Trends in Food Science & Technology 163 (2025) 105143

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Sustainable food packaging system: Status of regulatory initiatives and issues on plastic use in Tunisia, Kenya, Uganda and Tanzania African countries

Maria Alessia Schouten [a,*], Ines Ben Rejeb [b], Faten Khamassi [c], Samuel Edgar Tinyiro [d], Cassius Aruho [d], Isa Kabenge [e], John Muyonga [e], Isaac Maitha [f], Michael Wandayi Okoth [f], Akwilina Mwanri [g], Rashid Suleiman [h], Susan Nchimbi Msolla [h], Marco Setti [a], Santina Romani [a,i]

[a] *Department of Agricultural and Food Sciences, Alma Mater Studiorum, University of Bologna, Piazza G. Goidanich 60, 47521, Cesena (FC) and Viale Fanin 50, 40127, Bologna, Italy*

[b] *Laboratory of Microbial Ecology and Technology, Biocatalysis and Industrial Enzymes Group, University of Carthage, National Institute of Applied Sciences and Technology, BP 676, 1080, Tunis, Tunisia*

[c] *National Agronomic Institute of Tunisia, University of Carthage, 1082, Tunis, Tunisia*

[d] *National Agricultural Research Organization, P.O. Box 7065, Kampala, Uganda*

[e] *College of Agricultural and Environmental Sciences, Makerere University, P.O. Box 7062, Kampala, Uganda*

[f] *Department of Food Science, Nutrition and Technology, University of Nairobi, Nairobi, 29053-00625, Kenya*

[g] *Department of Human Nutrition and Consumer Sciences, Sokoine University of Agriculture, P.O. Box 3006, Morogoro, Tanzania*

[h] *Department of Food Science and Agro-Processing, Sokoine University of Agriculture, P.O. Box 3004, Morogoro, Tanzania*

[i] *Interdepartmental Centre for Agri-Food Industrial Research (CIRI), Alma Mater Studiorum, University of Bologna, Via Q. Bucci 336, 47521, Cesena, FC, Italy*

A R T I C L E I N F O

Handling Editor: Dr. S Charlebois

Keywords:
Traditional packaging material
Regulatory framework
Single-use plastic
Bio-based material
African raw material
By-product valorisation

A B S T R A C T

Background: Sustainable food packaging is not only an environmental necessity, but also a crucial part of the broader strategy to reduce food waste and promote sustainable development in Africa, as in all countries around the world.

Scope and approach: The review gives an overview of the current landscape of food packaging systems in Africa, with a specific focus on Tunisia, Kenya, Uganda and Tanzania, countries actively involved in sustainable food packaging researches under the EU Horizon2020 FoodLAND project. The analysis begins with a description of the most used packaging materials and highlights the environmental and health issues of fossil-based plastics. National policies aimed at reducing plastic use and pollution are then examined. Finally, some relevant studies on bio-based alternatives using local resources are reviewed.

Key findings and conclusions: The development of sustainable food packaging in Africa faces major challenges, but also holds a great potential. The continent is still largely reliant on traditional (e.g. plant leaves) and conventional (e.g. fossil-based plastics) materials. The former offer limited food protection, while the latter contribute to environmental pollution. Some policy/regulatory initiatives have been introduced to reduce plastic use, their effect is often limited due to several challenges. The reviewed studies demonstrate the interest of the African scientific communities on sustainable packaging solutions, however most of them remain at lab-scale and need validation. Customised approaches that consider the different socio-economic and cultural realities of African countries can help overcome current limitations of local packaging system, especially through collaboration between academia, industry and policy makers.

* Corresponding author. Department of Agricultural and Food Sciences, Alma Mater Studiorum, University of Bologna, Piazza Goidanich, 60, 47521, Cesena, FC, Italy.

E-mail address: maria.schouten2@unibo.it (M.A. Schouten).

https://doi.org/10.1016/j.tifs.2025.105143
Received 27 March 2025; Received in revised form 2 June 2025; Accepted 17 June 2025
Available online 18 June 2025

1. Introduction

Sustainable food packaging is a multi-layered concept that integrates environmental, economic and social aspects to minimize the environmental footprint while ensuring functionality. Key attributes of sustainable packaging include the use of recycled or recyclable materials, reduced water consumption, waste prevention in landfills, reusability, reliance on renewable energy, and avoidance of greenhouse gas emissions and air pollutants, all while safeguarding human and ecosystem health (Russell, 2014). In addition, an often overlooked but essential feature of sustainable packaging is its ability to protect and deliver the food is contains, to ensure that it reaches the consumer in good quality and safe conditions, and to communicate the necessary information as well as being convenient and cost-effective. Packaging is a cornerstone of the food supply chain and its environmental footprint is relatively minor compared to the product it protects. Thus, food packaging plays a crucial role in preventing spoilage and contamination, thereby avoiding significant environmental and resource losses. Evaluating the sustainability of food packaging therefore requires a holistic approach that integrates all these attributes, prioritizing the primary function of protection and preservation (Mendes & Pedersen, 2021; Russell, 2014; Upadhyay et al., 2024), alongside other basic functions such as containment, communication, convenience, distribution and marketing. The required materials must have optimal mechanical strength, chemical stability and barriers against water vapour, oxygen, light and heat (Salgado et al., 2021). Besides these functions, sustainable food packaging has the potential to support the green economy and reduce the negative environmental impact of waste.

It is becoming increasingly clear that sustainable packaging is not only an environmental imperative, but also a critical component of the broader strategy to reduce food waste and promote sustainable development in Africa, as in all countries around the world. In some African countries, this urgency has been reflected in a series of policy and legislative measures, ranging from bans on thin single-use plastic bags to broader bans on plastic bags altogether. While these initiatives represent a significant step forward, they need to be carefully implemented to address comprehensive health and safety concerns, including access to clean drinking water and safe food, as well as the feasibility of local recycling initiatives for fossil-based plastics (Ncube et al., 2021).

In view of this need, recent European (EU) Horizon 2020 projects — InnoFoodAfrica, HealthyFoodAfrica and FoodLAND — have significantly contributed to advancing the food and packaging sectors in Africa. Taken together, these related EU projects represent a comprehensive effort to revolutionise African food systems through the integration of innovative processes, agrobiodiversity and community-based solutions. By addressing issues such as malnutrition, environmental sustainability and market connectivity, they contribute to the development of resilient, health-focused food networks while promoting equitable growth and economic opportunities for smallholder farmers and local communities.

In more detail, InnoFoodAfrica (2020–2024), involving 18 partners from Africa and Europe, aimed to enhance African value chains by promoting climate-smart crops among smallholder farmers in Ethiopia, Kenya, Uganda and South Africa. These crops were transformed into nutrient-rich and safe foods, while non-edible parts of the plant were repurposed for biocomposite packaging, improving resource efficiency and creating new value streams for rural communities (https://www.innofoodafrica.eu/). Similarly, HealthyFoodAfrica (2020–2024), with 17 African and European partners, worked on fostering sustainable, equitable and resilient food systems in urban and semi-urban areas of 10 cities of six African countries through localised food system labs. These labs explore topics such as sustainability, equity and resilience challenges, generating tailored solutions to enhance the local food networks (https://healthyfoodafrica.eu/). Complementing these efforts, FoodLAND (2022–2025), a consortium of 27 African and European partners, focused on the development of scalable and innovative technologies to improve nutritional performance while promoting agrobiodiversity, food diversity and healthy diets. The project tackled behavioural barriers such as neophobia towards food and limited access to knowledge while promoting systemic resilience and behavioural change across the food value chain, from farmers to consumers. Through interdisciplinary approaches, FoodLAND aimed to strengthen food networks by supporting sustainable agriculture, dietary diversity and several technological innovations to minimize environmental impacts (https://foodland-africa.eu/). In the framework of activities on the development of bio-based food packaging materials, four African research partners from Tunisia, Kenya, Uganda and Tanzania were involved. The new materials were produced using local agricultural products and/or by-products/waste, as shown in Fig. 1.

In this context, the present review aims to provide an updated and comprehensive analysis of the current status and future prospects of food packaging systems in the African countries mentioned above. The analysis begins with an overview of the most commonly used food packaging materials in Africa and highlights the environmental and health issues specifically associated with fossil-based plastics. It then examines the policy initiatives to reduce plastic use and pollution in Tunisia, Kenya, Uganda and Tanzania, assessing their negative or positive effects, where these are known. Finally, some relevant research studies on new bio-based packaging solutions developed in these countries using local raw materials are reviewed.

Overall, the analysed topics provide new insights into how policy frameworks and technological innovations can work together to support the development of a more circular and resilient food packaging system in the studied African countries.

2. The current status of food packaging sector in African environments

In developing regions, such as many African countries, the need of suitable food packaging solutions is particularly high due to rapid urbanisation, population growth and changing lifestyles (Ezeudu et al., 2021; Mlalila et al., 2017). Moreover, food production in Africa is often characterised by slow, manual operations and labour-intensive processes with inconsistent quality standards (Aworh, 2023). This contributes to significant challenges regarding food safety and the lack of appropriate packaging can increase unhygienic conditions and the risk of contamination (Aworh, 2023). In response, there has been an increasing shift towards synthetic fossil-based plastic packaging materials, which has also been driven in recent years largely by the need for improved food safety, quality, protection and delivery during intra/-intercontinental trade (Babayemi et al., 2019).

However, this trend has also raised serious environmental concerns about the sustainability of food packaging, especially in African regions where resource/waste management systems are underdeveloped (Babayemi et al., 2019). The transition to sustainable packaging is therefore important to reduce fossil-based plastic waste, promote recycling and add value to the potential use of renewable resources for material production (Hounsou et al., 2022).

2.1. Overview of utilized materials: traditional vs conventional food packaging

In Africa, a variety of materials are used for food packaging, including both traditional and conventional options (Hounsou et al., 2022). Traditional food packaging materials refer to natural and locally available products that are culturally rooted, often drawing on indigenous knowledge. Conventional packaging, on the other hand, comprises industrially produced materials introduced by modern food systems for their versatility, durability, convenience and technological performances. Fig. 2 provides a comparative overview of the food packaging materials used in African countries, highlighting their diversity in terms of distribution context, environmental impact, functional roles, cultural

Fig. 1. Bio-based packaging materials developed within the EU FoodLAND project by research partners from Tunisia, Kenya, Uganda and Tanzania.

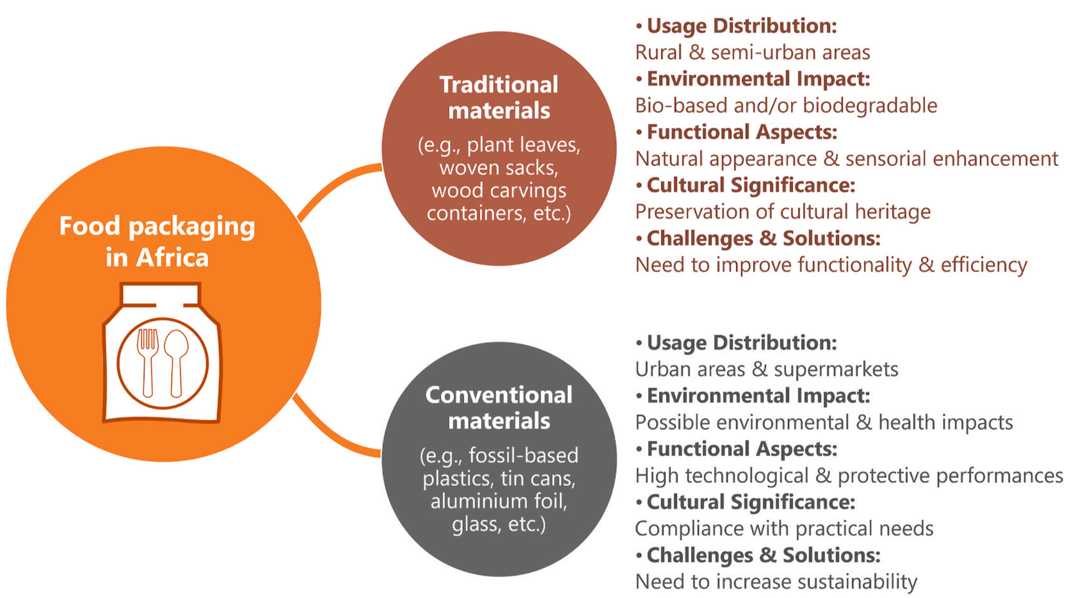

Fig. 2. Traditional and non-traditional food packaging materials used in African environments.

relevance and related main challenges and solutions.

Traditional food packaging materials are currently used in rural and semi-urban areas such as local/open markets, canteens, traffic jams, churches, picnic sites, informal local restaurants, fast food joints, road-side snack bars and food vendors (Ezeudu et al., 2021). Common examples include homemade clay pots, cane baskets, containers made from wood carvings (calabashes), woven sacks/baskets made from palm/bamboo fronds, plant fibres, wood threads and animal skins, hides, horns and other by-products (Ezeudu et al., 2021). Moreover, wrapped/packaged foods made from green plant leaves are widely used. The green leaves are usually sourced from backyard farms and nearby forests, bushes and farms, as most rural households have farms on the family land and/or nearby (Ezeudu et al., 2021; Hounsou et al., 2022). Depending on the location and situation, different types of plant leaves are traditionally used as packaging material for food (Boateng et al., 2022). Corn, plantain and banana leaves, for example, are used to wrap certain foods and serve as both packaging material and plates (Boateng et al., 2022; Ezeudu et al., 2021). Some spices and condiments, that cannot be consumed in large quantities at once, are usually packaged with multiple layers of vegetable leaves to extend their shelf-life or to obtain a specific shape to facilitate stacking during storage or sampling for sale (Ezeudu et al., 2021). The popularity of these leaves as a food packaging material is very high and even reaches the elites because the leaves can enhance the aroma, taste and colour of food and are an expression of tradition and culture (Boateng et al., 2022; Hounsou et al., 2022). All the used traditional materials are cost-effective and easy to obtain, moreover, most of them are bio-based, naturally biodegradable and thus environmentally friendly (Boateng et al., 2022). However, despite these advantages, most of traditional materials do not always guarantee the quality, stability and hygiene to the packaged food products (Ezeudu et al., 2021; Hounsou et al., 2022).

These limitations and the urbanisation in Africa have led to an increased use of conventional food packaging ones, such as tin cans, aluminium foil, cardboard boxes, glass bottles, jars and, above all, various fossil-based plastics and multilayer materials, which have taken a prominent position in urban areas and supermarkets (Ezeudu et al., 2021; Hounsou et al., 2022). The widespread use of conventional materials reflects their ability to fulfil the demands of mass production and distribution while ensuring the integrity, quality and safety of food during its shelf-life. Another reason is that traditional packaging is not abundant in urban areas due to the lack of farms, forests and bushes (Ezeudu et al., 2021).

Among conventional food packaging materials, fossil-based plastics are the most popular, in both flexible and rigid forms, due to their widespread applicability and established role in modern food systems thanks to their remarkable versatility, convenience, durability and cost-effectiveness (Ezeudu et al., 2021; Hounsou et al., 2022). Nevertheless, the widespread use of fossil-based plastics raises concerns about their impact on human and animal health as well as on the environment, including pollution and contribution to the global plastic waste crisis (Hounsou et al., 2022).

2.2. Environmental and health impact of plastic materials

In 2023, the global production volume of plastics reached 413.8 million metric tons (Mt), with the Middle East and Africa contributing around 9 % of this total (Plastic Europe, 2024; Statista, 2025). Packaging is the leading application of plastics worldwide, representing 35 % of total consumption in 2022, highlighting its role in protecting and preserving goods throughout global supply chains (Statista, 2025). Within the packaging sector, food packaging is the fastest growing segment. The increase in single-use plastic and the popularity of convenience foods, which generally rely on durable plastic packaging, further contribute to this trend (Ncube et al., 2020).

In parallel with the increase in plastic production and consumption, the global volume of plastic waste increased more than seven-fold between 1980 and 2020, reaching an estimated 360 Mt in 2020, and is projected to exceed 615 Mt by 2040 (Statista, 2025). Among all sectors, plastic waste from packaging continues to be the largest contributor, alone accounting for 142 Mt of in 2019 (Statista, 2025). Nevertheless, the management of plastic waste remains largely inadequate at a global level, leading to significant environmental and public health impacts. In 2019, an estimated 82 Mt of plastic waste was mismanaged or littered, much of which ended up polluting terrestrial and marine ecosystems. In the same year, Africa was the second largest contributor to global mismanaged plastic waste, accounting for 22.2 %, following Asia (65 %) (Statista, 2025).

The durability and resistance to degradation of fossil-based plastics, whether as single-use, worn-out or discarded items, allow them to persist and spread from points of original deposition to other points in the environment (Akan et al., 2021). From the soil surface to watercourses, they degrade slowly and interact with the environment and biodiversity around them (Akan et al., 2021; Deme et al., 2022). Non-biodegradable plastics can remain in the environment for decades and break down into macro- (>25 mm), meso- (from 5 to 25 mm), micro- (<5 mm) and nano-plastics (<100 nm) depending on their composition, exposure conditions and degradation time (Hartmann et al., 2019). These fragments may enter food chains by contaminating public drinking water or being ingested by marine organisms and terrestrial animals, such as livestock with negative effects on animal and human health (Babayemi et al., 2019; Khoaele et al., 2023). Indeed, ingestion and exposure to micro-/nano-plastics can lead to histopathological damage, oxidative stress, altered gene expression, enzymatic dysfunction, reproductive toxicity and potentially carcinogenic effects (Patra et al., 2022). Apart from the risks of ingestion/exposure, plastic waste has also been shown to serve as a breeding ground for mosquitoes, contributing to malaria, dysentery and cholera epidemics etc. (Akan et al., 2021; Khoaele et al., 2023). Overall, plastic pollution alters the global carbon cycle and affects economic activities such as aquaculture, tourism and waterborne transport. The global environmental costs of plastic pollution are therefore significant and are estimated at up to USD 2.5 trillion/year in terms of value of benefits derived from marine ecosystem services (Beaumont et al., 2019).

These problems are particularly acute in low-to middle-income countries, including Africa where inadequate waste management infrastructure and recycling facilities are insufficient to handle the rapid generation of plastic waste (Akan et al., 2021; Babayemi et al., 2019; Kosore et al., 2024). Open dumps and incinerators, without effective solid waste sorting systems, are a common option for solid waste management in African countries, releasing harmful substances such as carbon monoxide, carbon dioxide and nitrous oxide into the environment (Babayemi et al., 2019; Khoaele et al., 2023).

Given the widespread mismanagement of waste, improvements in waste handling systems and infrastructure in Africa are urgently needed (Babayemi et al., 2019). This can be done by encouraging the involvement of proactive stakeholders and governments, but also by investing in extensive research into more sustainable packaging materials alternative to fossil-based plastics (Khoaele et al., 2023; Ncube et al., 2021).

3. Policy and regulatory initiatives to address plastic use and pollution in some African countries

As previously reported, plastic packaging and its harmful effects on the environment and health have become a global problem that has also reached the African continent (Hira et al., 2022). The urgency to tackle the environmental, health and economic impacts emphasise the need for improved waste management strategies in Africa (Deme et al., 2022). In response to this urgent need, numerous African countries have taken various measures to combat plastic pollution over time, with varying degrees of success. The severity of the problem has led to an increasingly strong anti-fossil-based plastic sentiment, characterised by the use of diverse measures such as bans, taxation, incentives and voluntary initiatives (Muposhi et al., 2022).

The effectiveness of plastic pollution policies varies widely across African countries and is influenced by factors such as population dynamics, economic landscape and socio-cultural distinctions (Deme et al., 2022). These factors contribute to the different strategies for dealing with plastic consumption and waste patterns in individual countries. Nonetheless, the actions taken emphasise the growing need to regulate the use of plastic for packaging and increase the demand for more sustainable packaging alternatives in the food sector to maintain both safety and quality standards.

In recent years, Tunisia, Kenya, Uganda and Tanzania have taken various policy and regulatory measures to directly tackle plastic pollution. These initiatives include the ban on single-use plastic bags and regulations on the thickness of plastic materials, as well as economic mechanisms such as taxes and levies targeting suppliers, retailers or consumers. A comprehensive overview of these measures for each considered African country can be found in **Tables from 1 to 4** and discussed in more detail in the following paragraphs.

3.1. Tunisia

Tunisia is a North African country with a population of around 12 million, which is projected to reach 13.4 million by 2040 (Chaabane, 2020; Statista, 2024). In this country 0.25 Mt of plastic waste are generated, of which 0.05 Mt (20 %) is not collected and 0.20 Mt (80 %) is collected for waste treatment (Chaabane et al., 2019). Of the collected waste, 0.15 Mt (60 %) went to landfills, 0.04 Mt (16 %) was openly dumped and only 0.01 Mt (4 %) was recycled. Annually, 8.5 kilotons of plastic end up in the Mediterranean Sea, mainly from post-consumer packaging such as plastic bottles and yogurt cups, which has a

Table 1
Relevant measures proposed or implemented to reduce plastic pollution in Tunisia.

Policy initiatives	Objective	Year
Decree No. 843 (modifying the decree No. 1102 of June 2, 1997)	- Establishment of conditions and modalities for the resumption and management of used packaging bags and materials.	2001
Decree No. 2317	- Establishment of the National Agency for Solid Waste Management agency (ANGeD).	2005
Agreements signed with the union chamber of supermarkets Agreements signed with the union chamber of the union of pharmacists-	- Ban of single-use plastic bags with a thickness <40 μm and plastic bags at the checkout of the shops.	2016 2017
Finance Law	- Elimination of the environmental protection tax that was previously imposed on imported biodegradable plastic raw materials.	2018
Decree No. 32	- Ban of manufacturing, importing, marketing, distributing, and possessing single-use plastic bags with a thickness <40 μm or a capacity of not more than 30 L for the national market.	2020
"Let us be responsible" Tunisian Minister of Environment campaign supported by the UNEP/MAP Regional Activity Centre 'MedWaves'	- Clarification of the objectives of Decree No. 32 (2020) to actively involve citizens in the ambitious effort to eliminate single-use plastic bags.	2022

negative impact on tourism, shipping and fishing (Chaabane, 2019; 2020).

Over the years, Tunisia has actively developed a national solid waste management programme aimed at integrated waste strategies. An important legal milestone was Decree No. 1102 of June 2, 1997, later amended by Decree No. 843 of April 10, 2001 (Table 1), establishing the procedures for the collection and management of used packaging and bags.

Another important step was the establishment of the National Agency for Solid Waste Management (ANGeD) by Decree No. 2317 of August 22, 2005. ANGeD manages and finances a public system called ECO-Lef, which was created in 2001 for the recovery and recycling of post-consumer packaging waste and complies with the provisions of the above-mentioned Decree No. 843 of 2001 (Bünemann et al., 2020). This public waste system is a pioneering organisation for packaging management in Africa, based on a strong legal and institutional framework. Specifically, small licenced collection companies buy the packaging materials from households or informal collectors/waste pickers (known as "*barbechas*") by weight and can resell them to ANGeD at the ECO-Lef collection points. At these centres, the materials are stored, compacted and prepared for sale to local recycling companies or exporters. However, there is no obligation to sell exclusively to ECO-Lef, therefore, collectors may opt for private recyclers who offer better prices (Bünemann et al., 2020; Chaabane, 2020). Depending on the polymer type, 70–90 % of the collected plastic waste is valued. For instance, PET bottles are usually cleaned, crushed and exported mainly to Turkey and occasionally to Vietnam. On the other hand, HDPE caps and opaque bottles are usually processed locally into raw materials (Watkins et al., 2020).

In addition to waste management, Tunisia has taken significant steps to curb plastic pollution by banning and restricting single-use plastics (Table 1). Initial efforts included voluntary agreements with the supermarket union (October 2016) and the pharmacists' union (September 2017), which came into force on March 1, 2017 and 2018 respectively. These agreements aimed to eliminate single-use plastic bags thinner than 40 μm and those handed out at shops checkout. As a result, the consumption of plastic bags in supermarkets, which accounted for about 30 % of total plastic consumption, dropped by 94 % within the first years (2017–2018) (Bünemann et al., 2020).

In 2018, the Ministry of Local Affairs and Environment abolished the environmental protection tax on the import of biodegradable plastic raw materials to reduce production costs for biodegradable bag manufacturers. However, these producers continue to face limitations as they are dependent on imported raw materials such as corn, potatoes and wheat, which poses logistical challenges. To solve this problem, discussions are ongoing with foreign investors to establish local production facilities for plant-based and biodegradable raw materials to improve cost-efficiency and global competitiveness (Watkins et al., 2020).

An important regulatory step was Decree No. 32 of January 16, 2020, which targets plastic pollution by banning all single-use plastic bags with the exception of those ticker than 40 μm with a volume higher than 30 L, bags made of biodegradable material or ultra-light bags for weighing fruit/vegetables (Guerfi, 2020; United Nations Environment Programme (UNEP), 2022). Effective March 1, 2020 for shopping centres and pharmacies, and from January 1, 2021 for all manufacturers, importers, distributors and holders of plastic bags, the decree marks a firm stance against plastic waste (Speakman Cordall, 2020; United Nations Environment Programme (UNEP), 2022; Watkins et al., 2020).

In support of this legislation, a national awareness campaign titled "Let us be responsible" was launched on May 11, 2022 by the Ministry of Environment in collaboration with the UNEP/MAP Regional Activity Centre "MedWaves" specialized in sustainable consumption and production. The campaign aims to clarify the objectives of the Decree No. 32 and to actively involve citizens in the ambitious effort to eliminate single-use plastic bags and promote sustainable alternatives, such as reusable bags (United Nations Environment Programme (UNEP), 2022).

These policy initiatives underline Tunisia's commitment to reducing plastic pollution, especially in ecologically sensitive and tourism-heavy areas. This not only to supports the conservation of biodiversity, but also brings economic benefits. Nevertheless, the production costs for biodegradable and/or bio-based materials in Tunisia are still high compared to conventional plastics (Biopack).

3.2. *Kenya*

Kenya is located in East Africa and has a population of around 52.44 million, which is expected to grow to 57.04 million by 2029 (Statista, 2024). The country also faces major challenges in terms of solid waste, with plastic being the most common type of macro-litter found on the beaches. Food packaging, particularly PET, PP and polyester, accounts for around 10 % of total solid waste of the country. Bottles, lids and dairy packaging contribute significantly to environmental pollution. Despite that, Kenya leads the entire continent in the management of plastic waste, with private recycling efforts dating back to the 1980s (Kosore et al., 2024; Singh et al., 2023).

The first measure against single-use plastic in Kenya was introduced in 2005 (Table 2) with a "10-point plastic waste management strategy" that banned plastic bags thinner than 30 μm (Kiprop, 2020; Niño et al., 2021). However, the plan failed due to limited resources and opposition from plastic manufacturers who feared job losses (Behuria, 2021; Kiprop, 2020; Niño et al., 2021). The National Environment Management Authority (NEMA, www.nema.go.ke/) sided with the manufacturers, fearing economic repercussions (Behuria, 2021).

In 2007, the government tried again to ban plastic bags below 30 μm and introduced a 120 % tax to promote eco-friendly alternatives. However, manufacturers protested again and threatened to pass on the costs to consumers (Behuria, 2021; Kiprop, 2020; Niño et al., 2021). A third attempt in 2011 targeted plastic bags below 60 μm, but faced similar resistance and delayed implementation until 2017 (Behuria, 2021; Niño et al., 2021; Paul & Mironga, 2020).

Significant progress was made in 2015 with the Nairobi City County

Table 2
Relevant measures proposed or implemented to reduce plastic pollution in Kenya.

Policy initiatives	Objective	Year
10-point plastic waste management strategy by government of Kenya	- Ban of the use of thin plastic bags <30 μm.	2005
Government of Kenya ban	- Ban of the use of thin plastic bags <30 μm. - Establishment of a 120 % excise tax on plastic bags <30 μm.	2007
Kenya Bureau of Standards ban and National Environment Management Authority (NEMA) ban	- Ban of the use of plastic bags <60 μm.	2011
The Nairobi City County Solid Waste Management Act	- Establishment of a legal structure for waste management. Classification and organization of waste sub-country collection scheme. - Ban of manufacturing, possession, sale, or distribution of plastic bags with a thickness <30 μm, a size <8 × 12 inches and deviating from prescribed Kenyan colour standards. - Introduction of an environmental levy up to 2 %. - Fines of 300,000 Kenyan Sh (approx. US$ 2783) for non-compliance.	2015
Gazette Notice No. 2334 and No. 2356 (Plastic Bag Ban for Secondary Packaging)	- Ban of single-use plastic bags for retail or household packaging. Exceptions include garbage bin liners, medical waste, construction and food. - Recommendations for alternatives such as plastic-based reusable bags, cotton bags, paper bags, jute bags, canvas bags and 100 % biodegradable bags packaging. - Fines of two to four million Kenyan Sh (approx. US$ 20,000–40,000) and/or imprisonment of one to four years for non-compliance.	2017
National Sustainable Waste Management Bill	- Implementation of systems for used product return, recycling, and reuse applicable to all manufacturers and importers, ensuring broader coverage. - Ban of littering and improper waste disposal. - Fines of 200,000 Kenyan Sh (approx. US$ 1855) and/or one-year imprisonment for non-compliance. - Establishment of reward programmes for reporting littering and encouraging compliance.	2019
Gazette Notice No. 4858 (Ban on Single Use Plastics in Protected Areas or the Wildlife Conservation and Management Act) and Ministry of Tourism and Wildlife	- Ban of single-use plastic use and littering in protected areas. - Implementation of guidelines for the appropriate use of single-use plastics. - Inclusion of plastic-related topics in educational programs. Conducting campaigns to educate the public about the impacts of plastic pollution. - Implementation of increased fees for single-use plastic products. - Fines of two to four million Kenyan Sh (approx. US$ 20,000–40,000) or imprisonment for one to four years for non-compliance.	2019
Kenyan Plastics Pact (KPP)	- Promote financial and innovative support for the smart management of plastic waste within the Kenya borders in order to create a circular economy for plastics, also taking into account the food packaging, by 2030.	2021
Legal notice No. 176 (Sustainable Waste Management (Extended Producer Responsibility) Regulations)	- Establishes mandatory Extended Producer Responsibility (EPR) obligations for producers, importers and brand owners. - Requires the registration of producers, the implementation of product take-back schemes and the establishment of an EPR fund. - Introduces strict penalties for non-compliance and supports a circular economy approach.	2024
Legal notice No. 178 (Environmental Management and Co-ordination (Waste Management) Regulations)	- Establishes regulations for waste disposal, waste transport and recycling. - Introduces strict authorisation requirements for waste transporters and disposal facilities. - Emphasises extended producer responsibility, separation of waste at source and penalties for non-compliance.	2024
Legal notice No. 181 (Environmental Management and Co-ordination (Management and Control of Plastic Packaging Materials) Regulations)	- Controls on plastic packaging by banning the manufacture, import, export, sale and use of plastic bags and film without authorisation. - Mandatory inclusion of at least 30 % recycled content in plastic packaging. - Introduction of annual licencing for manufacturers and importers, requiring an EPR plan. - Strict penalties for non-compliance, including fines and imprisonment. - Establishment of a public register of authorised producers and plastic waste collection and recycling centres.	2024

Sh = shillings.

Solid Waste Management Act, which provided waste classification, set penalties for non-compliance and banned plastic bags under 30 μm, smaller than 8 × 12 inches and in non-standard colours. An environmental levy of 2 % was also introduced to support waste management (Griffin & Karasik, 2022).

A major breakthrough was achieved on February 28, 2017 with Gazette Notices No. 2334 and No. 2356 banning the manufacture, importation and use of plastic carrier bags and flat bags (both without handles and with or without gussets) for commercial and household packaging. Key exemptions include primary packaging, duty-free bags and wrapping film. Alternatives such as reusable non-woven, cotton, jute, canvas, paper and 100 % biodegradable bags were promoted. Violators faced fines up to 4 million KSh (approx. USD 38,835) and/or imprisonment for one to four years, making it the world's strictest plastic bag ban (Griffin & Karasik, 2022; Omondi & Asari, 2021).

To strengthen enforcement, the 2019 National Sustainable Waste Management Bill placed responsibility for waste management on all levels of government, the private sector and citizens. It mandated the closure of uncontrolled landfill and promoted recycling markets. It also introduces deposit-refund systems for packaging products, prohibits littering and irresponsible waste disposal with corresponding fines and imprisonment (Griffin & Karasik, 2022).

Table 3
Relevant measures proposed or implemented to reduce plastic pollution in Uganda.

Policy initiatives	Objective	Year
Government of Uganda ban	- Ban of the production and use of polyethylene carrier bags called "*kaveera*" (single-use plastic).	2007
Finance Act and Finance (Permitted Plastic Bags and Other Plastics for Exceptional Use) Regulations	- Ban of the import, local production, sale and use of plastic bags <30 μm. - Ban of the import, local manufacture, sale and use of bags and sacks made of ethylene and polyethylene polymers. - Proposal for a 120 % excise duty tax on all plastic products.	2009 and 2010
National Environment Management Authority (NEMA) of Uganda	- Enforce the ban on the production and use of polyethylene bags.	2015
Government of Uganda ban	- Ban of plastic bags, ordering 45 plastic manufacturers to stop the manufacture, distribution, sale and use of plastics.	2018
National Environment Act	- Ban of the import, export, local production, use and reuse of certain categories of plastics. Abolition of single-use bags <30 μm and obligation for producers of polythene bags to recycle plastic waste and label the bags. - Fines of 10 million Sh (approx. US$ 2850) for non-compliance. - Introduction of Extended Producer Responsibility (EPR) in line with the "polluter pays" principle, which requires product manufacturers to control the life cycle of their products.	2019

Sh = shillings.

In the same year, former Kenyan President Uhuru Kenyatta announced a ban on the use and littering of single-use plastic products in protected areas such as forests, beaches, national parks, national reserves and all other designated wildlife areas. This ban came into effect in June 2020, known as the ban on Single Use Plastics in Protected Areas or the Wildlife Conservation and Management Act. The ban extended the 2017 plastic bag restrictions to other items such as cutlery, straws, plates, food containers and packaging made from LDPE, PS, EPS, PP, PET and HDPE. The action plan included the integration of plastic education into school curricula, the implementation of awareness campaigns and the introduction of economic incentives such as higher fees on single-use products. Guidelines were also issued to improve plastic disposal practices (Gazette Notice No. 4858, 2019; Ministry of Tourism and Wildlife, 2020).

In 2021, Kenya launched the Kenyan Plastics Pact (KPP) (https://kpp.or.ke/) to promote a circular economy. Its goals include eliminating problematic plastics, ensuring recyclability, achieving a 40 % recycling rate and using 15 % recycled content in packaging by 2030. These multi-faceted efforts include a range of measures, including workshops, awareness campaigns and similar activities involving key stakeholders, notably the Kenya PET Recycling Company (PETCO), the Nairobi Waste Collectors Association and the Kenya Extended Producer Responsibility Organisation (KEPRO) founded in 2021 by the Kenya Association of Manufacturers (KAM) (Singh et al., 2023). The Extended Producer Responsibility (EPR), first formulated by the Swedish Ministry of the Environment in the 1990s, promotes the improvement of the environmental performance of product systems throughout their life cycle by extending the product manufacturer's responsibility to the take-back, recycling and final disposal of the product and by promoting waste reduction, resource recovery and eco-design (Diggle et al., 2023).

More recently, in 2024, Kenya introduced three important regulations: the Sustainable Waste Management (Extended Producer Responsibility) Regulations, the Environmental Management and Co-ordination (Waste Management) Regulations and the Environmental Management and Co-ordination (Management and Control of Plastic Packaging Materials) Regulations (Legal Notice 176, 2024, Legal Notice 178, 2024; Legal Notice 181, 2024). The first set of regulations gives manufacturers, importers and brand owners more responsibility for the entire life cycle of their products, including collection, recycling and disposal. It requires registration, compliance with EPR, take-back programmes and contributions to an EPR fund and provides for penalties for non-compliance. The second regulations introduce a comprehensive framework for waste disposal, transport and recycling. These regulations emphasise EPR, waste separation at source and strict licencing requirements for waste transporters and disposal facilities. The third regulations focus on reducing plastic waste and promoting sustainable packaging by banning the unauthorised production and trade of plastic bags and mandating a 30 % recycled content in plastic packaging. Annual licences for manufacturers and strict enforcement through fines and imprisonment are introduced. Moreover, a public register ensures transparency with regard to licenced manufacturers and recycling centres.

As a result of these efforts, Kenya has seen a significant decrease in the use of plastic bags and a remarkable tripling of the use of reusable bags. More than two-thirds of Kenyans now support the transition to sustainable alternatives (Singh et al., 2023). Although Kenya's efforts to ban single-use plastics have had some success, it is still essential to increase vigilance and rigorously enforce regulations to combat illegal plastic imports and trade (Griffin & Karasik, 2022).

3.3. Uganda

Uganda is the fourth largest country in the East African, with a population of approximately 46.85 million, projected to reach 55.90 million by 2029 (Statista, 2024). The country generates an estimated 600 metric tons of plastic waste daily. A significant proportion of this waste remains uncollected, estimates show that Kampala Capital City Authority spends USD 1.5 million per month to remove only 30 % of the total waste generated, leading to numerous environmental and health problems (Wandeka et al., 2022). Recyclable materials, including plastics, are often collected by the informal sector, where itinerant buyers purchase waste from households. Overall, inadequate collection rates, suboptimal plastic waste disposal practises, the proliferation of poverty and the prevalence of informal recycling processes pose an urgent threat to Uganda's environment and society (Singh et al., 2023).

In 2007 (Table 3), the Ugandan government announced a ban on the production and use of polyethylene bags, known locally as "*kaveera*" (single-use plastics) (Behuria, 2021). However, similar to Kenya scenario, plastic bag manufacturers protested and continued to produce and distribute plastic bags. Parliament later passed the 2009 Finance Act and, in 2010, the Finance (Permitted Plastic Bags and Other Plastics for Exceptional Use) Regulations, banning the import, production, sale and use of plastic bags under 30 μm and proposing a 120 % excise duty on all plastic products. These measures also encountered strong opposition from large corporations, traders and industry groups (Behuria, 2021; Singh et al., 2023).

In April 2015, the National Environment Management Authority of Uganda (NEMA, www.nema.go.ug) attempted again to enforce the ban, but with limited success (Singh et al., 2023). In the following years, NEMA intensified enforcement by inspecting shops, closing factories and impounding plastic products. In June 2018, a decision was again taken by the Ugandan government to implement a ban on plastic bags, ordering 45 plastic manufacturers to stop the manufacture, distribution, sale and use of plastics (Behuria, 2021).

A major step came in 2019 with the National Environment Act, which imposed a comprehensive ban on the import, export, manufacture, use or reuse of certain types of plastic. Specifically, it prohibits single-use carrier bags under 30 μm and confirms NEMA's role as regulatory body in Uganda, charged with the responsibility of coordinating, monitoring, regulating and supervising environmental management (Behuria, 2021). In parallel, Uganda has introduced the principle of EPR as part of the polluter pays principle. This legal framework outlines the responsibilities of stakeholders like the Office of the Prime Minister, Uganda National Bureau of Standards (UNBS), Uganda Revenue Authority and NEMA. Plastic manufacturers are now required to establish recycling facilities and track the full life cycle of their plastic products (Singh et al., 2023).

Although regulations exist, enforcement remains inconsistent and plastic bags are still commonly used. This dilemma is further underscored by the government's lack of options and viable alternatives for plastic bags, which further exacerbates the major problem of plastic pollution in the country. Nonetheless, NEMA and UNBS continue conducting inspections and certifying production facilities, while educating producers on compliance. In the education sector, a complete ban on plastic bags is enforced, with initiatives like Education for Sustainable Development (ESD), Environmental Education Programmes for Schools (SEEP), UNESCO's Associated Schools Network (ASPnet) and others raising awareness and building environmental knowledge (Singh et al., 2023).

Despite having established policies, legal frameworks and institutional mechanisms to address plastic pollution, Uganda faces challenges in translating these measures into effective implementation. To effectively tackle current and future plastic pollution challenges in Uganda, comprehensive awareness campaigns and community education are imperative to foster an understanding of the environmental risks associated with plastic waste (Singh et al., 2023).

3.4. Tanzania

Tanzania, another large African country with a population of around 65.23 million, is expected to grow to 75.55 million by 2029 (Statista, 2024). Like many other African countries, Tanzania has joined continent-wide efforts to tackle plastic pollution and introduced a ban on plastic bags. It is one of over 30 African nations (including Kenya, Uganda, Tunisia, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Congo-Brazzaville, the Democratic Republic of Congo, Côte d'Ivoire, Djibouti, Eritrea, Ethiopia, Gambia, Gabon, Guinea-Bissau, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Niger, Nigeria, Rwanda, Senegal, Seychelles, South Africa, Togo, Zambia and Zimbabwe) which have adopted similar policies to address plastic pollution (Buchholz). Despite this commitment, plastic pollution remains a significant issue in Tanzania. The country has a solid waste collection rate of about 40 % and a recycling rate of only 10 %. Household waste accounts for 75 % of total waste and the use of plastic packaging by local businesses is increasing. Common packaging materials include PET, PE, PP and polystyrene. Plastics contribute approximately 7 % of total municipal solid waste (Paruta et al., 2021).

The first ban in Tanzania was issued by the government of Zanzibar, a semi-autonomous island. The ban came into force in 2006 (Table 4) for plastic bags with a thickness of less than 30 μm. Building on this, the Tanzanian government initially decided to ban plastic bags in 2006, but this was postponed due to enforcement issues (Bezerra et al., 2021).

A more targeted effort was taken several years later on February 24, 2017 with Government Notice No. 76, which banned the production, import and use of plastic bags for packaging alcoholic beverages, regardless of their thickness. It also prohibited licensing any entity intending to manufacture or import these bags. Violations of the law could result in fines, imprisonment, confiscation or deportation (Bezerra et al., 2021).

Table 4
Relevant measures proposed or implemented to reduce plastic pollution in the United Republic of Tanzania.

Policy initiatives	Objective	Year
Government of Zanzibar ban	- Ban of the import, production and use of plastic bags <30 μm. - Promotion of biodegradable materials for shopping.	2006
Government Notice No. 76 (Environmental Management (Prohibition of Manufacture, Importation and Use of Plastic Sachets for Packaging Distilled & other Alcoholic Beverages) Regulations)	- Ban of the manufacture, import and use of plastic sachets for alcoholic beverages, regardless of their thickness. - Ban of the registration or granting of licences for the manufacture or importation of plastic sachets. - Penalties for non-compliance, including fines, imprisonment, repatriation, confiscation and disposal.	2017
Government Notice No. 394 (Environmental Management (Prohibition of Plastic Carrier Bags) Regulations)	- Ban of plastic carrier bags (with and without handles and regardless of their thickness), including import, export, manufacture, sale, storage, delivery and use. - Exemptions for certain sectors such as medical services, industrial products, construction, agriculture, food, sanitation and waste management. - Obligation for suppliers of products in plastic bottles to establish or participate in a take-back system for recycling. - Penalties for non-compliance, which vary depending on the role of the offender (e.g., production, storage, sale, etc.).	2019
Government Notice No. 291 (Environmental Management (Prohibition of Plastic Carrier Bags and Plastic Bottle Cap Seals) Regulations)	- Ban of all plastic carrier bags regardless of their thickness. - Ban of the import, export, manufacture, storage, distribution, supply, sale or offering beverages with plastic bottle cap seals. - Ban of the sale or offer of beverages or commodities wrapped in plastic without necessity. - Penalties for non-compliance, including fines between 30,000–1 billion Sh (approx. US$ 12–400,000) or/and imprisonment between seven days and two years.	2022

Sh = shillings.

The most important step came on May 17, 2019 with the adoption of new environmental regulations published under Government Notice No. 394, known as the "plastic carrier bag ban". The law came into force on June 1, 2019 and applies to the use, sale, manufacture, import, storage and export of plastic carrier bags by individuals (citizens and non-citizens in Tanzania mainland), businesses and industry. It covers all plastic bags made of film, with or without handles, regardless of their thickness. Exemptions are granted for plastic packaging used in sectors such as medical services, construction, agriculture, food processing, sanitation and industrial production, provided they meet the quality standards set by the Tanzania Bureau of Standards (Bachuba, 2019). The law also stipulates that supplier of products in plastic bottles must set up or participate in a take-back system for the recycling of used plastic bottles. This service must be offered at no additional cost to the consumer. Violations of this regulation attract significant penalties. Manufacturers or importers face fines of between 20 million and 1 billion Tanzanian shillings (TSh) (approx. USD 8000–400,000) and up to two years in prison. Exporters can be fined between 5 million and 20 million TSh, while offences relating to the supply, storage or distribution of plastic bags are punishable by fines of between 5 million and 50 million TSh and/or up to two years in prison (Bachuba, 2019). These strict regulatory measures have led to a significant reduction in the use of plastic bags, which are a major contributor to littering in urban and rural areas. However, plastic pollution remains a broader problem that requires more attention than just single-use bags.

On May 6, 2022, Tanzania issued Government Notice No. 291 to extend the existing regulations. This legislation bans not only plastic carrier bags but also plastic bottle cap seals. The new regulations cover the import, export, manufacture, sale and use of plastic bags and bottle cap seals, regardless of their thickness. One of the aims is to reduce the negative impact of plastic on human and animal health as well as on the environment. The regulations also aim to create economic incentives that promote the production and import of sustainable alternatives to plastic carrier bags (Government Notice No. 291, 2022).

While these measures demonstrate the local government's commitment to curbing the proliferation of certain single-use plastic items, they are only a first step towards the ultimate goal. However, to seriously address the problem of excessive production, importation and proliferation of single-use plastic items in Tanzania, different actions are essential. Such interventions require a deep focus on the origins of the problem, especially the manufacturers and producers of single-use plastic items (Nipe Fagio, 2021).

4. New trends in food packaging materials in the studied African countries

In recent years, interest in the use of biopolymeric materials or bioplastics in food packaging has increased significantly worldwide as one of the proposed strategies to curb plastic pollution. However, it must be emphasised that the generic term "bioplastics" includes bio-based (fully or partially derived from biological matter), biodegradable (capable of being broken down by microorganisms into water, carbon dioxide and biomass, but only under specific conditions) or both, depending on the chemical composition and the external environment required for disposal (Ammendolia & Walker, 2024; European Bioplastics, 2025). This means that not all bioplastics are truly biodegradable, and some of them may contain varying degrees of petroleum-based plastics, contributing to microplastics and plastic pollution.

Given this complexity, bioplastics need to be clearly defined and carefully regulated, particularly under the ongoing Global Plastics Treaty. This international legal agreement, adopted by the United Nations Environment Assembly (UNEA), addresses the entire life cycle of plastics, including production, design and disposal, with the main goal of reducing global plastic pollution (Ammendolia & Walker, 2024; Walker & Fequet, 2023). Although the simple substitution of conventional fossil-based plastics with these alternative materials may not be completely sustainable without specific international regulations and a cradle-to-grave life cycle assessment, the acceptance of bioplastics is gradually increasing. However, these materials currently account for less than 1 % of the over 400 Mt of plastic produced globally each year (Ammendolia & Walker, 2024). In Africa, interest towards bio-based materials is particularly high in countries where governments have introduced bans on fossil-based and single-use plastics (Sapuan & Ilyas, 2021), and over the past decade, African researchers have made remarkable progress in exploring sustainable solutions for food packaging.

The most relevant research studies on bio-based packaging carried out in Tunisia, Kenia, Uganda and Tanzania were here reviewed, through a systematic search conducted in the Scopus database, covering all research published up to January 2025. The search terms "bio-based and packaging", "sustainable and packaging", "bio-based and materials" and "food and packaging" were applied to the "Title, Abstract, and Keyword" field and combined with country-specific filters in the "Affiliation" field, to ensure both contextual relevance and geographical precision. From the initial results, duplicate records were identified and removed, resulting in approximately 300 articles. These were then manually screened, resulting in the selection of 43 relevant studies which used local biomass resources to develop and improve bio-based packaging materials.

The resulted findings show that researchers from Tunisia (n. 33 articles), Kenya (n. 4 articles) and Uganda (n. 6 articles) have been working on sustainable, versatile and high-performance packaging solutions using local raw materials, by-products and waste. Although no specific studies on bio-based packaging were found in Tanzania, the approaches explored in the other three countries, especially in East Africa, could also be relevant there. A summary of the bio-based packaging materials developed in these studies, with their main performance characteristics and key findings, is presented in Table 5 and discussed in the following sections.

4.1. Cassava-based

One important area of research is cassava-based packaging, which takes advantage of the abundance of this tuber in several African countries. Cassava is highly valued for its remarkable resilience and adaptability to poor soils (Tumwesigye, Oliveira, & Sousa-Gallagher, 2016). This root crop proves its versatility with numerous applications ranging from staple food to industrial products thanks to its high starch content, which also makes it a valuable resource for bio-based packaging materials (Panghal et al., 2019). Several studies in Uganda and one in Kenya have investigated the use of cassava, mainly the bitter type, for packaging material development with remarkable results.

In their first work, Tumwesigye, Oliveira, & Sousa-Gallagher (2016) developed a novel simultaneous release, recovery and cyanogenesis (SRRC) process to utilize the entire bitter cassava tuber (*Tongolo* var.) for packaging film production. Using cassava biopolymer derivatives (3 % w/v) and glycerol (30 % w/w), a film was obtained by casting. The SRRC process significantly increased the yield, reduced the waste and cyanogen levels to a safe threshold (<1.0 ppm). The resulting material had improved properties compared to peeled bitter cassava and commercially available polylactic acid (PLA) biopolymers, but its strength was lower than that of commercially available NatureFlex (NVS) and oriented polypropylene (OPP) films (Tumwesigye, Oliveira, & Sousa-Gallagher, 2016).

Subsequent optimization of the SRRC method (Tumwesigye, Peddapatla, et al., 2016) examined different biopolymers extraction conditions, including cassava waste solids (15–30 % w/w), buffer concentrations (0–4 % v/v) and extraction times (4–10 min). Optimized conditions (23–30 % w/w waste solids, 4 % v/v ionic buffer, 10 min) yielded about 40 %, surpassing the 17–26 % yield from commercial sweet cassava methods. Analytical techniques (SEM, DSC, TGA, FTIR) confirmed uniform microstructure, high thermal stability and strong barrier properties of the biopolymer derivates and obtained film (3 % w/v biopolymers in 30 % w/w of glycerol), demonstrating efficiency and sustainability.

Further research analysed the mass transport phenomena of the above bio-based film developed to assess its suitability for food packaging (Tumwesigye, Oliveira, & Sousa-Gallagher, 2017). Permeability tests under varying RH and temperature conditions revealed a wide pore size distribution and different mass transfer mechanisms, suggesting potential for various packaging applications. However, careful validation under specific environmental conditions was recommended to maintain film integrity.

Building on these findings, Tumwesigye, Sousa, et al. (2017) investigated the suitability of intact bitter cassava-based film for equilibrium modified atmosphere packaging (EMAP) of cherry tomatoes stored at 10–20 °C and 75–95 % RH. Specifically, tomatoes were packaged in polypropylene trays sealed with continuous or microperforated cassava film and compared to a non-bio-based OPP film. Compared to the non-bio-based OPP film, the cassava film achieved better oxygen equilibrium (reached in 180 h) and extended the shelf-life effectively. No significant difference in O_2 equilibrium was found between continuous and microperforated films, indicating that perforation was unnecessary. More recently, Maitha and co-authors (2024) investigated cassava-based biofilms using starch extracted from cassava tubers purchased in Nairobi, Kenya, plasticized with local coconut oil. The films, composed of 80 % starch, 10 % glycerol and 10 % coconut oil, were produced by casting in various thicknesses (150 vs 200 μm). Functional tests showed that thickness influenced water vapour permeability. Biodegradability tests confirmed significant degradation in soil after 120 days, highlighting the potential of cassava starch and coconut oil-based films for sustainable local food packaging, particularly for dry foods.

4.2. Other plant and industry waste/by-products-based

In addition to cassava tubers, other products, by-products and waste from agriculture and the food industry have also been explored for bio-based food packaging. Several studies in Tunisia, Kenya and Uganda have analysed various natural resources for these applications.

One such material is the mucilage obtained from cactus. Gheribi et al. (2019) developed polyvinyl alcohol (PVA, 4 % w/w) films reinforced with mucilage (4 % w/w) from *Opuntia ficus-indica* cladodes harvested in Mnihla (Tunisia) (80:20 ratio) and PEG 200 (30 % w/w) that exhibited optimal tensile strength, elongation and water resistance. Similarly, Mannai et al. (2023) incorporated *O. ficus-indica* mucilage collected in El-Guettar (Tunisia) into styrene-butadiene rubber latex (SBL) films using a casting method. The addition of cactus mucilage resulted in flexible and hydrophobic films with improved water barrier properties.

Another promising approach is the use of date palm-derived biopolymers. Kharrat et al. (2020) developed PLA-based films, produced by film blowing extrusion, containing leaves of *Phoenix dactylifera* L. collected in southern Tunisia. The use of 1 % (w/w) leaf extract as a filler improved the tensile properties of the film, but higher concentrations reduced the crystallinity. Complementary research by Khwaldia et al. (2023) developed alginate-based films (3 % w/v) activated with date palm pits extract (DPPE) from a local date processing industry in Tozeur, Tunisia (0–40 % w/w), which improved water barrier properties, tensile strength and elongation at break. The optimized film (10 % DPPE) showed the best performance, while 20 % DPPE maintained antioxidant activity for three months, making these films particularly effective for the preservation of lipid-rich foods such as nuts and seeds.

Raw materials derived from olives have also been investigated to improve bio-based packaging films. Grabska-Zielińska et al. (2021) added poly(ethylene glycol) (5 % w/w) and olive leaf extract (1–5 % w/w) from *Chemlali* var. olives harvested in Sfax City (Tunisia) to PLA film, improving antioxidant properties while maintaining good water vapour permeability for food packaging. Similarly, Taktak et al. (2023) incorporated olive wood flour (OWF, 0–10 % w/w) from olive wood waste collected from Tunisian producers into PLA. FTIR spectroscopy confirmed the interactions between the OWF cellulose and the PLA matrix, and the films with 1 % OWF showed the best dispersion, thermal stability and tensile strength.

Biopolymers derived from algae and seaweed have also shown promising results. The recent study by Madivoli et al. (2025) combined carrageenan (4 %) from the alga *Eucheuma denticulatam* with starch (1–50 % w/w) to produce flexible, bio-based, biodegradable and edible films by casting, demonstrating the possibility of obtaining different material properties to meet tailored functionalities for edible food packaging. In parallel, Oualha et al. (2019) investigated flame-retardant EVA composite films with magnesium hydroxide nanoparticles derived from seawater (Seaw-Mg$(OH)_2$) from Marsa Beach (Tunisia), and calcium hydroxide nanoparticles from chicken eggshells (Ceg-Ca$(OH)_2$. The partial substitution of magnesium hydroxide with calcium hydroxide has significantly improved the flame-retardant properties, making them suitable for packaging applications that require increased heat resistance.

Another analysed by-product/waste product from the food industry was tomato pomace from a tomato processing company in Sidi Thabet, Tunisia. In detail, Aloui et al. (2019) developed sodium caseinate composite films with lipid fractions from tomato pomace (10–40 % w/w), which improved flexibility, thermal stability and antioxidant properties. However, the mechanical resistance and stiffness could be further improved with bio-based nanofillers or crosslinking agents to utilize this formulation as a stand-alone film packaging material.

In addition, gum Arabic coatings were tested for the preservation of fresh fruit. Daisy et al. (2020) found that gum Arabic extracted from *Acacia senegal* var. *kerensis* (Isiolo County, Kenya) reduced weight loss and slowed the ripening of mangoes, extending the shelf-life from 10 to 15 days. Citrus waste in the form of peels of *Citrus aurantium* (bitter orange) harvested in Bir Marwah, Nabeul (north-east Tunisia) was also evaluated for the production of an active packaging film (Djebbi et al., 2023). The *C. aurantium* peel pectin-based film activated with *C. aurantium* peel essential oil (3 mL) and emulsified with Tween 80 (1:0.8 v/v) showed significant fumigant activity against *Rhyzopertha dominica*, highlighting their potential for insect-repellent food packaging.

Other bio-based materials investigated include agave leaf fibres, rice husks, clay fibres, maize straw and sugarcane bagasse. Turki et al. (2023) impregnated agave fibre films from Tunisian agave leaves with thymol (2–10 % w/w) or clove oil (2.5–10 % w/w) and produced antibacterial films that were effective against *S. aureus* and *E. coli*. Yiga et al. (2023) formulated PLA composites reinforced with rice husk from Tororo and clay from Kaolin Buwambo (Uganda) and improved thermal stability and thermodynamic properties. Nyerere et al. (2024) developed another bioplastic film for food packaging from maize straw cellulose collected from Busitema village (Busia district, Uganda) and sugarcane bagasse fibres from a sugar company in Bugiri district (Uganda). The film with a 75:25 cellulose to fibre ratio had the best mechanical and barrier properties, including low moisture content, low water absorption, low water vapour permeability, high tensile strength and high biodegradability in soil.

Lastly, Madivoli et al. (2024) produced smart PVA/lactic acid (1:1 w/w) films with anthocyanins extracted from *Brassica oleracea* var. *capitata* (red cabbage from Kenya), which have antimicrobial properties (against *E. coli*, *S. aureus*, *S. epidermidis*, *P. aeruginosa*), good hydrophilic properties and colour changes indicating food freshness when used as packaging for meat under ambient conditions.

4.3. Chitosan-based

Chitosan, a versatile biopolymer usually extracted from crustacean shells or fungi and obtained from chitin by deacetylation, has proven to be a promising material for bio-based packaging due to its strong film formation and flexibility, excellent barrier properties and antimicrobial activity. Several Tunisian studies have utilized locally sourced chitosan for bio-based food packaging solutions, promoting the sustainability and economic growth of marine litter.

One of the first studies in Tunisia about this field investigated chitosan-PVA blended films (Hajji et al., 2016). Solutions of chitosan (2 % w/v in 2 % v/v acetic acid) and PVA (2 % w/v) were blended in different ratios (30:70, 50:50, 70:30; Ch/PVA). These blends showed improved tensile strength, elongation and antioxidant activity compared to pure chitosan or PVA, making them suitable for various applications. Hajji et al. (2017) extended the above formulation by incorporating silver nanoparticles (AgNPs) (0.02 M) into chitosan-PVA films (1:1 w/w ratio) at different concentrations (0.1, 1, 5 mL). The films showed improved antimicrobial properties against Gram-positive and Gram-negative bacteria, making them a promising antioxidant and antibacterial food packaging material. Similarly, Balti et al. (2017) formulated chitosan-based films derived from crab shells (*Maja crispata*) using 2 % chitosan (in 1 % acetic acid). Spirulina extract (2.5–20 %) was also added, which improved mechanical and barrier properties, increases antioxidant activity and has an antibacterial effect, making these films suitable for active food packaging.

Further innovations were explored by Hamdi et al. (2019), who incorporated carotenoproteins extract (CPE) into chitosan-based films. Both CPE and chitosan were extracted from the blue crab (*Portunus segnis*). Films were prepared by mixing 2 % chitosan (in 0.15 M acetic acid) with different CPE fractions (5–50 % w/w, based on chitosan weight). These films exhibited improved UV protection and thermal stability, although higher CPE concentrations reduced transparency (good for protecting food from light). Hamdi et al. (2020) have further modified chitosan-based films by Maillard reactions (MR) to improve their functionalities. Film-forming solutions (2 % chitosan in 0.15 M acetic acid) were mixed with sugars (0.5–2 % w/w) and heat-treated at 90 °C and 30 % RH for 24 h to induce MR. MR were most pronounced with arabinose and xylose, resulting in improved mechanical properties, UV and water barrier properties and antioxidant activity, making these films suitable for active food packaging. A shift towards plant-based bioactive additives was also observed in Moalla et al. (2021), where chitosan films (2 % in 1 % acetic acid) were enriched with a hydroalcoholic extract, aqueous and essential oil extracts from *Artemisia campestris*, an aromatic herb widely used in North Africa. These bioactive films showed promising physical and mechanical properties for alternative food packaging, although further permeability studies are required.

More recent studies have continued along this path by including marine-derived bioactive compounds. Azaza et al. (2023) developed composite films using chitosan from the blue crab (*P. segnis*) and collagenous proteins (BTCP) from bluefin tuna by-products, both sourced from fisheries in Sfax City, Tunisia. The films were prepared by dissolving chitosan in 2 % aqueous acetic acid and BTCP in 2 % aqueous solution. The 90 % chitosan-10 % BTCP ratio showed the best balance between mechanical stability, antioxidant activity and barrier properties. As an edible coating, the chitosan-BTCP solution effectively preserved shrimp during refrigerated storage by reducing bacterial growth and lipid oxidation. Beji et al. (2023) additionally expanded the application possibilities of chitosan by developing a ternary composite packaging material containing commercial cellulose (Cel) and aluminium chloride ($AlCl_3$). Chitosan/Cel films were prepared by mixing cellulose (0.1 g in 15 mL of water) and chitosan (0.5 g in 20 mL of 5 % acetic acid). The ternary composite was prepared by adding 0.1 % $AlCl_3$ at concentrations of 2–20 % w/w of chitosan. These films showed improved hydrophilicity, antimicrobial activity (against Gram-positive and Gram-negative bacteria) and UVA/UVB protection, making them suitable for active food packaging.

Fakraoui et al. (2023) developed another nanocomposite material of chitosan/PVA (1:4 v/v) mixed with cellulose nanocrystals (CNC) or cellulose nanofibrils (CNF) (1–5 % w/w). CNC reduced elasticity and tensile strength, while CNF improved them. They found that CS/PVA/CNF 5 % films had the best mechanical properties and biodegraded over 70 % within 30 days, making them ideal for sustainable packaging. Recently, the same authors developed bio-based and biodegradable food packaging films containing lemon peel powder (LP) in a PVA/chitosan matrix (20 % w/v:1 % w/v in 1 % citric acid). The mixed solution (4:1 v/v PVA/CS) was combined with LP powder (1–5 % w/w) and the films were obtained by casting. The films showed improved mechanical strength, thermal stability and biodegradability. LP addition reduced UV–Vis transparency, moisture content and swelling. In tests with cherry tomatoes, the films reduced weight loss and inhibited microbial growth, demonstrating their potential as a sustainable packaging material (Fakraoui et al., 2024).

4.4. Gelatin-based

The potential of gelatin as a biopolymer for bio-based food packaging materials has also gained interest in recent years. In Tunisia, numerous studies have focused on the improvement of gelatin-based films with natural additives (e.g., proteins, polysaccharides, peptides, vine leaves, agar, beetroot peel, pectin, date pits, chamomile) and treatments such as Maillard reactions and ultrasound to improve their functionality and packaging application.

Abdelhedi et al. (2018) developed films from the smooth-hound (*Mustelus mustelus*, Tunisia) viscera waste. Two formulations were tested: blended films (BL-F) combining bovine gelatin (2 % w/v) with smooth-hound gel (6 % w/v) and bilayer films (BI-F) in which a bovine gelatin layer was cast and dried before a smooth-hound gel layer was added. BL-F showed higher tensile strength and lower water vapour permeability, while BI-F showed better elongation. Sulfated polysaccharides (SP) or peptides (SHP) (1 mg/mL) were also tested and improved the antioxidant activity and hydrophobicity of both films. Further improved the mechanical properties of gelatin-based films (4 % w/v) by Maillard reactions (MR) with glucose at different glucose/lysine ratios (Kchaou et al., 2018). The most efficient glucose/lysine molar ratio was found to be 0.5/1.0 and the heat treatment (90 °C, 24 h) at a pH of 5.5 enhanced the tensile strength, elongation, thermal stability, UV resistance and antioxidant activity of the films, making them suitable for edible packaging. The integration of bioactive compounds by developing bioactive edible films (blended or bilayer) using gelatin (3 % w/v), extracted from grey triggerfish (*Balistes capriscus*, Tunisia) skin and agar (3 % w/v) in combination with an ethanolic extract of vine leaves (VLE) (5 or 10 mg/mL) from Sfax City (Tunisia) was also studied (Jridi et al., 2019). The film activated with 10 mg/mL VLE had the strongest antioxidant properties. SEM confirmed the agar-gelatin compatibility, making this film suitable as an active packaging material.

The reinforcement of gelatin films with nanocomposites was researched by Boughriba et al. (2020). They developed nanocomposite films using gelatin (4 g/100 mL) from *Rhinobatos cemiculus* skin and titanium dioxide-silver nanoparticles (1–4 % w/w). These nanoparticles increased the film rigidity, thermal stability and antioxidant activity, but reduced the elongation at break. Jridi et al. (2020) extended these findings by mixing gelatin from grey triggerfish (*Balistes capriscus*) skin with blood orange peel pectin (Beja, Tunisia) in a 50:50 ratio. The film showed improved mechanical strength, antioxidant and antibacterial activity. In addition, the films significantly improved microbial stability and physico-chemical properties when used as a cheese wrap.

The effectiveness of polymer blends was further researched by Salem et al. (2021). They investigated agar-gelatin from smooth-hound skin blends (3 % w/v each) in a ratio of 75:25 and 50:50 (v/v). Sonicated (24 kHz, 10 min) and untreated films were compared. The addition of agar improved the water barrier properties and rigidity of the blended films. In contrast, ultrasonic treatment had less effect on these properties (mechanical and colour), suggesting that the addition of agar alone is sufficient to achieve the desired improvements. The study by Chaari et al. (2022) incorporated beetroot (*Beta vulgaris* L.) peel extract (0.25–1 %) into gelatin-sodium alginate films, which resulted in improved mechanical, antioxidant and antibacterial properties. Applied to beef stored at 4 °C for 14 days, these films delayed spoilage and oxidation, effectively preserving the quality of the meat and extending its shelf-life.

In a recent study, Elhadef et al. (2024) added date pit extract (DPE, 0.37–1.5 % w/w) to gelatin-sodium alginate films. The addition of DPE improved the physical, optical, antioxidant and antibacterial properties of the films. These films with 1.5 % DPE preserved minced beef at 4 °C for 14 days, highlighting their potential to improve the safety and quality of meat. Salem et al. (2024) developed active coatings using gelatin from smooth-hound fish skin (Sfax City, Tunisia) enriched with garden cress seed extract (GCSE, 0.67 mg/g gelatin) from Gabes (Tunisia). The enriched gelatin-based coatings reduced microbial spoilage and lipid oxidation in fish fillets stored at 4 °C. Quinic acid, the

Table 5
Summary of the results of research studies on the development of bio-based packaging materials carried out in Tunisia, Kenya and Uganda.

Ingredients/Production method	Standard/Edible/ Active/Smart	Mechanical properties TS (MPa)/E (%)/YM (MPa)	Barrier properties at water vapour (WVP/WVTR) and oxygen (OP/OTR)	Key findings	Country/Reference
Cassava-based					
- Intact bitter cassava derivatives (3 %) and glycerol (30 %) - Casting	- Standard	- TS = 41.1 - E = 17.4 - YM = 200.0	- WVTR (38 °C - 96 % RH) = 438.6 $g \cdot m^{-2} \cdot day^{-1}$ - OTR (23 °C - 50 % RH) = 812.9 $cm^3 \cdot m^{-2} \cdot day^{-1}$	Promising film for food and non-food applications, with good mechanical properties, high WVTR, moderate OTR, good transparency, thermal stability and sealability.	- Uganda - Tumwesigye et al. (2016a)
- Intact bitter cassava derivatives (3 %) and glycerol (30 %) - Casting	- Standard	n.r.	n.r.	Promising film for food and non-food applications, with a uniform microstructure and high thermal stability.	- Uganda - Tumwesigye et al. (2016b)
- Intact bitter cassava derivatives (3 %) and glycerol (30 %) - Casting	- Standard	n.r.	- WVP (10 °C - 85 % RH) = 3.5* $g \cdot mm \cdot m^{-2} \cdot day^{-1} \cdot kPa^{-1}$ - WVP (30 °C - 85 % RH) = 4.2* $g \cdot mm \cdot m^{-2} \cdot day^{-1} \cdot kPa^{-1}$ - OP (10 °C - 75 % RH) = 7.6 $\times 10^{-5} \cdot cm^3$ $cm \cdot cm^{-2} \cdot s^{-1} \cdot cmHg^{-1}$ - OP (40 °C - 75 % RH) = 2.0 $\times 10^{-5}$ $cm^3 \cdot cm \cdot cm^{-2} \cdot s^{-1} \cdot cmHg^{-1}$	Promising film for food and non-food applications, with good transparency, self-sealing capacity and thermal stability.	- Uganda - Tumwesigye et al. (2017a)
- Intact bitter cassava derivatives (3 %) and glycerol (30 %) - Casting	- Standard	n.r.	- WVTR (n.r.) = 438.6 $g \cdot m^{-2} \cdot day^{-1}$ - OTR (23 °C - 54 % RH) = 812.9 $cm^3 \cdot m^{-2} \cdot day^{-1}$	Suitable film for fresh cherry tomatoes (and possibly other high-respiring products) under equilibrium modified atmosphere packaging (EMAP), maintaining good quality for 15–19 days at 10 °C.	- Uganda - Tumwesigye et al. (2017b)
- Cassava starch (4 %), coconut oil (0.5 %) and glycerol (0.5 %) and water (95 %) - Casting	- Standard	- TS = 17.9 - E = 3.0 - YM = 319.3	- WVP (25 °C - 53 % RH) = 5.3 $\times 10^{-9}$ $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Promising film for dry solid food, with good strength, barrier, sealing properties and high biodegradability (90 % after 120 days).	- Kenya - Maitha et al. (2024)
Other plant and industry waste/by-products-based					
- Sodium caseinate (6 % in water), glycerol (25 % based on sod. casein.), Lipidic Fraction of Tomato Pomace (LFTP, 10–40 %) - Casting	- Edible film/coating - Active (antioxidant)	- TS = 14.0-2.5* - E = 55–80* - YM = 450-50*	n.r.	Promising edible material for food application, with good flexibility, thermal stability, light barrier properties and antioxidant activity; the best results were observed at 40 % LFTP content.	- Tunisia - Aloui et al. (2019)
- *O. ficus-indica* Cactus Mucilage (CM, 4 %) + PVA (4 %) (from 90:10 to 60:40) with PEG 200 (30 %) - Casting	- Standard	- TS = 2.7–7.3* - E = 55–60* - YM = n.r.	- WVP (25 °C - 75 % RH) = 35.6–46.1 $g \cdot mm \cdot m^{-2} \cdot day^{-1} \cdot kPa^{-1}$ - OP/OTR = n.r.	Promising film for food application, with good mechanical properties, thermal stability and light barrier; the best performances were achieved at 80:20 (CM:PVA) ratio.	- Tunisia - Gheribi et al. (2019)
- Ethylene-vinyl acetate + seawater seaw-$Mg(OH)_2$ + Chicken eggshell Ceg-$Ca(OH)_2$ (from 40/0/60 to 40/60/0) - Brabender mixer and hot pressing	- Standard resistant to heat and fire	n.r.	n.r.	Promising film for food application, with high thermal stability, strong flame-retardant performance and thermo-oxidation resistance; the best results were obtained at 40 % Ceg-$Ca(OH)_2$ content.	- Tunisia - Oualha et al. (2019)
- *A. Senegal* var. *kerensis* gum Arabic (10–20 %) - Dipping	- Edible coating	n.r.	n.r.	Suitable edible coating to preserve the shelf-life of whole mangoes for up to 15 days at room temperature (23 °C).	- Kenya - Daisy et al. (2020)
- PLA and date palm leaves powder (1–5 %) - Twin-screw extruder (for pellets) and blowing extrusion	- Standard	- TS = 18-4* - E = 250-5* - YM = 1100-400*	n.r.	Film with good mechanical properties; the best results were achieved at 1 % date palm leaves powder content.	- Tunisia - Kharrat et al. (2020)

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Table 5 (*continued*)

Ingredients/Production method	Standard/Edible/Active/Smart	Mechanical properties TS (MPa)/E (%)/YM (MPa)	Barrier properties at water vapour (WVP/WVTR) and oxygen (OP/OTR)	Key findings	Country/Reference
- Olive leaf extract (1–5 %), PLA (1.5 g), poly(ethylene glycol) (5 % based on PLA) - Casting	- Active (antioxidant)	- TS = n.r. - E = 110-90* - YM = 900-700*	- WVTR (30 °C - 75 % RH) = 9.1–11.0 $g \cdot m^{-2} \cdot h^{-1}$ - OP/OTR = n.r.	Promising film for food applications, with stable WVTR, progressively darker colour with increasing olive leaf extract content and good antioxidant properties.	- Tunisia - Grabska-Zielinska et al. (2021)
- Alginate (3 %), date palm pit extract (10–40 %), glycerol (0.6 g) - Casting	- Active (antioxidant)	- TS = 46.4-25.5 - E = 20.2–37.2 - YM = n.r.	- WVP (25 °C - 75 % RH) = 44.0–58.0 $g \cdot \mu m \cdot m^{-2} \cdot day^{-1} \cdot kPa^{-1}$ - OP/OTR = n.r.	Promising film for food rich in unsaturated fats (e.g., nuts and seeds), with good mechanical properties, low WVP, light barrier and good antioxidant properties; the best results were observed at 10–20 % date palm pit extract content.	- Tunisia - Khwaldia et al. (2023)
- *C. aurantium* fruit peel pectin (3 % in water), glycerol (30 %), *C. aurantium* fruit peel essential oil (3 mL) + Tween 80 1:0.8 (Tween 80:essential oil) - Casting	- Active (insecticidal)	n.r.	n.r.	Suitable film for whole cereals, with insecticidal activity against *R. dominica*; specifically tested on durum wheat (*Triticum durum* Desf. var. *Karim* and *Khiar*) and proved to be effective in reducing grain weight loss and damage, while preserving germination rate during extended storage.	- Tunisia - Djebbi et al. (2023)
- *O. ficus-indica* Cactus Mucilage precipitated with EThanol (CMET) or ISopropanol (CMIS) in water (4–8 %) and 1 g of Styrene-Butadiene rubber Latex (SBL) - Casting	- Standard	CMET: - TS = 2*-1* - E = 11*-2* - YM = 1200*-1000* CMIS: - TS = 3*-2* - E = 16*-5* - YM = 1600*-1000*	CMET: - WVP (25 °C - 75 % RH) = 1.3–1.6 $g \cdot mm \cdot m^{-2} \cdot h^{-1} \cdot kPa^{-1}$ CMIS: - WVP (25 °C - 75 % RH) = 1.4–1.9 $g \cdot mm \cdot m^{-2} \cdot h^{-1} \cdot kPa^{-1}$ - OP/OTR = n.r.	Promising films for low-moisture food, with good mechanical and barrier properties, thermal resistance and full biodegradability after 40 days; the best performances were observed at 6 % CMIS content.	- Tunisia - Mannai et al. (2023)
- PLA (2 g in 50 mL dichloromethane) and olive wood flour (1–10 % containing 2 % ethanol) - Casting	- Standard	- TS = 29.7-17.5 - E = 3.3-3.8 - YM = 1199.2-810.4	n.r.	Promising film for food application, with good mechanical properties and thermal stability; the best results were observed at 1 % olive wood flour content.	- Tunisia - Taktak et al. (2023)
- Agave fibres sheet impregnated with thymol (2–10 % in ethanol) or clove oil (2.5–10 % in ethanol) - Automated sheet maker and impregnation	- Active (antimicrobial)	Thymol oil 10 %: - TS = 24.1 - E = 2.6 Clove oil 10 %: - TS = 14.1 - E = 2.8 - YM = n.r.	n.r.	Suitable film for food application, with good mechanical properties and antimicrobial activity against S. aureus and E. coli; the best performances were observed at 10 % thymol or clove oil content.	- Tunisia - Turki et al. (2023)
- Rice husks (10–30 %), clay fibres (1–5 %), PLA (87-67 %) - Compression molding machine	- Standard	n.r.	n.r.	Film with high thermal stability, low flammability and combustion rates.	- Uganda - Yiga et al. (2023)
- PVA + lactic acid (1:1) and *B. oleracea* var. *capitata* anthocyanins methanolic extracts - Casting	- Active (antimicrobial) - Smart (pH-indicator)	- TS = 0.0017* - E = 116.3 - YM = 4.5×10^{-3}	- WVP (25 °C - 98 % RH) = $14.3 \times 10^{-3} \cdot g\ m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Suitable film for raw meat, with good mechanical properties, high antimicrobial activity against *E. coli*, *S. aureus*, *P. aeruginosa*, *S. epidermidis* and pH-responsive colour change for freshness indication.	- Kenya - Madivoli et al. (2024)
- Maize straw cellulose (2 g, 2 mL glycerol, 40 mL 1 % acetic acid) + sugarcane bagasse fibre (2 g, 1 mL glycerol, 40 mL 1 % acetic acid) (from 75:25 to 25:75) - Casting	- Standard	- TS = 3.8-2.3 - E = n.r. - YM = n.r.	- WVP (25 °C and 50 % RH) = 0.1–0.2 $g \cdot mm \cdot m^{-2} \cdot h^{-1} \cdot mmHg^{-1}$ - OP/OTR = n.r.	Promising film for food application, with high tensile strength, low WVP, good thermal stability and biodegradability; the best performances were observed at 75:25 cellulose:fibre ratio.	- Uganda - Nyerere et al. (2024)

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Table 5 (*continued*)

Ingredients/Production method	Standard/Edible/Active/Smart	Mechanical properties TS (MPa)/E (%)/YM (MPa)	Barrier properties at water vapour (WVP/WVTR) and oxygen (OP/OTR)	Key findings	Country/Reference
- *E. denticulatam* seaweed carrageenan (10 g in 250 mL water) and starch (1–50 %) - Casting	- Edible film	- TS = n.r. - E = 30 - YM = n.r.	- WVP (n.r.) = 2.7×10^{-7} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Promising edible film for food application, with good mechanical properties, low WVP, good light barrier, thermal stability and impermeability to vegetable oil; the effect on properties was proportional to the starch content.	- Kenya - Madivoli et al. (2025)
Chitosan-based					
- Crab (*C. mediterraneus*) shells chitosan (2 % in 2 % acetic acid) + PVA (2 % in water) (from 30:70 to 70:30), glycerol (10 % based on chitosan) - Casting	- Edible - Active (antioxidant and antimicrobial)	- TS = 46.9-13.4 - E = 116-25.6 - YM = n.r.	n.r.	Promising film for food application, with good mechanical properties, homogeneous structure, high antioxidant activity and moderate antibacterial efficacy against Gram+ and Gram- bacteria.	- Tunisia - Hajji et al. (2016)
- Crab shells chitosan (2 % in 2 % acetic acid) + PVA (2 % in water) (1:1), glycerol (10 % based on chitosan), silver nanoparticle solution (0.02 M) (0.1–5 mL each 20 mL of chitosan-PVA mix) - Casting	- Active (antioxidant and antimicrobial)	n.r.	n.r.	Promising film for food and biomedical applications, with non-cytotoxic, high antioxidant and antibacterial (against Gram+ and Gram- bacteria) activities; the effect on properties was proportional to the silver nanoparticle content.	- Tunisia - Hajji et al. (2017)
- Spider crab (*M. crispata*) (2 % in 1 % acetic acid), glycerol (30 % based on chitosan), *Spirulina* ethanol extract (2.5–20 %) - Casting	- Edible - Active (antioxidant and antimicrobial)	- TS = 22.4–29.6 - E = 27.5–34.3 - YM = n.r.	- WVP (25 °C - 75 % RH) = 0.47–0.38 $g \cdot mm \cdot m^{-2} \cdot d^{-1} \cdot Pa^{-1}$ - OP (25 °C - 50 % RH) = 0.31–0.16 $cm^3 \cdot mm \cdot m^{-2} \cdot d^{-1} \cdot atm^{-1}$	Promising edible film for food application, with good mechanical and barrier properties, excellent antioxidant activity and antibacterial activity against *E. coli, S. aureus, P. aeruginosa, L. monocytogenes* and *S. typhimurium*; the effect on properties was proportional to the *Spirulina* content.	- Tunisia - Balti et al. (2017)
- Blue crab *P. segnis* shells chitosan (2 % in 0.15 M acetic acid) + CarotenoProteins Extract - CPE (2 % in 0.15 M acetic acid) (5–50 % based on chitosan), glycerol (15 % based on polymer) - Casting	- Active (antioxidant, antimicrobial and antifungal)	- TS = 17.2-11.2 - E = 28.5-19.5 - YM = n.r.	n.r.	Promising film for food and pharmaceutical applications, with good mechanical properties, light barrier, high thermal stability, antioxidant activity, antimicrobial activity (against *S. aureus, M. luteus, E. coli, K. pneumoniae, S. enterica*), and antifungal effects (*F. oxysporum, A. niger, A. flavus*); the best results were observed at 15 % CPE content.	- Tunisia - Hamdi et al. (2019)
- Blue crab shells chitosan (2 % in 0.15 M acetic acid) + sugars (glucose, fructose, xylose or arabinose) (0.5–2.0 % based on chitosan), glycerol (15 % based on chitosan) - Casting and Maillard reaction crosslinking induced by heating at 90 °C - 24 h	- Active (antioxidant)	Glucose: - TS = 19.7–23.3 - E = 30–33.6 Fructose: - TS = 19.3–22.8 - E = 28.5–32.9 Xylose: - TS = 19.4–24.9 - E = 28.5–34.8 Arabinose: - TS = 21.2–26.7 - E = 32.1–37.1 - YM = n.r.	Glucose: - WVP (25 °C - 30 % RH) = 3-1.1 $\times 10^{-10}$ $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ Fructose: - WVP (25 °C - 30 % RH) = 2.9-1.4 $\times 10^{-10}$ $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ Xylose: - WVP (25 °C - 30 % RH) = 2.3-1.4 $\times 10^{-10}$ $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ Arabinose: - WVP (25 °C - 30 % RH) = 1.8-1.2 $\times 10^{-10}$ $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Promising film for food (e.g., oil, fish fillets, etc.), with good mechanical strength, water and light barrier properties, thermal resistance and high antioxidant activity; the best results were observed with aldopentoses and depending on the saccharide concentration.	- Tunisia - Hamdi et al. (2020)

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Table 5 (*continued*)

Ingredients/Production method	Standard/Edible/Active/Smart	Mechanical properties TS (MPa)/E (%)/YM (MPa)	Barrier properties at water vapour (WVP/WVTR) and oxygen (OP/OTR)	Key findings	Country/Reference
- Chitosan (2 % in 1 % acetic acid), glycerol (0.6 %) and *A. campestris* aqueous (ACAE) or hydroalcoholic (ACHE) extract (1 %) or essential oil (ACEO) (1 %) + Tween 80 (0.2 % based on ACEO) - Casting	- Active (antioxidant)	ACAE: - TS = 0.4 - E = 13.3 ACHE: - TS = 1.7 - E = 89.7 ACEO: - TS = 2.2 - E = 65.2 - YM = n.r.	n.r.	Promising film for food application, with variable tensile strength and extensibility depending on the type of *A. campestris* extract, high water resistance, good light barrier and high antioxidant properties.	- Tunisia - Moalla et al. (2021)
- Blue crab (*P. segnis*) shell chitosan (2 % in 1 % acetic acid) + bluefin tuna (*T. thynnus*) collagenous proteins (2 % in water) (90:10 and 50:50), glycerol (15 % based on polymers) - Casting for film/dipping for coating	- Edible film/coating - Active film/coating (antioxidant, antimicrobial and antifungal)	- TS = 19.5 and 4.9 - E = 11.3 and 8.7 - YM = n.r.	- WVP (25 °C - 50 % RH) = 4.1×10^{-10} and 3.1×10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Suitable edible film/coating for food application, with good mechanical stability, low WVP, high light barrier and antioxidant activity; the best results were observed at 90:10 (chitosan: protein) ratio and proved to be effective in inhibiting microbial growth (*S. aureus*, *M. luteus*, *E. coli*, *K. pneumoniae*, *S. enterica*, *F. oxysporum*, *A. niger*, *A. flavus*) and the oxidation of peeled shrimps during cold storage.	- Tunisia - Azaza et al. (2023)
- Cellulose (0.1 g in 15 mL water), chitosan (0.5 g in 20 mL 5 % acetic acid) + aluminium chloride ($AlCl_3$, 0.1 % in water) (2–20 % based on chitosan) - Casting	- Active (antimicrobial)	- TS = 19*-10* - E = 4.5*-17* - YM = 900*-550*	n.r.	Promising film for oxygen-sensitive food (e.g., chilled meat), with good mechanical properties, light barrier (UVA/UVB) and high antimicrobial activity against Gram+ and Gram- bacteria; the best results were achieved at 20 % $AlCl_3$ content.	- Tunisia - Beji et al. (2023)
- PVA (20 % in water) + chitosan (1 % in 1 % citric acid) (4:1), Cellulose NanoCrystals (CNC) or Cellulose NanoFibrils (CNF) (1–5 %) - Casting	- Standard (nanocomposite)	CNC: - TS = 67-62* - YM = 654-450* CNF: - TS = 104-151 - YM = 881-1008 - E = n.r.	n.r.	Promising film for food application, with high biodegradability (>70 % after 30 days); while CNC reduced mechanical properties, CNF improves them considerably, especially at 5 % content.	- Tunisia - Fakraoui et al. (2023)
- PVA (20 % in water) + chitosan (1 % in 1 % citric acid) (4:1) and lemon peel powder (LP, 1–5 %) - Casting	- Active film (antioxidant and antimicrobial)	- TS = 146-193 - E = n.r. - YM = 1236-1322	n.r.	Suitable film for food application, with good mechanical properties, water resistance, light barrier, thermal stability and good biodegradability (74 % after 30 days); the best performances were observed at 5 % LP content and proved to be effective in reducing weight loss and microbial spoilage of fresh cherry tomatoes (30 days at 26 °C).	- Tunisia - Fakraoui et al. (2024)
Gelatin-based					
- Smooth-hound gel (6 % in water) + bovine gelatin (2 % in water) (1:1 ratio), glycerol (15 % of protein), visceral wastes of Smooth-Hound (*M. mustelus*) Peptides (SHP) or Sulfated Polysaccharides (SP) (1 mg/mL) - Casting (for blend)/two-step casting (for bilayer)	- Active (antioxidant)	Blend film - SHP and SP: - TS = 90.2 and 87.8 - E = 13.4 and 12.3 Bilayer film - SHP and SP: - TS = 61.9 and 61.8 - E = 16.9 and 23.4 - YM = n.r.	Blend film - SHP and SP: - WVP (25 °C - 30 % RH) = 2.1×10^{-10} and 1.9×10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ Bilayer film - SHP and SP: - WVP (25 °C - 30 % RH) = 2.3×10^{-10} and 2.2×10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Promising film for food application, with high tensile strength, low WVP, good hydrophobic surface and high antioxidant activity; the best results were observed in the blend material formulated with SP or SHP addition.	- Tunisia - Abdelhedi et al. (2018)

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Table 5 (*continued*)

Ingredients/Production method	Standard/Edible/Active/Smart	Mechanical properties TS (MPa)/E (%)/YM (MPa)	Barrier properties at water vapour (WVP/WVTR) and oxygen (OP/OTR)	Key findings	Country/Reference
- Gelatin (4 % in water), glucose (in final molar Glucose:Lysine 0.5:1.0 and 1.0:1.0), glycerol (15 % based on gelatin) - Casting and Maillard reaction induced by heating at 90 °C - 24 h	- Edible film - Active (antioxidant)	- TS = 100* and 90* - E = 5.5* and 5* - YM = 33* and 30*	- WVP (25 °C - 30 % RH) = 1.5×10^{-10} and 1.4×10^{-10} $g{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}Pa^{-1}$ - OP/OTR = n.r.	Promising edible film for food application, with good mechanical properties, high water resistance, light barrier, good thermal properties and high antioxidant activity; the best results were obtained at 0.5:1.0 (Glu:Lys) molar ratio.	- Tunisia - Kchaou et al. (2018)
- Grey triggerfish (*B. capriscus*) skin gelatin (3 % in water) + agar (3 % in water) (1:1), glycerol (15 % based on polymers), vine leaves ethanolic extract (5 or 10 mg/mL) - Casting (for blend)/two-step casting (for bilayer)	- Edible film - Active (antioxidant and antimicrobial)	Blend film: - TS = 62.5 and 60.5 - E = 25.2 and 22.4 Bilayer film: - TS = 71.6 and 69.5 - E = 20.1 and 19.5 - YM = n.r.	Blend film: - WVP (25 °C - 30 % RH) = 1.5×10^{-10} and 1.4×10^{-10} $g{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}Pa^{-1}$ Bilayer film: - WVP (25 °C - 30 % RH) = 22.8×10^{-10} and 2.3×10^{-10} $g{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}Pa^{-1}$ - OP/OTR = n.r.	Promising edible film for food application, with good mechanical and thermal properties and high antioxidant activity; the best results were observed at 10 mg/mL.	- Tunisia - Jridi et al. (2019)
- Grey triggerfish (*B. capriscus*) gelatin (3 % in water) + blood orange peel pectin (3 % in water) (from 90:10 to 50:50), glycerol (15 % based on protein: polysaccharide) - Casting	- Edible film - Active (antioxidant and antimicrobial)	- TS = 7.8–14.4 - E = 7.0-4.4 - YM = n.r.	- WVP (25 °C - 30 % RH) = 1.9-1.5 × 10^{-10} $g{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}Pa^{-1}$ - OP/OTR = n.r.	Suitable edible film for cheese, with good mechanical and thermal properties, high antioxidant and antibacterial activities; the best performances were observed at 50:50 (gelatin:pectin) ratio and proved to be effective in preserving the microbial and physicochemical quality of refrigerated semi-hard cheese during storage.	- Tunisia - Jridi et al. (2020)
- Blackchin guitarfish (*R. cemiculus*) skin gelatin (4 % in water), titanium dioxide-silver nanoparticles (TiO_2-Ag NPs, 1–4 %), glycerol (15 % based on polymer) - Casting	- Active (antioxidant)	- TS = 5.9-5.2 - E = 21.6-16.0 - YM = n.r.	n.r.	Promising film for food application, with good mechanical properties, thermal stability and high antioxidant activity; the effect on properties was proportional to TiO_2-Ag NPs content.	- Tunisa - Boughriba et al. (2020)
- Smooth hound (*M. mustellus*) skin gelatin (3 % in water) + agar (3 % in water) (25:75 and 50:50), glycerol (15 % based on polymer) - With and without US treatment/casting	- Edible film	With US: - TS = 10.8 and 11.2 - E = 145 and 151 Without US: - TS = 12.3 and 11.2 - E = 135 and 140 - YM = n.r.	n.r.	Promising edible film for food application, with good tensile strength, low water solubility; the optimum barrier properties were achieved at a 25:75 (gelatin:agar) ratio.	- Tunisia - Salem et al. (2021)
- Gelatin (4 %), sodium alginate (3 %), beetroot (*Beta vulgaris* L.) peel extracts (0.25–1 %), glycerol (20 %) - Casting	- Active (antioxidant and antimicrobial)	- TS = 23.2–36.4 - E = 66.1–91.1 - YM = n.r.	n.r.	Suitable edible film for meat, with good mechanical, physical, antioxidant and antimicrobial properties; the best performances were observed at 1 % beetroot peel extract content and proved to be effective in preserving the quality of raw minced beef during cold storage.	- Tunisia - Chaari et al. (2022)
- Gelatin (4 %), sodium alginate (3 %), glycerol (20 %) and date pits powder (0.37–1.5 %) - Casting	- Edible - Active film (antioxidant and antimicrobial)	n.r.	n.r.	Suitable edible film for meat, with high antioxidant and antibacterial properties; the best performances were observed at 1.5 % date pit extract content and proved to be effective in inhibiting *L. monocytogenes* growth and preserving the quality of raw minced beef during cold storage.	- Tunisia - Elhadef et al. (2024)

(continued on next page)

Table 5 (*continued*)

Ingredients/Production method	Standard/Edible/Active/Smart	Mechanical properties TS (MPa)/E (%)/YM (MPa)	Barrier properties at water vapour (WVP/WVTR) and oxygen (OP/OTR)	Key findings	Country/Reference
- Smooth-hound shark (*M. mustelus*) gelatin (3 % in water) and garden cress seeds extract (0.67 mg/g based on gelatin) - Dipping solution	- Active coating (antioxidant and antimicrobial)	n.r.	n.r.	Suitable edible coating for fish, with high antioxidant activity and proved to be effective in inhibiting mesophilic and psychrophilic bacteria (*Pseudomonas* spp. and Enterobacteriaceae) in preserving the quality of smooth-hound fillets during cold storage.	- Tunisia - Salem et al. (2024)
- Gelatin (4 % in water), Smectite (Sm) or iLlite (iL) (3 % of gelatin), glycerol (15 % based on polymers), Chamomile (Chm) aqueous extract (1 and 2 %) - Casting	- Active (antioxidant)	Sm-Chm 1 % and 2 %: - TS = 45.3 and 61.8 - E = 3.8 and 6.4 iL-Chm 1 % and 2 %: - TS = 46.1 and 54.5 - E = 5.7 and 6.5 - YM = n.r.	Sm-Chm 2 %: - WVP (25 °C – 50 % RH) = 2.2×10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ iL-Chm 2 %: - WVP (25 °C - 50 % RH) = 2.8×10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Promising film for food application, with good mechanical strength, thermal stability and high antioxidant activity; the best performances were observed at 2 % Chm extract content.	- Tunisia - Sayah et al. (2024)
Combined chitosan and gelatin-based					
- Chitosan (10 %), gelatin (24.3 %), pectin (0.5 %), glycerol (65.2 %), rosemary essential oils in Tween 20 at 25 % (1.99 *Troglodytarum* var. + 1.25 mg/g *Typicus* var. as a single mixture) - Casting	- Edible film - Active (antibacterial)	n.r.	- WVP (25 °C - 30 % RH) = 0.42×10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Promising edible film for food application, with good mechanical strength, good WVP, light barrier and high antibacterial activity against *B. subtilis*, *S. aureus*, *E. aerogenes*, *E. faecalis* and *E. coli*.	- Tunisia - Yeddes et al. (2020)
- Crab shells chitosan (2 % in 2 % acetic acid) + golden grey mullet gelatin (2 % in water) (1:1), Shrimp (SPH) or Crab (CPH) Hydrolysates (1.5–6 %) - Casting	- Edible film - Active (antioxidant and antimicrobial)	SPH: - TS = 24.9–31.9 - E = 37.5-31.9 CPH: - TS = 13.0-9.0 - E = 48.1–50.1 - YM = n.r.	n.r.	Promising edible film for food application, with good light barrier, antioxidant and antibacterial (against *E. coli*, *S. aureus* and *L. monocytogenes*) activities; the optimum bioactive performance was achieved at 6 % CPH content.	- Tunisia - Hajji et al. (2021)
- Chitosan (1 % in 1 % acetic acid) + bovine skin gelatin (4 %) (1:1), glycerol (3.75 g based on polymers), rosemary extract (EE) or essential oil (EO) (0.5–2 %) + Tween 20 (0.5 % for EO) - Casting	- Edible film - Active (antimicrobial)	EE: - TS = 28.2–36.1 - E = 41.0-38.7 EO: - TS = 27.0–31.4 - E = 41.4-35.3 - YM = n.r.	EE: - WVP (25 °C - 30 % RH) = 1.56-0.60 × 10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ EO: - WVP (25 °C - 30 % RH) = 1.42-0.72 × 10^{-10} $g \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ - OP/OTR = n.r.	Promising edible film for food application, with good tensile strength, low WVP, high thermal stability and antibacterial activity against *E. coli*, *P. aeruginosa*, *C. jejuni* and *S. enterica*; the effect on properties was proportional to EE or EO content.	- Tunisia - Walid et al. (2022)

Standard = neither edible, active nor smart; TS = Tensile strength; E = Elongation at break; YM = Young's modulus; WVP = Water vapour permeability; WVTR = Water vapour transmission rate; OP = Oxygen permeability; OTR = Oxygen transmission rate; Promising = potentially useful, as reported by the authors; Suitable = already tested on specific food products; n.r. = not reported. Values marked with an asterisk (*) are estimated from graphical data in the original article.

major phenolic compound in GCSE, probably contributed to the observed preservative effects. In line with the previous researches, Sayah et al. (2024) combined fish gelatin (4 % w/v) with smectite or illite clays (3 % w/w, origin Jebel Haidoudi, Tunisia), enriched with chamomile extract (1 % or 2 % w/v) from northwest Tunisia. Similar to other studies, the addition of chamomile extract improved the mechanical, barrier-forming and antioxidant properties of the films.

4.5. *Combined chitosan and gelatin-based*

The combined use of chitosan and gelatin in bio-based packaging materials has also proven to be a promising strategy to improve the mechanical strength, barrier function and antimicrobial activity. Some Tunisian researchers have recently investigated different formulations and natural additives (i.e., rosemary essential oil and extract, crustacean protein hydrolysates) to optimise the performance of these films for food packaging applications (Table 5).

Yeddes et al. (2020) optimized edible gelatin-chitosan films by incorporating rosemary essential oil (REO) from two local Tunisian varieties (*Rosmarinus officinalis*, *Typicus* and *Troglodiytarum* var.) collected in Zaghouan and Chaab Tweel. The optimal film composition with 24.3 % gelatin, 10 % chitosan and 0.5 % pectin was prepared by casting. The REO enriched film showed antibacterial activity against *B. subtilis*, *S. aureus*, *E. aerogenes*, *E. faecalis* and *E. coli*, demonstrating their potential to control common foodborne bacteria during storage.

An active chitosan-gelatin film containing protein hydrolysates (SPH and CPH) extracted from local shrimp (*Penaeus kerathurus*) and crab (*Carcinus mediterraneus*) shells was also studied (Hajji et al., 2021). Chitosan (2 % w/v) from crab shells and gelatin (2 % w/v) from golden grey mullet (*Liza aurata*) were blended in a 1:1 ratio. Crustacean protein hydrolysates as bioactive additives were also incorporated into the activated film formulation in different ratios (1.5–6 %). The result was a film with improved UV-barrier, mechanical strength, thermal stability, antioxidant capacity and antimicrobial activity, although hydrophilicity increased.

In parallel, Walid et al. (2022) activated a gelatin/chitosan-based film with local rosemary (collected at Chaab el Tweel region, Tunisia) ethanol extract (EE) and essential oil (EO) to improve its physico-chemical and antibacterial properties. The optimal formulation for the best mechanical properties consisted of 1 % chitosan and 4 % gelatin. The addition of rosemary EE and EO significantly increased the tensile strength and hydrophobicity, while the elongation at break decreased. The enriched films also showed strong antibacterial activity against *E. coli*, *P. aeruginosa*, *C. jejuni* and *S. enterica*, making them effective for the preservation of food during storage.

5. Conclusions and future perspectives

The coexistence of traditional and conventional packaging materials across many African countries reflects a complex interplay between cultural heritage and technological development, which continues to influence today's packaging practises. In many rural areas of the African continent, traditional packaging materials such as plant leaves, jute sacks, etc. are still widespread but offer very limited protection and hygiene for food. In addition, fossil-based plastics continue to dominate, especially in markets, densely populated residential and other urban areas; however, plastic waste is often poorly managed, dumped in public places or openly burned, contributing significantly to environmental pollution.

To tackle these problems, Tunisia, Kenya, Uganda and Tanzania, as well as other African countries, have started to awareness and implement initiatives and policies since the early 2000s. As a result of a comparative analysis of the effectiveness of regulatory measures in the considered countries, it can be summarised that Tunisia has developed an advanced management and recycling system, but the production costs for biodegradable and/or bio-based materials are still high compared to conventional plastics. Kenya stands out for a progressive, multi-level strategy, albeit with a strict regulatory approach. In Uganda, the ambitious regulations remain largely ineffective due to a lack of real enforcement capacity and viable alternatives. Finally, Tanzania has achieved notable successes in reducing plastic bags and, together with Kenya, is the country with the most restrictive policy measures in terms of the types of plastic bags banned and the strict fines/prison sentences for non-compliance.

Generally, to make these initiatives more effective and overcome some associated challenges and limitations, it is important that legislative efforts are accompanied by both information and awareness-raising initiatives that actively engage consumers and communities, also encouraging the adoption of sustainable packaging alternatives. In many cases, governments and institutions have not invested sufficiently in public education campaigns to inform citizens/stakeholders about the environmental and health risks associated with plastic consumption. Consumer awareness is indeed a crucial but often underestimated aspect in the fight against plastic pollution.

The studies reviewed on the development of new bio-based packaging suitable for food made from various local raw materials or by-products/waste demonstrate the interest of the African scientific communities in sustainable packaging solutions. However, several researches remain at laboratory scale and most of the materials obtained have not been verified for their food suitability through shelf-life studies nor tested for their long-term environmental and socio-economic impacts. Therefore, there is an urgent need for further research to assess their feasibility and bring them to real industrial level with collaborations between academia, industry and policy makers.

Ultimately, customised approaches that take into account the different socio-economic and cultural realities of each country, together with international cooperation and increased public investment in research, can help to improve the efficiency and sustainability of the entire African food packaging system.

Funding

This work was supported by the European Union's Horizon 2020 research and innovation programme [grant agreement number: 862802].

Declaration of competing interest

There are no conflicts of interest.

Acknowledgements

This review paper was carried out in the framework of the H2020 FoodLAND (Food and Local, Agricultural, and Nutritional Diversity) project. FoodLAND has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement (GA No 862802). The views and opinions expressed in this document are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission. We thank all the FoodLAND partners for the fruitful discussions and the enumerators for the proactive collaboration we had during the past few years.

List of abbreviations

DSC	Differential Scanning Calorimetry
EPS	Expanded Polystyrene
EVA	Ethylene-vinyl Acetate
FTIR	Fourier Transform Infrared Spectroscopy
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
OPP	Oriented Polypropylene
PE	Polyethylene
PET	Polyethylene Terephthalate
PLA	Polylactic Acid
PP	Polypropylene
PS	Polystyrene
PVA	Polyvinyl Alcohol
RH	Relative Humidity
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
UV	Ultraviolet

Data availability

No data was used for the research described in the article.

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