1228.

Mayowa Kuyoro. (2023). In The path to greater productivity and prosperity in Africa. McKinsey Podcast. Available at: https://www.mckinsey.com/industries/public-sector/our-insights/the-path-to-greater-productivity-and-prosperity-in-africa.

Mazhandu, Z., Muzenda, E., Mamvura, T., Belaid, M., & Nhubu, T. . (2020). Integrated and Consolidated Review of Plastic Waste Management and Bio-Based Biodegradable Plastics: Challenges and Opportunities. Sustainability, 12, 1-57. Available at: https://doi.org/https://doi.org/10.3390/su12208360.

Meikle, J. (1995). American plastic: a cultural history. New Brunswick. Rutgers University Press.

Mgolozeli, S. (2021). Agri-mat and grass mulch effects on selected soil physical and chemical properties, runoff, crop growth and yield in South Africa University of South Africa. Available at: https://uir.unisa.ac.za/handle/10500/27933.

Mgolozeli, S., Nciizah, A. D., Wakindiki, I. I. C., & Mudau, F. N. (2020). Innovative Pro-Smallholder Farmers' Permanent Mulch for Better Soil Quality and Food Security Under Conservation Agriculture. Agronomy, 10(4), 605. Available at: https://www.mdpi.com/2073-4395/10/4/605.

Mgolozeli, S., Nciizah, A. D., Wakindiki, I. I. C., Mudau, F. N., & Onwona-Agyeman, S. (2023). Investigation of Infiltration and Runoff Rate on Agri-Mats Using a Laboratory Rainfall Simulation Study. Communications in Soil Science and Plant Analysis, 54(8), 1005-1014. Available at: https://doi.org/10.1080/00103624.2022.2137187.

Micheaux, H., & Aggeri, F. . (2016). The emergence of hybrid co-regulation: empirical evidence and rationale in the field of e-waste management. In 32nd EGOS colloquium organizing in the shadow of power.

Miezah, K., Obiri-Danso, K., Kádár, Z., Fei-Baffoe, B., & Mensah, M. Y. (2015). Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana. Waste management (Elmsford), 46, 15-27. Available at: https://doi.org/10.1016/j.wasman.2015.09.009.

Millette, S. (2023, 14 June 2023). Deposits by Numbers. Resource Recycling Inc. Available at: https://resource-recycling.com/recycling/2023/04/04/deposits-by-the-numbers/.

Ministry of Environment and Natural Resources MENR. (2016). Kenya strategic investment framework for sustainable land management 2017 – 2027. Available at: https://faolex.fao.org/docs/pdf/ken198041.pdf.

Ministry of Environment, C. C. a. F. (2023). Tender for supply and delivery of biodegradable potting tubes for tree seedling 2023. Available at: https://www.tenderyetu.com/tender-for-supply-and-delivery-of-biodegradable-potting-tubes-for-tree-seedling-2023/.

Moulds, S., Chan, A. C. H., Tetteh, J. D., Bixby, H., Owusu, G., Agyei-Mensah, S., Ezzati, M., Buytaert, W., & Templeton, M. R. (2022). Sachet water in Ghana: A spatiotemporal analysis of the recent upward trend in consumption and its relationship with changing household characteristics, 2010-2017. PLoS ONE, 17(5), e0265167-e0265167. Available at: https://doi.org/10.1371/journal.pone.0265167.

Mujtaba, M., Lipponen, J., Ojanen, M., Puttonen, S., & Vaittinen, H. (2022). Trends and challenges in the development of bio-based barrier coating materials for paper/cardboard food packaging; a review. Science of the Total Environment, 851, 158328. Available at: https://doi.org/10.1016/j.scitotenv.2022.158328.

Mura, R., Vicentini, F., Botti, L. M., & Chiriacò, M. V. (2023). Achieving the circular economy through environmental policies: Packaging strategies for more sustainable business models in the wine industry. Business Strategy and the Environment. Available at: https://doi.org/10.1002/bse.3556.

Muriuki, J., Kuria, A., Muthuri, C., Mukuralinda, A., Simons, A., & Jamnadass, R. (2013). Testing Biodegradable Seedling Containers as an Alternative for Polythene Tubes in Tropical Small-Scale Tree Nurseries. Small-scale Forestry, 13. Available at: https://doi.org/10.1007/s11842-013-9245-3.

Mwangi, A. (2023). Memorandum on Nema Notice On Requirements For Plastic Bags Issued On 16th November 2023 To Manufacturers, Importers, And Users Of Plastic Flat And Carrier Bags. Kenya Association of Manufacturers.

Mwangi, W., Kariuki, S., & Wagara, N. (2021). Substitution of Plastics with Organic Pots in Tree Seedlings Production for Sustainable Environmental Conservation. East African Journal of Science, Technology and Innovation. Available at: https://doi.org/10.37425/eajsti.v2i3.207.

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2020). Environmental Impact of Food Packaging Materials: A Review of Contemporary Development from Conventional Plastics to Polylactic Acid Based Materials. Materials (Basel), 13(21). Available at: https://doi.org/10.3390/ma13214994.

Ni, R., Zhu, X., Lei, Y., Li, X., Dong, W., Zhang, C., Chen, T., Mburu, D. M., & Hu, C. (2022). Effectiveness of Common Preprocessing Methods of Time Series for Monitoring Crop Distribution in Kenya. Agriculture, 12(1), 79. Available at: https://www.mdpi.com/2077-0472/12/1/79.

Northampton, U. o. (2023). The challenge. Mitigating Plastic Pollution From Agricultural Mulch Used In Ghana. Available at: https://app.freshppact.org/challenges/21.

Nova-Institute. (2024). Biodegradable Polymer in various environments. Available at: https://www.biocycle.net/wp-content/uploads/2024/10/poster_l.jpg.

Odifa, D. (2023). Nigeria's top 10 agric exports in Q1 2023. Business Day

OEC. (2023). World Profile – Ghana. Available at: https://oec.world/en/profile/country/gha.

One.Five. (2023). AI powered packaging for modern products. Available at:https://www.one-five.com/.

Onwona, S., Nakamura, S., Kawabata, Y., Yamada, M., Sabi, E. B., & Tanahashi, M. (2012). Utilization of Forestry Residue in Erosion Control and Soil Moisture Conservation. Journal of Arid Land Studies, 279 -282. Available at: https://nodaiweb.university.jp/desert/pdf/JALS-P54_279-282.pdf.

Onyeaka, H., Obileke, K., Makaka, G., & Nwokolo, N. (2022). Current Research and Applications of Starch-Based Biodegradable Films for Food Packaging. Polymers, 14(6), 1126. Available at: https://doi.org/10.3390/polym14061126.

Pinkse, J., & Kolk, A. (2012). Addressing the climate change sustainable development nexus: the role of multi-stakeholder partnerships. Business & Society, 51(1), 176-210. Available at: https://doi.org/10.1177/0007650311427426.

PlantVillage. (2023). PlantVillage is crafting biodegradable potting tubes for high-value fruit trees in Kenya. Available at: https://plantvillage.psu.edu/blogposts/299-plantvillage-is-crafting-biodegradable-potting-tubes-for-high-value-fruit-trees-in-kenya.

Qasim, M., Oyegoke, T., & Omale, S. (2021a). Production Of Biodegradable Plastics As Substitute For Conventional Plastics In Nigeria. FUDMA Journal of Sciences, 5, 326-331. Available at: https://fjs.fudutsinma.edu.ng/index.php/fjs/article/view/715.

Qasim, M., Oyegoke, T., & Omale, S. (2021b). Production Of Bioplastics as Substitute for Conventional Plastics in Nigeria. FUDMA Journal of Sciences, 5, 326-331. Available at: https://www.researchgate.net/publication/358834416_Production_Of_Bioplastics_As_Substitute_For_Conventional_Plastics_In_Nigeria.

Qu, S., Guo, Y., Ma, Z., Chen, W., Liu, J., Liu, G., Wang, Y., & Xu, M. (2019). Implications of China's foreign waste ban on the global circular economy. Resources, Conservation and Recycling. Available at: https://doi.org/10.1016/J.RESCONREC.2019.01.004.

Richardson, K., Hardesty, B. D., Vince, J., & Wilcox, C. (2022). Global estimates of fishing gear lost to the ocean each year. Science Advances, 8(41), eabq0135-eabq0135. Available at: https://doi.org/10.1126/sciadv.abq0135.

Richardson, K., Hardesty, B. D., & Wilcox, C. (2019). Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis. Fish and Fisheries (Oxford, England), 20(6), 1218-1231. Available at: https://doi.org/10.1111/faf.12407.

Røine, K., & Lee, C. . (2006). With a Little Help from EPR?: Technological Change and Innovation in the Norwegian Plastic Packaging and Electronics Sectors Journal of Industrial Ecology, 10. Available at: https://doi.org/10.1162/108819806775545448.

Romão, S. B., A.; Ribeiro, I.A.C. (2022). Novel Features of Cellulose-Based Films as Sustainable Alternatives for Food Packaging. Polymers, 14, 4968. Available at: https://doi.org/10.3390/polym14224968.

Rossi, J., & Bianchini, A. (2022). "Plastic waste free" – A new circular model for the management of plastic packaging in food value chain. Transportation Research Procedia, 67, 153-162. Available at: https://doi.org/10.1016/j.trpro.2022.12.046.

RWDC Industries. (2023). Solon: The Science of Solon.

Sadeghizadeh-Yazdi, J., Habibi, M., Kamali, A. A., & Banaei, M. (2019). Application of Edible and Biodegradable Starch-Based Films in Food Packaging: A Systematic Review and Meta-Analysis. Current research in nutrition and food science, 7(3), 624-637. Available at: https://doi.org/10.12944/CRNFSJ.7.3.03.

Sahai, H., García Valverde, M., Murcia Morales, M., Hernando, M. D., Aguilera del Real, A. M., & Fernández-Alba, A. R. (2023). Exploring sorption of pesticides and PAHs in microplastics derived from plastic mulch films used in modern agriculture. Chemosphere, 333, 138959. Available at: https://doi.org/10.1016/j.chemosphere.2023.138959.

Salama, K., & Geyer, M. (2023). Plastic Mulch Films in Agriculture: Their Use, Environmental Problems, Recycling and Alternatives. Environments, 10(10).

Sea6 Energy. (2023). Sea6 Purpose: Disruptive Solutions for a Sustainable Planet. Retrieved 29 November 2023 from Available at: https://www.sea6energy.com.

Seglah, P. A., Wang, Y., Wang, H., & Bi, Y. (2019). Estimation and Efficient Utilization of Straw Resources in Ghana. Sustainability, 11(15), 4172. Available at: https://www.mdpi.com/2071-1050/11/15/4172.

Shi, K., Zhang, H., Xu, H., Liu, Z., Kan, G., Yu, K., & Jiang, J. (2022). Adsorption behaviors of triclosan by non-biodegradable and biodegradable microplastics: Kinetics and mechanism. Science of the Total Environment, 842, 156832. Available at: https://doi.org/10.1016/j.scitotenv.2022.156832.

Shlush, E., & Davidovich-Pinhas, M. (2022). Bioplastics for food packaging. Trends in Food Science & Technology, 125. Available at: https://doi.org/10.1016/j.tifs.2022.04.026.

SMEP. (2022a). The Agrimulchfilm Project Profile Sheet. Retrieved 8 March 2024 from Available at: https://smepprogramme.org/wp-content/uploads/2022/07/CSIR.pdf

SMEP. (2022b). The FreshPPact Impact Hub. Available at: https://southsouthnorth.org/wp-content/uploads/2022/06/Blue-skies-.pdf.

SMEP. (2023). The Agrimulchfilm Project. Available at: https://smepprogramme.org/project/the-agrimulchfilm-project/.

Sorasan, C., Edo, C., González-Pleiter, M., Fernández-Piñas, F., Leganés, F., Rodríguez, A., & Rosal, R. (2022). Ageing and fragmentation of marine microplastics. Science of the Total Environment, 827, 154438. Available at: https://oi.org/10.1016/j.scitotenv.2022.154438.

SPREP. (2023). Fiji National Waste Audit Analysis Report. Secretariat of the Pacific Regional Environment Programme.

Stoica, M., Bichescu, C. I., Cretu, C.-M., Dragomir, M., Ivan, A. S., Podaru, G. M., Stoica, D., & Stuparu-Cretu, M. (2024). Review of Bio-Based Biodegradable Polymers: Smart Solutions for Sustainable Food Packaging. FOODS, 13(19), 3027. Available at: https://doi.org/10.3390/foods13193027.

Tarrant, A. R., Brainard, D. C., & Hayden, Z. D. (2020). Cover Crop Performance between Plastic-mulched Beds: Impacts on Weeds and Soil Resources. HortScience horts, 55(7), 1069-1077. Available at: https://doi.org/10.21273/hortsci14956-20.

TIS. (2024). Cocoa/Cocoa beans. Available at: https://www.tis-gdv.de/tis_e/ware/genuss/kakao/kakao-htm/.

Tudor, D., & Williams, A. (2021). The effectiveness of legislative and voluntary strategies to prevent ocean plastic pollution: Lessons from the UK and South Pacific. Marine Pollution Bulletin, 172, 112778. Available at: https://doi.org/ https://doi.org/10.1016/j.marpolbul.2021.112778.

Tuure, J., Räsänen, M., Hautala, M., Pellikka, P., Mäkelä, P. S. A., & Alakukku, L. (2021). Plant residue mulch increases measured and modelled soil moisture content in the effective root zone of maize in semi-arid Kenya. Soil and Tillage Research, 209, 104945. Available at: https://doi.org/10.1016/j.still.2021.104945.

UNCTAD. (2018). From regional conomic communities to a contineta free trade area:

Strategic tools to assist negotiators and agricultural policy design in Africa. Available at: https://unctad.org/system/files/official-document/webditc2017d1_en.pdf.

UNCTAD. (2019). Advancing Sustainable Development Goal 14: Sustainable Fish, Seafood Value Chains, Trade and Climate. Available at: https://unctad.org/system/files/official-document/ditcted2019d3_en.pdf.

UNCTAD. (2022a). Global Plastics Trade Hits Record $1.2 trillion. UNCTAD. Available at: https://unctad.org/data-visualization/global-plastics-trade-reached-nearly-1.2-trillion-2021.

UNCTAD. (2022b). Revealed Comparative Advantage. Available at: https://unctadstat.unctad.org/EN/RcaRadar.html.

UNCTAD. (2022c). Substitutes for Single-Use Plastics in Sub-Saharan Africa and South Asia Case Studies from Bangladesh, Kenya and Nigeria. Available at: https://unctad.org/publication/substitutes-single-use-plastics-sub-saharan-africa-and-south-asia.

UNCTAD. (2023a). Chemicals in Plastics - A Technical Report. Available at: https://www.unep.org/resources/report/chemicals-plastics-technical-report.

UNCTAD. (2023b). Plastic Pollution: The pressing case for natural and environmentally friendly substitutes to plastics. Available at: https://unctad.org/publication/plastic-pollution-pressing-case-natural-and-environmentally-friendly-substitutes.

UNCTAD. (2023c). Scaling up plastic substitutes is key to tackling pollution.

UNCTAD. (n.d.). Revealed Comparative Advantage. Available a:t https://unctadstat.unctad.org/en/RcaRadar.html.

United Nations. (2022). International Trade Database Intelligence. Available at: https://frsabido.shinyapps.io/COMTRADE/.

Verghese, K., Lewis, H., Lockrey, S., & Williams, H. (2015). Packaging's Role in Minimizing Food Loss and Waste Across the Supply Chain. Packaging technology & science, 28(7), 603-620. Available at: https://doi.org/10.1002/pts.2127.

Vivas Eugui, D and Pacini, H. (2022). Plastic Substitutes, HS Codes, Life Cycle Analysis and Tariffs Consideration. Presented at the WTO Dialogue on Plastic.

Wang, Y., Wei, W., Bi, Z., Cao, R., Li, J., Shu, D., & Lou, Z. . (2021). Decomposing the decoupling of plastics consumption and economic growth in G7 and China: Evidence from 2001 to 2020 based on China's import ban. Journal of Environmental Management, 296, 113225. Available at: https://doi.org/10.1016/j.jenvman.2021.113225.

Wang, Z. C., Song, Q. B., You, Y., Duan, H. B., Yuan, W. Y., & Li, J. H. (2021). Identifying the lifecycle ODP and GWP effects of the refrigerants from household air-conditioners in Macau. Environmental Impact Assessment Review, 90. Available at: https://doi.org/10.1016/j.eiar.2021.106639.

Watson, R., Revenga, C., & Kura, Y. (2006). Fishing gear associated with global marine catches I. database development. Fisheries Research, 79(1-2), 97-102. Available at: https://doi.org/10.1016/j.fishres.2006.01.010.

Waweru, S. (2023). Plastic mulching has improved my harvests. Available at: https://nation.africa/kenya/business/seeds-of-gold/plastic-mulching-has-improved-my-harvests-4180866.

Wu, C., Pan, S., Shan, Y., Ma, Y., Wang, D., Song, X., Hu, H., Ren, X., Ma, X., Cui, J., & Ma, Y. (2022). Microplastics mulch film affects the environmental behavior of adsorption and degradation of pesticide residues in soil. Environmental Research, 214, 114133. Available at: https://oi.org/10.1016/j.envres.2022.114133.

Annex I

Annex table 1.
Revealed comparative advantage (RCA): Pacific Ocean region (2022)

Feature	Commodity	RCA	Export (KUS$)
The Cook Islands	Fish, fresh (live or dead), chilled or frozen	151.7	5,798
	Fish, aqua. Invertebrates, prepared, preserved, n.e.s.	7.3	159
Federated States of Micronesia	Fish, fresh (live or dead), chilled or frozen	246.3	113,817
	Crustaceans, mollusks and aquatic invertebrates	3.1	645
Fiji	Fish, aqua. Invertebrates, prepared, preserved, n.e.s.	20.9	36,119
	Fish, fresh (live or dead), chilled or frozen	18.9	53,495
Kiribati	Fish, fresh (live or dead), chilled or frozen	118.3	4,672
Marshall Islands	Fish, fresh (live or dead), chilled or frozen	5.5	819
Nauru	Fish, fresh (live or dead), chilled or frozen	117.7	47,484
Niue	Fish, fresh (live or dead), chilled or frozen	2.3	6
Palau	Fish, fresh (live or dead), chilled or frozen	26.4	248
	Crustaceans, mollusks and aquatic invertebrates	7.1	30
Samoa	Fish, fresh (live or dead), chilled or frozen	38.5	5,116
	Crustaceans, mollusks and aquatic invertebrates	6.5	388
Solomon Islands	Fish, dried, salted or in brine, smoked fish	83.8	8,085
	Fish, aqua. Invertebrates, prepared, preserved, n.e.s.	50.4	32,981
	Fish, fresh (live or dead), chilled or frozen	10.1	11,660
Tokelau	n/a	—	—
Tonga	Fish, fresh (live or dead), chilled or frozen	49.8	2,808
	Crustaceans, mollusks and aquatic invertebrates	31	781
	Fish, aqua. Invertebrates, prepared, preserved, n.e.s	18.1	581
	Fish, dried, salted or in brine, smoked fish	3.8	18
Tuvalu	Fish, fresh (live or dead), chilled or frozen	66.6	12
Vanuatu	Fish, fresh (live or dead), chilled or frozen	95	18,821
	Crustaceans, mollusks and aquatic invertebrates	8.1	711
	Fish, aqua. Invertebrates, prepared, preserved, n.e.s	5.3	598

Source: Prepared by UNCTAD,, based on UN Comtrade Database.

Annex table 2.
Revealed comparative advantage (RCA): Indian Ocean region (2022)

Feature	Commodity	RCA	Export (KUS$)
Madagascar	Crustaceans, mollusks and aquatic invertebrates	18.1	99,814
	Fish, aqua. Invertebrates, prepared, preserved, n.e.s.	5.8	40,684
Seychelles	Fish, aqua. Invertebrates, prepared, preserved, n.e.s.	118	137,353
	Fish, fresh (live or dead), chilled or frozen	49.9	102,122
Comoros	n/a	—	—
Maldives	Fish, fresh (live or dead), chilled or frozen	197.8	272,630
	Fish, dried, salted or in brine, smoked fish	101.4	11,731
	Fish, aqua. Invertebrates, prepared, preserved, n.e.s.	78.2	61,341
Mauritius	Fish, aqua. Invertebrates, prepared, preserved, n.e.s.	56.8	256,486
	Fish, fresh (live or dead), chilled or frozen	10.2	80,936
Sri Lanka	Fish, fresh (live or dead), chilled or frozen	4.5	209,691
	Crustaceans, mollusks and aquatic invertebrates	3.2	66,104

Source: Prepared by UNCTAD,, based on UN Comtrade Database.

Annex table 3.
Fishing gear imports: Fiji (2017–2022)

Product	Code	Year	Trade value (in 1,000 USD)	Quantity	Unit
Twine, cordage or rope; fishing net	**HS 560811**	2017	165.98	21,762	kg
		2018	124.08	15,916.42	kg
		2019	198.571	17,496.52	kg
		2020	158.462	33,707.54	kg
		2021	814.064	128,140.5	kg
		2022	121.84	19283.79	kg
Fishing rods	**HS 950710**	2017	28.821	1,388	Item
		2018	23.802	572	Item
		2019	20.858	1,103	Item
		2020	14.391	7,552	Item
		2021	36.665	561	Item
		2022	37.812	1,111	Item
Fish-hooks; whether or not snelled	**HS 950720**	2017	915.325	51,502.65	kg
		2018	974.613	53,664.54	kg
		2019	926.962	40,659.69	kg
		2020	674.97	30,406.43	kg
		2021	901.89	28,942.09	kg
		2022	656.842	29,410.77	kg
Fishing reels	**HS 950730**	2017	39.932	14,973	Item
		2018	34.326	41,845	Item
		2019	69.708	19,400	Item
		2020	43.333	22,538	Item
		2021	31.057	3,669	Item
		2022	67.895	7,422	Item
Fishing tackle n.e.c.; butterfly net	**HS 950790**	2017	1,196.463	2,478,608	Item
		2018	833.802	6,708,334	Item
		2019	794.21	2,930,161	Item
		2020	655.381	5,547,494	Item
		2021	479.018	3,860,639	Item
		2022	804.792	3,518,601	Item

Source: Prepared by UNCTAD,, based on UN Comtrade Database.