Bioplastic packaging for fresh meat and fish

Uysal-Unalan, Ilke; Sogut, Ece; Realini, Carolina E.; Cakmak, Hulya; Oz, Emel; Espinosa, Eduardo; Morcillo-Martín, Ramón; Oz, Fatih; Nurmi, Maristiina; Cerqueira, Miguel A.; Perera, Kalpani Y.; Ayhan, Zehra; Arserim-Ucar, Dilhun Keriman; Kanakaki, Chrysoula; Chrysochou, Polymeros; Marcos, Begonya; Corredig, Milena

Published in:
Trends in Food Science and Technology

DOI:
10.1016/j.tifs.2024.104660

Published: 01/10/2024

Document Version
Final published version

Please cite the original version:
Uysal-Unalan, I., Sogut, E., Realini, C. E., Cakmak, H., Oz, E., Espinosa, E., Morcillo-Martín, R., Oz, F., Nurmi, M., Cerqueira, M. A., Perera, K. Y., Ayhan, Z., Arserim-Ucar, D. K., Kanakaki, C., Chrysochou, P., Marcos, B., & Corredig, M. (2024). Bioplastic packaging for fresh meat and fish: Current status and future direction on mitigating food and packaging waste. *Trends in Food Science and Technology*, *152*, Article 104660. https://doi.org/10.1016/j.tifs.2024.104660

Trends in Food Science & Technology 152 (2024) 104660

Contents lists available at ScienceDirect

Trends in Food Science & Technology

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

Bioplastic packaging for fresh meat and fish: Current status and future direction on mitigating food and packaging waste

Ilke Uysal-Unalan[a,b,*], Ece Sogut[a,c], Carolina E. Realini[d], Hulya Cakmak[e], Emel Oz[f], Eduardo Espinosa[g], Ramón Morcillo-Martín[g], Fatih Oz[f], Maristiina Nurmi[h], Miguel A. Cerqueira[i], Kalpani Y. Perera[j], Zehra Ayhan[k], Dilhun Keriman Arserim-Ucar[l], Chrysoula Kanakaki[m], Polymeros Chrysochou[n], Begonya Marcos[o], Milena Corredig[a,b]

[a] Department of Food Science, Aarhus University, Agro Food Park 48, 8200, Aarhus N, Denmark
[b] CiFOOD - Center for Innovative Food Research, Aarhus University, Agro Food Park 48, 8200, Aarhus N, Denmark
[c] Suleyman Demirel University, Food Engineering Department, 32000, Isparta, Turkey
[d] AgResearch Limited, Te Ohu Rangahau Kai, Massey University Campus, Palmerston North, 4474, New Zealand
[e] Hitit University, Department of Food Engineering, 19030, Corum, Turkey
[f] Department of Food Engineering, Faculty of Agriculture, Atatiirk University, 25240, Erzurum, Turkey
[g] BioPren Group (RNM 940), Chemical Engineering Department, Instituto Químico para la Energía y El Medioambiente (IQUEMA), Universidad de Córdoba, 14014, Córdoba, Spain
[h] Åbo Akademi, Laboratory of Natural Materials Technology Henrikinkatu 2, FI-20500, Turku, Finland
[i] International Iberian Nanotechnology Laboratory (INL), Av. Mestre José Veiga, 4715-330, Braga, Portugal
[j] School of Food Science and Environmental Health, College of Sciences and Health, Technological University Dublin—City Campus, Central Quad, Grangegorman, Dublin, D07 ADY7, Ireland
[k] Sakarya University, Faculty of Engineering, Food Engineering Department, 54050, Sakarya, Turkey
[l] Department of Nutrition and Dietetics, Faculty of Health Sciences, Bingöl University, 12000, Bingöl, Turkey
[m] Laboratory of Analytical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, Athens, Greece
[n] MAPP Centre, Department of Management, Aarhus University, Fuglesangs Alle 4, 8000, Aarhus, Denmark
[o] IRTA, Food Quality and Technology, Finca Camps i Armet s/n, 17121, Monells, Spain

ARTICLE INFO

Handling Editor: Dr. S Charlebois

Keywords:
Active packaging
Bio-based food packaging
Consumer perception
Food safety
Intelligent packaging
Waste management

ABSTRACT

Background: This work evaluates the preparedness of the packaging industry towards more circular, sustainable solutions for fresh meat and fish. The term bioplastic is ill-defined, creating confusion between all stakeholders in the value chain. The implementation of bioplastic as food contact material will only occur when there are demonstrated solutions that can equally or better protect fresh meat and fish from spoilage, compared to conventional plastic. Price, supply chain availability, machinability, and safety will also be key in the shift from fossil to bioplastic.

Scope and approach: The application of bioplastic as food contact material for fresh meat and fish is at its infancy. In this work, a multidisciplinary approach was employed to highlight the need for a holistic eco-design that minimizes food and packaging waste, due to the high environmental footprint and value of fresh fish and meat.

Key findings and conclusions: Although bioplastics are positively perceived by all end-users, including consumers, there is widespread confusion in their market implementation. Their sorting and end-of-life are major challenges. Their supply chains are underdeveloped, in terms of costs, scale-up, sorting, and recycling even for the most promising materials. Most bioplastics still do not meet the specified technological functionalities required to substitute their fossil-fuel counterparts. For appropriate eco-design, it is important to quantify the bioplastic solutions using life cycle assessment considering the material-food unit and most importantly, ensure their safety, by demonstrating the absence of migration of harmful substances from packaging, especially when derived from waste byproducts. The development of active and intelligent bioplastic solutions to increase the shelf life of fresh fish and meat products will also add significant value to the food-packaging unit.

---

* Corresponding author. Department of Food Science, Aarhus University, Agro Food Park 48, 8200, Aarhus N, Denmark.
E-mail address: iuu@food.au.dk (I. Uysal-Unalan).

https://doi.org/10.1016/j.tifs.2024.104660
Received 23 November 2023; Received in revised form 29 July 2024; Accepted 7 August 2024

List of abbreviations

ASTM	American Society for Testing and Material
CEN	European Committee for Standardization
EDTA	ethylenediaminetetraacetic acid
EVOH	ethylene vinyl alcohol
GA	glycolic acid
HDPE	high density polyethylene
LLDPE	low density polyethylene
IAS	intentionally added substances
ISO	International Organization for Standardization
MAP	modified atmosphere packaging
NIAS	non intentionally added substances
OP	oxygen permeability
OTR	oxygen transmission rate
PA	polyamide
PBAT	polybutylene adipate terephthalate
PBT	polybutylene terephthalate
PBS	polybutylene succinate
PBSA	polybutylene succinate adipate
PCL	polycaprolactone
PE	polyethylene
PEG	polyethylene glycol
PET	polyethylene terephthalate
PGA	polyglycolic acid
PHA	polyhydroxyalkanoates
PHB	poly-3-hydroxybutyrate
PHBH	polyhydroxybutyrate-co-hexanoate
PHBV	poly-3-hydroxybutyrate-co-valerate
PLA	polylactic acid
PLLA/PDLA	poly-L-lactide/poly-D-lactide
PP	polypropylene
PPS	polypropylene succinate
PS	polystyrene
PTT	polytrimethylene terephthalate
PVA	polyvinyl acetate
PVC	polyvinyl chloride
PVDC	polyvinylidene dichloride
PVOH	polyvinyl alcohol
RH	relative humidity
TBARS	thiobarbituric acid reactive substances
TPS	thermoplastic starch
TPSB	thermoplastic styrene-butadiene copolymers
TS	tensile strength
TVBN	total volatile basic nitrogen
YM	Young's modulus
WVP	water vapor permeability
WVTR	water vapor transmission rate

1. Introduction

The rising concerns about environmental pollution, as well as the recent reports on microplastics residues in food and environment, and their global impact on one health (Liu et al., 2023) have forced all stakeholders, from policymakers, to manufacturers and even conscious consumers to take immediate action. A reduction in the use of plastic material would indeed contribute to a substantial reduction of greenhouse gas emissions (Klemeš et al., 2021), and the use of bioplastic in food packaging, instead of fossil-based plastic materials would also contribute to re-establishment of a food systems within circular value chains. However, the term "bioplastic" is still a source of great confusion in the industry. According to the European Bioplastics Organization there are three main bioplastics categories: (1) non-biodegradable, but bio-based or partially bio-based; (2) bio-based and biodegradable; (3) biodegradable but fossil-based (European Bioplastics, 2023a). The source of raw material for such polymers is increasingly from food and agricultural waste, which can be utilized for both conventional as well as bioplastic polymers (Jõgi & Bhat, 2020).

A recent definition of sustainable food packaging has been developed which encompasses the role of the material as a resource to ensure a safe, affordable and high-quality food (Dörnyei et al., 2023). Clearly, how the material is produced, the renewable energy and bio-resources used, their recovery and effective recycling are also important. In sum, the time is right for a true transformation of the food packaging industry to more bio-based solutions, and this can be achieved only with a holistic approach that considers all aspects of the food-packaging unit.

The food industry across the globe is then facing a pressing challenge: the need to reduce food and packaging waste without compromising on food quality and safety. Among the numerous food products demanding effective packaging solutions, meat and fish stand out. Due to their perishable nature and susceptibility to spoilage, the use of compostable bioplastic for meat and fishcould have more sense than for other product, since they have a rather short shelf life and compostable bioplasticsmight tend to be more fragile and prone to degradation during their use compared to the conventional plastic packaging, this can be a successful combination. This type of compostable packaging waste contaminated with meat and fish scraps could be treated through organic recycling (i.e., anaerobic digestion and composting) (Gadaleta et al., 2022; Kosheleva et al., 2023) by diverting the waste from the landfills as in current mechanical recycling streams the decontamination with food is a challenge. To ensure the viability of composting fresh meat and fish waste with its package, significant research is needed on the use of sequential anaerobic-aerobic degradation, evaluating several factors, namely disintegration rates, degradation media, compostable bioplastic-food waste ratio.

Designing food packaging is not trivial, and solutions are not "one size fits all". The choice of material to be used is highly dependent on the type of food product and its supply chain. Although many reviews have been recently published on biomaterials for food packaging solutions, this work deals with the critical aspect of designing the appropriate packaging for fresh meat, poultry and fish, due to the importance of the food-package unit. Fresh meat, poultry and fish are highly perishable commodities because of their high moisture content; their shelf life is limited by microbial spoilage, oxidation or enzymatic degradation caused by improper handling, packaging or storage (Coppola et al., 2021; Karwowska et al., 2021; Umaraw et al., 2020). Therefore, a package which can conserve the quality and extend the shelf life of these products is quite critical to decreasing their footprint. Reducing fresh meat waste is of particular importance, as meat production requires large resource inputs such as energy, clean water, and feed (Henchion et al., 2014). In the western world, approximately 23% of meat production goes to waste, with the largest share of 64% occurring at the consumer level, 20% during processing, 12% in distribution, and the rest at the farm level (Karwowska et al., 2021). Furthermore, about two-thirds of the total amount of fish is discarded as waste, contributing to environmental concerns (Coppola et al., 2021).

Currently, meat and fish are still mostly packaged in fossil-based plastic films, trays, lids, and absorbent pads. These materials are readily available, low cost, and provide optimal technical performance. Although bioplastic packaging is becoming available, particularly for items like trays, lids, or protective sheets for fresh meat, their use will come with some trade-offs when compared to conventional petroleum-based packaging, due to their differences in technical performance. All new solutions need to be tested before their implementation as sustainable alternatives. For example, bio-based films may have higher

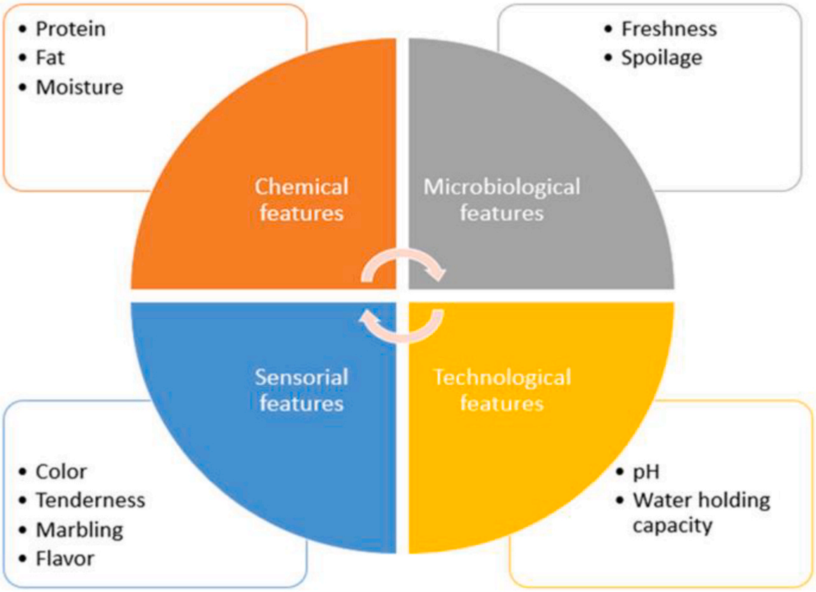

Fig. 1. Meat quality attributes (Adapted from (Xiong et al., 2014)).

water vapor and oxygen permeability and be more brittle, compared to the petroleum-based counterparts, which show mechanical properties ideal to be used in flexible packaging (Hernández-García et al., 2022). However, it has been recently demonstrated that the replacement of fossil-based trays made of recycled polyethylene terephthalate (PET)/-polyethylene (PE) with polylactic acid (PLA) for fresh fish and meat trays could reduce the carbon footprint by 49%, when the food-packaging unit is considered (Nejad et al., 2021).

This review provides a holistic overview of the key factors affecting the future implementation of bioplastic packaging for fresh meat and fish. Food specific focus on packaging is critical in packaging eco-design. The review addresses all aspects, from safety, consumer perception, technical performance, as well as the unique challenges associated with the end-of-life phase of biodegradable packaging materials. This work uniquely gauges the industry's preparedness to a transition from conventional packaging towards more sustainable alternatives. This endeavor represents a critical step towards the harmonization of practices and may also aid in new strategies/recommendations for stakeholders, from industry practitioners to policy makers and regulators, shaping the landscape of sustainable practices and serving as a resource in fostering positive change.

2. Reducing waste of fresh meat and fish by ensuring quality requirements through the packaging

Traditional retail packaging solutions have been optimized to extend product shelf life (Yildirim et al., 2018). There is now a renewed interest in innovative technologies, such as active and intelligent packaging, to satisfy the demands of consumers who seek high-quality, preservative-free, and additive-free foods while simultaneously further extend shelf life (Schumann & Schmid, 2018). This effort has to come, hand in hand, with reducing reliance on single-use packaging materials, as well as multi-material, multilayer plastic films and trays which pose recycling challenges. In this context, bioplastic packaging materials sourced from renewable resources and/or with circular end-of-life hold promise for mitigating the environmental impact of packaging waste (Nilsen-Nygaard et al., 2021). However, the physical properties of these new packaging materials must align with specific requirements aligned with product needs, to attain the right chemical, microbiological and sensory product quality (Fig. 1) that ensure desired shelf life, and thus the amount of food waste along the supply chain is minimized.

Meat can be categorized based on the quantity of red and white muscle fibers, with beef, pork, and lamb falling under the classification of red meat, while poultry and fish (Zaukuu et al., 2019) fall in the white meat category. The color of fresh meat is a crucial quality parameter at the point of purchase. For fresh red meat with high myoglobin content, it is desirable to have sufficient oxymyoglobin to maintain a bright red color during display (Schumann & Schmid, 2018). Unfortunately, in a low oxygen environment, the color of the flesh becomes purple (deoxymyoglobin state) instead of the familiar bright cherry red color (oxymyoglobin state), which substantially decreases product's desirability in retail displays. This is a significant challenge. The exclusion of oxygen using vacuum results in meat with a longer shelf life compared to the use of oxygen permeable overwrap or high oxygen modified atmosphere packaging (MAP) (Lorenzo & Gómez, 2012); however, this also results in a color change. Many fish species also have a high percentage of red muscle tissue, requiring the presence of oxygen to maintain a good color (Robertson, 2013). Poultry muscle instead generally has low myoglobin content, and a limited level of oxymyoglobin is formed when exposed to air, so this is not a quality issue for consumers (Gill, 2003). In summary, while color, is a significant limiting factor for shelf-life preservation of fresh meat and fish, microbial and chemical oxidation spoilage come as close seconds. Aerobic conditions stimulate the growth of aerobic bacteria, inhibit anaerobic bacteria proliferation, but also accelerate oxidative reactions, resulting in rancidity and unappealing flavors and odors (Wickramasinghe et al., 2019). Modified atmospheres creating CO_2-rich conditions provide bacteriostatic effect, by either prolonging the lag phase or reducing the growth rate of certain strains (Kerry, 2012); this generates an environment more suited to the growth of anaerobic and facultative anaerobic bacteria. Generally, Pseudomonas species in fresh meat stored under aerobic conditions, and lactic acid bacteria species such as *Lactobacillus* and *Leuconostoc* in fresh meat stored in anaerobic conditions constitute the predominant flora. The absence of oxygen provides suitable conditions for the growth of i.e., *Bacillaceae and Clostridia,* which could also lead to toxin formation (Wang et al., 2017). Lipid oxidations result in the formation of numerous unwanted products, affecting the sensorial, functional, and nutritional quality features of fresh meat (Domínguez et al., 2019). The ferrous iron located in the center of myoglobin can trigger lipid oxidation (Domínguez et al., 2019). The consequences of oxidation are different depending on the type of meat and fish. For example, fish species vary significantly in fat composition and concentration. Non-fatty fish such as cod and haddock typically contain 1–2% lipids, while fatty fish such as herring and mackerel can have lipid contents exceeding 30%. In red meat, the amount of visible intramuscular fat and its distribution, commonly referred to as marbling (Ladeira et al., 2018), is also a determining factor to quality and value (Xiong et al., 2014). However, high marbled meats are more susceptible to lipid oxidation than those with low marbling scores. High levels of unsaturated lipids, especially polyunsaturated fatty acid content, lead to rancid taste and off-aroma formation, and loss of nutritional value, especially omega-3 fatty acids. Another cause of quality deterioration by oxidation is the production of various oxidation derivatives from proteins leading to protein aggregation and polymerization. This can affect many properties such as solubility, hydrophobicity, water holding capacity, meat tenderness, and gelation functions (Zhang et al., 2013). The reduction of water holding capacity results in significant moisture losses, which manifest as an undesirable visible drip in the package at the point of purchase. It has also been reported that the quality of fresh meat during refrigerated storage is adversely affected by the oxidation of calpain, an enzyme involved in the breakdown of myofibrillar proteins and the development of meat tenderness (Rowe et al., 2004).

3. Current packaging practices

Gas and water vapor barrier performance of bioplastics greatly impact their food packaging applications. For example, oxygen present in the package of fresh meat above the threshold can cause degradation reactions such as fat and oil rancidity and microbial growth. Therefore, distinct types of fresh meat and fish will have different packaging barrier requirements to maintain the product fresh for the desired shelf life, and these should be chosen with the consideration of packaging technologies (Table S1). Oxygen transmission rate (OTR) of about 1700 mL/m^2/day at 23 °C at 50% RH is considered sufficient to provide oxymyoglobin formation (Robertson, 2013). Similarly, for fresh ground chicken leg meat, intermediate oxygen gas barrier films with transmission rates of 2000 and 4700 mL/m^2/day are considered ideal to maintain most quality attributes during refrigerated storage of 14 days. Low barrier films with 7000 and 12000 mL/m^2/day transmission rates become desirable to control oxymyoglobin level, whereas the high gas barrier film with low transmission rates e.g. 30 mL/m^2/day are better at inhibiting aerobic growth (Dawson et al., 1995). When it comes to commercially available fresh meat and fish bioplastic packaging solutions (Table 4), their barrier properties have scarcely been reported. For those whose gas transmission values have been provided, differences in testing conditions make comparison quite challenging. For example, bio-based and biodegradable starch-based bioplastic (PLANTIC™) is reported to have 0.13 mL/m^2/day (38 °C, 50 RH%) for oxygen and 35–40 g/m^2/day (38 °C, 50% RH) for water vapor, and if compared to fossil-based non-bioplastic polyvinylidene dichloride (PVDC) packaging (Ixan® PVDC) (Table S2) the values are of 5–9.4 mL/m^2/day (23 °C, 85 RH%) for oxygen and 2–3.7 g/m^2/day (38 °C, 90% RH) for water vapor. These values can help understand optimal conditions that are needed for microbial safety of fresh meat and fish. In overwrap packaging, air-permeable, moisture-barrier and stretchable films are used, the most common being polyvinyl chloride (PVC) or PVDC (McMillin, 2008). In addition, polystyrene (PS) trays are traditionally used as the base for the stretchable PVC wrapping film, resulting in high OTRs. Recyclable or recycled alternatives are becoming widespread in the market (i.e. rPET). As previously mentioned, high OTRs of packaging material (7000–12.000 mL/m^2/day) can control oxymyoglobin level of meat when it is formed at the ideal level inside packaging. Modified Atmosphere Packaging, MAP is more effective technology in extending microbiological shelf life than the traditional oxygen permeable overwrap (Hur et al., 2013). For example, when MAP is the chosen technology, transmission rates from 10 to 100 mL/m^2/day for oxygen and 1–10 g/m^2/day for water vapor are recognized within the optimum range (Wu et al., 2021). In another study of traditional MAP packaging, trays composed of PS, polypropylene (PP) and PVC are laminated with a film having good gas barrier properties, such as ethylene vinyl alcohol (EVOH). OTR of these packages is less than 0.42 mL/m^2/day (Robertson, 2013), limiting gas exchange. Various combinations of O_2, CO_2 and N_2 are generally used and combined in MAP applications (Mc Millin, 2008). In the EU, argon, helium, hydrogen and nitrogen monoxide are also allowed. MAP requires an understanding of the post-harvest properties of the product during storage, to maintain the right balance of the various components. While the gas mixture varies depending on the product type, in general, it is composed of 60–70% O_2, 20–30% CO_2, and 10–20% N_2 or 30% CO_2 and 70% N_2 (Day, 2003). For meat, MAP with a high level of oxygen (70–80%) is required to maintain the acceptable red color. In the packaging of poultry meats, CO_2 and N_2 gas mixtures without O_2 are commonly preferred (Robertson, 2013). High CO_2 levels prevent the growth of bacteria, mold and yeast, dissolving in the water phase of the food and lowering its pH. N_2 is an inert gas that dissolves poorly in water and fat, so its primary use is as a filler, replacing O_2 while preventing the package from collapsing.

Packaging under vacuum relies upon negative pressure to remove ambient air, using films of low gas permeability closely applied to the surface of the product (O'Sullivan & Kerry, 2012). Materials with OTR (at 23 °C and 75% RH) less than 10 mL/m^2/day, considerably extend the shelf life of the meat regardless of the type of packaging. However, mechanical pressure on meat due to vacuum can increase drip loss (Robertson, 2013). Typically, oxygen permeable and MAP packaging are preferred for short-term storage (e.g., retail display) for maintaining the bright red color of meat, while vacuum packaging is the preferred choice for achieving extended shelf life (e.g., long-distance distribution and retail frozen storage) (O'Sullivan & Kerry, 2012; Robertson, 2013).

Active and intelligent packaging strategies have demonstrated great promise to be used in packaging solutions for meat and fish. While active packaging can bring additional functionality to the material used for food contact, intelligent packaging monitors the status of food or the environment surrounding food and communicates the changes with consumers or others within the supply chain domain, supporting strategies to extend best-before dates and shelf life.

The most common strategies are related to either controlling the atmospheric gas composition or releasing active ingredients into the headspace and/or directly into the food. One of the challenges in developing active packaging materials is the selection, incorporation, and control of the active ingredients used, as these must be justified by a technological need and should be verified within the regulatory framework, i.e., as food contact material or as food additives (Enescu et al., 2019). The active agents can act as gas scavengers, to reduce the amount of oxygen, moisture or ethylene inside the packaging, or they can be active release systems, such as antimicrobial or antifungal compounds that reduce microbiological growth (Azevedo et al., 2022). The active materials can be natural, synthetic, organic and inorganic, and their safety has to be guaranteed, in addition to their regulatory compliance.

In the active scavenging systems, the most popular are oxygen and moisture absorbers. Oxygen absorbers are a way to further improve the barrier properties of the packaging material. Oxygen absorber can be applied as a sachet placed inside packaging or incorporated an additive formulated for blending with plastic resins and sucks up the oxygen inside acting as an additional oxygen barrier. This helps food product to reach its desired shelf life. Some commercially available oxygen absorbers are: Avient (product name: Amosorb™, USA/Canada)[1] and OxySorb Absorber (product name: OxySorbTM, India).[2] Likewise, moisture absorber is a thin pad mostly placed under meat and fishthat soaks the released fluids from food to control the relative humidity inside the packagingSome examples of products in the market are Interfresh Concepts (product name: InterSorb Pad, Netherlands),[3] Tipack Group (product name: Soaker Pad, China)[4] and Sirane Group (product name: Dri-Fresh®, United Kingdom).[5]

Intelligent indicators/sensors have also been proposed to decrease food waste and increasing sustainability by offering more dynamic “best-before” dates (Lee et al., 2019), and could be of great interest for fresh meat, fish, and poultry sectors (Obaidi et al., 2022). The spoilage of these products is mainly driven by microorganisms producing unwanted metabolites. As these metabolites accumulate in the package’s headspace, they can be monitored. For example, an elevation in pH can be detected with appropriate pH-sensitive dyes entrapped within an indicator matrix, causing a visible color change easily noticed by consumers (Kim et al., 2017).

4. Bioplastic packaging

4.1. Definitions, sources, and material properties

Bioplastics still account for roughly 0.5% of the plastics produced annually, but production continues to grow (European Bioplastics, 2023b). The global production capacity of bioplastics was estimated at around 2.18 million tons in 2023, and it is expected to be more than triple in next 5 years in 2028 (European Bioplastics, 2023b). Although the food and beverage sectors are the leading user of bioplastics in packaging, the supply of such material is still limited. Furthermore, the end-of-life of bioplastics continues to be a major environmental challenge due to the complexity of sorting and recycling heavily food-contaminated post-consumer plastic.

The emergence of new materials and solutions in this growing industry requires the development of standards. This will also include attention to the safety of these biomaterials both in relation to food and environment. The term "bioplastic" is ill-defined, currently creating misperception and enormous confusion, with different definitions used by different stakeholders of the value chain. Bioplastics can be assigned to three categories depending on the origin of the raw material and its biodegradability (Fig. 2). The concept of "bio-based" refers to the origin of the raw material. Bioplastics can be represented with their “bio-based carbon content” or “bio-based mass content”, which rely on two different measurement methods giving different respective percentage values. With this first approach, “bio-based carbon content" is typically determined by measuring the carbon fraction (C^{14}-method) and expressed as a percentage of the carbon the material contains (organic carbon or total carbon). This approach is recognized in standards such as EN 16640 in the EU, ISO 16620-2 internationally, and ASTM 6866 in the US with corresponding certification schemes (TÜV Austria, DIN CERTCO including OK bio-based and DIN geprüft bio-based labels). Currently, there is no obligation for producers to indicate the fraction of bio-based components in their products.

The term "biodegradable" instead refers to the ability of a material to decompose through microbial activity. Some, but not all, bio-based bioplastics are biodegradable, but some, such as bio-PE and bio-PP, are not. There are also fossil-based plastics which are biodegradable, as shown in Fig. 2. The lack of specific definitions leaves room for use of various qualifiers (ecological, sustainable, green, etc.), creating a false sense of sustainability of the products (greenwashing) (Bhagwat et al., 2020). “Biodegradation” is the term used to describe the process of microorganisms consuming organic carbon in a material, and it is the name of an important test criteria in the ASTM compostability standard specifications. It is not technically incorrect to refer to certified compostable products as “biodegradable”. However, a product labeled as biodegradable without any further context for the time and environmental conditions needed for degradation may lead to significant confusion. The term "compostable" which is used interchangeably with the term “biodegradable” has a distinct meaning referring to the ability of a material to biodegrade in a sufficiently short time under conditions suitable for composting (Cruz et al., 2022). There are three internationally accepted standardization bodies including the European Committee for Standardization (CEN), the American Society for Testing and Material (ASTM), and the International Organization for Standardization (ISO) (Jayakumar et al., 2023) along with other institutes from different countries such as Italian and German Institute of Standardization (UNI and DIN), Japanese Standardization for Association (JAS), Australian Standard (AS) (Folino et al., 2023). These standards are categorized into two main groups “standard specifications” describing product requirements, and setting a test scheme combining different test criteria, and pass levels. ASTM D6400 and EN 13432 are two widely used standard specifications for composting plastics in thermophilic conditions of which the most adapted standard testing methods, namely ISO 14855 and ASTM D5338 are core components. These standard specifications have been systematically reported in recent works (Bher et al., 2023; Folino et al., 2023; Jayakumar et al., 2023). Briefly, standard specification ASTM D6400 requires at least 60% of the material biodegraded in a maximum period of 180 days at thermophilic temperature (mainly at 58 °C) and 55% RH. However, the fate of the remaining 40% should also be of concern. The main European standard specification, EN 13432 standard, has a more stringent threshold, requiring disintegration within 12 weeks and biodegradation of 90% of the materials in a commercial composting unit at 58 °C and 55% RH within 180 days. It is then clear that universal standards are an essential first step to ensure that all packaging practitioners as well as all end users (consumers) can be well informed, can refer to the same conditions, and can choose the correct waste treatment stream.

In industrial composting facilities, the required conditions are provided for the conversion of certified compostable plastic products by using known processing parameters (European Bioplastics, 2023c). Contrary to industrial composting, home composting is climate dependent and environment dependent, and therefore it is very hard to develop harmonized standards, regulate or assess compostability claims (European Bioplastics, 2023d). Several national standards for home compostability of bioplastics and corresponding certification schemes, mainly based on EN 13432, require bioplastics to be tested under the conditions found in home composting to confirm compliance, which involves lower temperatures and longer dwell times compared to industrial composting facilities.

4.2. Bio-based, non-biodegradable bioplastics

It is possible to produce conventional plastic materials from

---

[1] Avient (product name: Amosorb™, USA/Canada), https://www.avient.com/products/polymer-additives/barrier-and-scavenger-additives/colormatrix-amosorb-4020r-rpet-booster. Accessed November 8, 2023

[2] OxySorb Absorbers (product name: OxySorbTM, India), https://www.oxygen-absorbers.com/dried-seafood-meat-packaging. Accessed April 29, 2024.

[3] Interfresh Concepts (product name: InterSorb Pad, Netherlands), https://www.interfreshconcepts.nl/en/absorbtion). Accessed April 28, 2024.

[4] Tipack Group (product name: Soaker Pad, China), https://www.tipackgroup.com/fresh-meat-absorbent-pads/62132342.html). Accessed April 28, 2024.

[5] Sirane Group (product name: Dri-Fresh®, United Kingdom), https://www.sirane.com/en/product/dri-fresh-absorbent-meat-pads/. Accessed April 28, 2024.

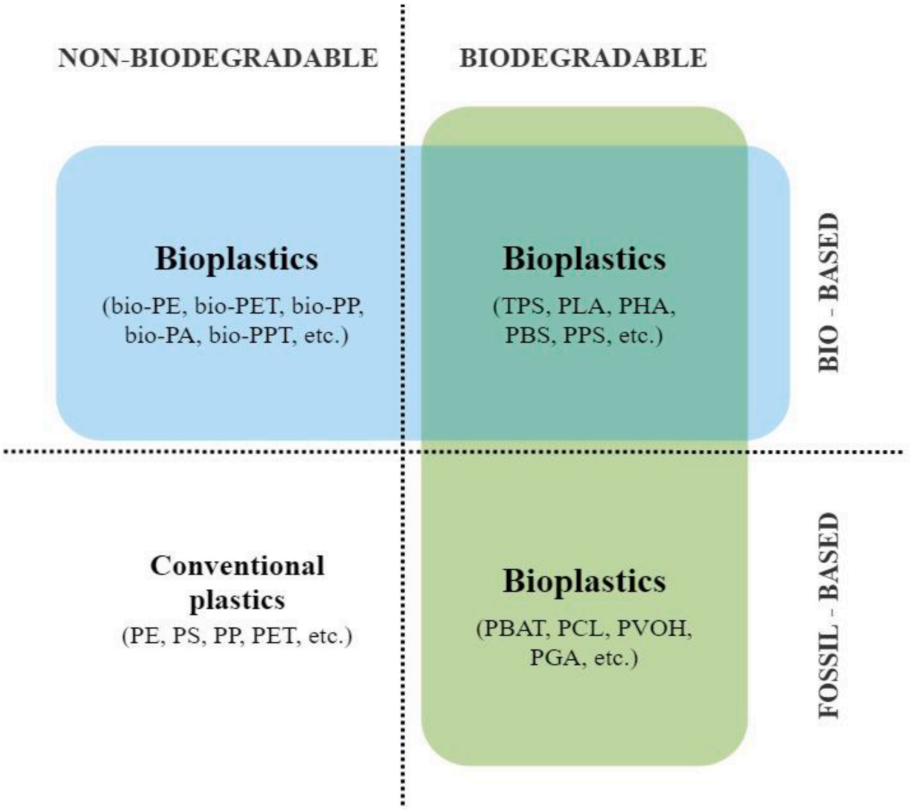

Fig. 2. Classification of bioplastics (Adapted from (Costa et al., 2023)).

renewable resources, i.e., from lignocellulosic biomass, through a series of processes including pretreatment, hydrolysis, fermentation, and chemical modifications. These bioplastics share a chemical composition that is identical to their fossil-based counterparts, allowing their integration into established recycling systems. Like conventional plastics, this series of bio-based plastics are not degraded in the environment, so if they are not properly disposed of at the end of their use, they continue to have a serious environmental impact. For these materials, approaches such as pyrolysis and gasification show potential as a means to add value to these discarded materials (Rahman & Bhoi, 2021). One significant challenge associated with these materials is that their "bio-based" designation may mislead consumers into thinking they can be disposed of in the environment or in landfills without adverse consequences. Presently, the accumulation of plastic waste in landfills represents a significant environmental issue, prompting the development of measures and policies aimed at mitigating its impact. Among the most prominent bio-based, non-biodegradable plastics, bio-polyethylene (Bio-PE) with a production rate of 14.8% among bioplastics, bio-polypropylene (Bio-PP) (3.9%), bio-polyethylene-terephthalate (Bio-PET) (4.2%), bio-polytrimethylene terephthalate (Bio-PTT) (13.3%) and bio-polyamide (Bio-PA) (11.1%) are known (European Bioplastics, 2023b).

Bio-polyethylene, Bio-PE, is obtained from bioethanol, which is dehydrated into ethylene and subjected to a complex chemical process to obtain bio-PE as a final product. Chemically speaking, this polymer is identical to conventional PE, and mirrors its properties, including its recyclability. Depending on the degree of polymerization Bio-PE can be distinguished in bio-HDPE, with a low degree of short-chain branching (about seven branches per 1000 C atoms), bio-LLDPE with a high degree of short-chain branching and bio-LDPE with a high degree of short-chain branching + long-chain branching (about 60 branches per 1000 C atoms) (Siracusa & Blanco, 2020). Bio-PE is used to prepare various products that can be used in food industries, some of special interest for fish and meat products are stretching films and crates approved for direct food contact (Sid et al., 2021).

Bio-polypropylene, Bio-PP, is mirror image of polypropylene (PP), the most important organic compound for poly-olefin production after ethylene. Bio-PP is obtained by dimerization of ethylene followed by other chemical steps including isomerization and metathesis to obtain propylene (Siracusa & Blanco, 2020).

Bio-polyethylene terephthalate, Bio-PET, is produced from the oxidation of bioethylene followed by hydration, polycondensation, and dehydration reactions to obtain PET monomers. Afterwards, a polymerization reaction takes place to finally obtain Bio-PET. Generally, all polyesters (e.g. PET, polybutylene succinate (PBS), polybutylene adipate terephthalate (PBAT), and polybutylene succinate adipate (PBSA)) present great potential to be produced from feedstocks (Rabnawaz et al., 2017). Its use, currently, for packaging applications is in bottles (76%), containers (11%) and films (13%).

Bio-polytrimethylene terephthalate, Bio-PTT, is produced similarly to bio-PET. This bio-polyester has extraordinary mechanical properties, processability, and thermal sturdiness (Grujić et al., 2017), making it suitable for its use in food packaging applications.

Bio-polyamide, Bio-PA, is made with repeating amide groups (-CO-NH-) (Marchildon, 2011). Bio-PA has physical and chemical properties well suited for widespread use as a bioplastic, as it exhibits higher thermal stability than many other polymers, it has impact resistance, abrasion resistance as well as chemical resistance (Rahman & Bhoi, 2021). Due to its thermal and fat resistance as well as its aroma and gas barrier properties, it is suited for oxygen-sensitive foods and fatty foods, showing great potential to be used to package fish, sausage casings, and oven/boil-in bags for cooked meats (Félix et al., 2014).

4.3. *Bio-based, biodegradable bioplastics*

Bioplastics belonging to this category are produced from plant biomass, microbial fermentation products, polymers of animal origin, and not from fossil resources. These materials have the characteristic of breaking down under specific environmental conditions. This biodegradation depends largely on the chemical properties of the polymers, it is therefore very difficult to generalize the conditions so as to have realistic end-of-life technologies for these materials. Bioplastics in this category include, for example, starch blends with a production rate of 17.9% in 2022, as well as polyesters such as polylactic acid (PLA) (20.7%), polyhydroxyalkanoates (PHA) (3.9%) and polybutylene succinate (PBS) (0.9%) (European Bioplastics, 2023b). Polymers with active and flexible functional groups in their structure have a higher degradation rate due to their ease of binding to enzymatic sites. Polymer's chain length as well as material's thickness, crystal morphology, microstructure and final composition impact degradation behavior and rate e.g., a shorter polymer chain structure degrading faster than those with more complex polymer chains (e.g., PHA). Hence, despite the potential biodegradability of these plastics, only a robust supply chain collection will lead to promising solutions for large-scale treatment. Composting, perhaps easy to apply on a large scale, can be implemented only if these plastics are collected and separated through the separate collection and transported to industrial composting facilities. Furthermore, a sufficient flow of material would be required to guarantee the continuity, efficiency, and cost-effectiveness of these end-of-life processes.

Recent studies have provided insights into the biodegradation rates of various biodegradable bioplastics under controlled composting conditions. When following ISO 14855 standard, almost 90% of biodegradation for TPS and PHA in the compost environment at 58 °C was achieved within 90 days (Iovino et al., 2008) and 70 days (Weng et al., 2011), respectively. For PLA and PBS, final biodegradability was reported ~60–80% at the end of 90 days (Bher et al., 2019; Luo et al., 2019). In the blend systems, some studies reported that the biodegradation of pure PLA increased from 80 to 100% within 180 days when blended with TPS (Mayekar et al., 2023) and reached to ~90% within 120 days when blended with PBAT (Nomadolo et al., 2022).

The characteristics of some of the most widespread bioplastics in this category are described below.

Thermoplastic starch, TPS, is prepared with native starch, water and/or plasticizers, such as sorbitol, glycerol, and glucose (Wang & Huang, 2007). Their main difference from the original native starch is their thermoplastic behavior. Depending on the starch source, different mechanical properties can be achieved. With the addition of plasticizers, thermal processes, and shear stress, native starch gelatinizes revealing its thermoplastic character. There is a multitude of plasticizers that are used for the production of TPS. The most effective, safest, and least influential in modifying the biodegradability of this material are water, glycerol, and sorbitol, although ethane-1,2-diol, sucrose, glucose, fructose, maltodextrin, urea, and amino acid have also been successfully tested (Bangar et al., 2021).

Polylactic acid, PLA, is a thermoplastic polyester produced through the condensation of lactic acid or the ring-opening polymerization of lactide. Both monomers are derived from fermented starch. PLA finds diverse applications in food packaging including paper coatings, lamination films and bevarage containers. The properties of PLA can vary, ranging from an amorphous, glassy polymer with a glass transition temperature of approximately 50–80 °C to a semi-crystalline polymer with a melting point of 130–180 °C. These variations are influenced by the sequence of enantiomeric repeating units (L and D) in the polymer's structure (Auras et al., 2004). Stereocomplex PLA generally produced in the crystallization of equimolar racemic poly-L-lactide (PLLA)/poly-D-lactide (PDLA) blend from the melt or solution imparts outstanding heat resistance (50 °C higher softening temperature) and gas barrier compared to standard PLA (Chen, Auras, & Uysal-Unalan, 2022; Chen et al., 2023). This temperature shift helps expand its use in currently challenging applications, for example, in coating of hot-filled drink cups.

Polyhydroxyalkanoate, PHA, represents a class of aliphatic polyesters derived from sustainable resources (Park et al., 2024). These biopolymers are synthesized through the fermentation of a carbon source within microorganisms. Depending on the specific microorganisms employed and the environmental conditions during cultivation, it is possible to produce either homopolymers or copolymers incorporating various hydroxyalkanoic acids. Among the most widely recognized PHAs available in the commercial market are poly-3-hydroxybutyrate (PHB), poly-3-hydroxybutyrate-co-4-hydroxybutyrate (P(3-HB-co-4-HB)), poly-3-hydroxybutyrate-co-valerate (PHBV), and polyhydroxybutyrate-co-hexanoate (PHBH). The PHAs are garnering significant interest within the realm of biodegradable polymers, owing to their remarkable attributes. These include exceptional biodegradability across various settings beyond just composting facilities, as well as their versatility. Indeed, PHAs can be formulated and processed for a wide array of applications, ranging from packaging, molded products, and paper coatings to nonwoven fabrics, adhesives, films, and performance-enhancing additives. In contrast to other biopolymers, PHAs stand out thanks to their excellent thermomechanical and barrier properties, making them exceptionally well-suited for use in packaging applications (Park et al., 2024; Plackett & Siró, 2011; Vicente et al., 2023).

Polybutylene succinate, PBS, is a biodegradable aliphatic polyester synthesized by a polycondensation between succinic acid and butanediol, a primary alcohol ($HOCH_2CH_2CH_2CH_2OH$) (Rudnik, 2013). When succinic acid is obtained by green transformations, such as fermentation by microorganisms, thus allows PBS to be considered bio-based. PBS or PBSA can improve the heat-sealability and reduce raw edge penetration/diffusion of the packaging material, for example, the penetration of hot coffee held in a drinking cup. This type of bioplastic has similar properties compared to LDPE, HDPE and PP, especially in terms of elongation-at-break and tensile strength properties. Unfortunately, PBS has a relatively slow degradation rate and poor flexibility due to its high crystallinity, limiting its use in some applications. To solve this drawback, PBS-based copolymers e.g., PBSA, have been developed to broaden the range of physical and chemical properties (Siracusa et al., 2015). PBS and PBSA can be processed by injection molding, extrusion, and film blowing using conventional equipment, thus being a promising polymer for food packaging applications.

Polypropylene succinate, PPS, is a 1,3-propanediol-based homopolyester, with a degradation rate similar to PBS (Umare et al., 2007). PPS can be molded, extruded or machined. In its pure solid form, it is opaque white to light tan in color. Its maximum service temperature is 218 °C. PPS is one of the most important high-temperature polymers because it exhibits several desirable properties. These properties include resistance to heat, acids and alkalis and mold, bleaches, aging, sunlight, and abrasion. Polyphenylene sulfide-based compounds are used for applications where high strength and chemical resistance at elevated temperatures are required.

4.4. *Fossil-based, biodegradable bioplastics*

Not all biodegradable plastics derive from renewable, bio-based sources. There are fossil-based polymers that are biodegradable. These, like the bio-based, biodegradable plastics identified above, are characterized by various end-of-life options. The most established of these biopolymers are PBAT, polycaprolactone (PCL), polyvinyl alcohol (PVOH), and polyglycolic acid (PGA). The biodegradation rates of these materials vary substantially. For example, according to ISO14855, ~90% of biodegradation under controlled compost at 58 °C was reached for PCL at 47 days (Funabashi et al., 2009); for PGA at 100 days (Jem & Tan, 2020), for PBAT at 90 days (Dammak et al., 2020). It is worth noting that the structure of PCL is analogous to that of a waxy natural polymer, cutin, and this makes it easily degraded by lipases and esterase of different microorganisms such as *Aspergillus* sp.*,* *Fusarium* sp.. *Clostridium* sp., among others. Other biopolymers have also been successfully blended with PCL, for instance; PCL/starch blends are commercialized for garbage bags in Korea (Yukong company) (McKeen, 2021). In the case of PVOH, high resistance of highly hydrolyzed PVOH to biodegradation in soil/compost environments was repeatedly reported, and when compared to other polymers, such as PHB and PCL, PVOH was attacked very slightly by microorganisms under the same conditions (Chiellini et al., 2003), addressing that PVOH-degrading microbial strains might have been absent in the studied environmental matrices. In agreement with this highlight, pure PVOH, according to ISO 14855, was only biodegraded ~50% within 45 days of testing but had a faster degradation rate when blended with starch and antimicrobial essential oils (Cano et al., 2016).

Polybutylene adipate-co-terephthalate, PBAT, is the most popular and promising among the aliphatic-aromatic co-polyesters, with prospects for development in a wide range of applications (Jian et al., 2020). In general, polyesters are synthesized by polycondensation by combinations of diols and dicarboxylic acids. PBAT can be produced by polycondensation reaction between butanediol (BDO), adipic acid (AA), and terephthalic acid (PTA), using very specific pressure and temperature conditions in the presence of different metals to favor the condensation reaction (Jian et al., 2020). PBAT shows similar characteristics to those of low-density PE (LDPE), being more flexible compared to most biodegradable polyesters such as PLA or PBS (Nagarajan et al., 2013).

Polycaprolactone, PCL, is another fossil-fuel based polymer that has been increasing its applications in food packaging. It has high mechanical resistance, and good elastic properties (Reshmy et al., 2021). Due to its high permeability, especially for oxygen and water vapor, it is usually blended with other materials to fulfill the requirements in food packaging applications (Corres et al., 2020). This synthetic polyester is made by ring-opening polymerization of ε-caprolactone, commonly derived from fossil carbon, using a catalyst such as stannous octanone. PCL can also be produced from renewable resources via the chemical treatment of saccharides (Gregory et al., 2017).

Polyvinyl alcohol, PVOH, is the outcome of the free radical polymerization of the vinyl acetate, further followed by hydrolysis of acetate groups into hydroxyl-activated groups. Due to its mechanical properties, it is widely used for food packaging. It shows good biodegradability, non-toxicity, good film-forming ability, water processability, and low cost (Zhang et al., 2022). However, it also has some limitations, such as high-water solubility, relatively low tensile strength, and a high capacity for water absorption (Zhang et al., 2022). Recently, it has been shown that such disadvantages can be overcome by blending with other natural polymers (i.e., starch, chitosan), because of its high hydrophilicity and polarity (Zhang et al., 2022).

Polyglycolic acid, PGA, is a bioplastic obtained by polycondensation of glycolid acid (GA) and ring-opening polymerization of glycolide. GA is currently obtained at industrial scale from petrochemical sources, but it has been also synthesized from renewable feedstocks such as sugarcane, sugar beets or pineapple (Jem & Tan, 2020). Although PGA shares a similar chemical structure with PLA, it shows a faster degradation, better gas barrier and mechanical properties compared to PLA due to its high stereoregularity (Samantaray et al., 2020). Nevertheless, due to its high cost, so far PGA has been mainly used in biomedical applications, but it shows great promise for other packaging applications.

5. Bioplastic packaging for fresh meat and fish

With technological advances and growing dynamic research on bioplastics, the packaging field for meat and fish is undergoing a transformation driven by technology, with bioplastics becoming increasingly visible (Table 1). However, a critical barrier to their widespread market implementation of bioplastic is high production costs (Ghasemlou et al., 2024; Rosenboom et al., 2022). For example, bio-based and biodegradable bioplastics range from $2.9 to 7.4/kg except for TPS (<$1.0/kg) while bio-based and non-biodegradable or fossil-based and biodegradable bioplastics are relatively cheaper which is around $1.0–2.0/kg but still higher compared to traditional plastics (Ghasemlou et al., 2024). The production cost can be lowered by implementing one or more strategies; *i)* abundant biomass, or agricultural waste or food waste as the major resources for bioplastic production, *ii)* reduction of the complexisty of biosynthesis process from resources, *iii)* tailoring of bioplastic melt processing techniques, *iv)* governmental policies that promote bioplastic usage and its industrial composting (Ghasemlou et al., 2024; Siddiqui et al., 2024).

Table 1
Bioplastic packaging applications for meat, poultry, and fish.

Food	Packaging material	Typical use
Fresh meat	PLA, PHA, bio-PET	Trays, thermoformed trays
	PLA, PHA, cellulose, starch	Covering films, overwrap, pouches
Fresh fish	PLA	Trays
	PLA, cellulose, starch	Top films – overwrap, pouches
	PVOH, bio-PA	Vacuum pack
Fresh poultry	PBAT, PCL	Overwrap
Organic poultry	PLA	Overwrap, thermoformed bowls, absorb pads
Processed meat products	PLA blend, bio-PE, cellulose	Casings
	PBS	Thermoformed trays
	Starch	Coating layer, overwrap

Abbreviations: PLA: Poly(lactic acid), PHA: Polyhydroxyalkanoates, bio-PET: bio-based Polyethylene terephthalate, PVOH: Polyvinyl alcohol, bio-PA: bio-based Polyamide, PBAT: Poly(butylene adipate-co-terephthalate), PCL: Polycaprolactone, bio-PE: bio-based Polyethylene, PBS: Polybutylene succinate.

Furthermore, optimizing the physical, chemical, and mechanical properties of the materials to fit the needs of the food product is a significant challenge. Finally, their sustainable waste management (i.e., reusability, recyclability, biodegradability, compostability) although technically possible, is not yet a fully implemented reality, as only with harmonization of material use it will be possible to improve sorting efficiencies and process economics.

PLA, cellulose, and starch-based composites, are currently evaluated as potential substitutes for conventional PS or PET trays for MAP, PE films for wrapping, and PS foam trays/boxes. These materials have shown promising oxygen barrier properties and are therefore suitable for MAP applications (Costa et al., 2023). For example, the viability of substituting conventional PVC lidding film sealed on amorphous PET and PE trays with a PLA-based system was evaluated for red meat under the modified atmosphere (66% O_2, 25% CO_2, and 9% N_2). The PLA solution maintained the red color of the meat and preserved it from oxidation (Panseri et al., 2018). This result was consistent with another study (Pettersen et al., 2011) that showed that PLA and starch-based packaging material can be a promising substitute for amorphous PET/PE and HDPE packaging in a modified atmosphere (60% CO_2 and 40% N_2) for fresh salmon fillets. A recent study (Nur Hanani et al., 2022) reported that fish gelatin/silver kaolinite in three different solutions (film, vacuum pack, and MAP (75% O_2, and 25% CO_2)) could comparably substitute the conventional LDPE, PA, PE, and PP packaging systems for fresh beef.

In vacuum packaging, bioplastics such as starch, PLA, TPS, and PHB (Hernández-García et al., 2022; Katekhong et al., 2022) for pork, and PBS (Vytejčková et al., 2017) for chicken have also shown to be a viable alternative to current.

5.1. Active and intelligent bioplastic packaging for fresh meat and fish

Several bioplastic applications have been proposed in this area (Tables 2 and 3), however, the use of bioplastics in scavenging systems is still rare. For example, PLA-based microparticles loaded with alpha-tocopherol have been tested as scavenging materials in food packaging applications (Scarfato et al., 2017). Other works with ascorbic acid and iron or copper chloride (Mahieu et al., 2015), or gallic acid (Pant et al., 2017) have demonstrated the potential of using materials such as TPS and PLC blends and PLA and bioPE multilayers, as active packaging

Table 2
Examples of performance of active bioplastic packaging applications tested in fresh meat and fish.

Product	Material/Production method	Packaging technology/Storage temperature	Active compound	Key highlights from active packaging application	Mechanical properties YM (MPa) TS (MPa) E (%)	Barrier properties WVP [g·mm/(m^2·day·atm)] OP [cm^3·mm/(m^2·day·atm)]	Reference
Fresh chicken meat	Starch (glycerol used as plasticizer)/ solvent casting	Packed in the films/ 3 °C	Torch ginger inflorescence EO (0, 0.1, 0.2, 0.4, 0.8%)	At the end of the storage period, the product showed the lowest coliform count (4.98 CFU/g) and (TBARS) value (0.212 mg MDA/kg). The active compound did not change the organoleptic properties.	YM: Control = 0.4 Active film = 1-3 TS: Control = 0.3 Active film = 0.1-0.6 E: Control = 187 Active film = 30-72	WVP (25 °C, 50% RH): Control = 25 × 10^6 Active film = 33-36 × 10^6	Marzlan et al. (2022)
Chicken meat	PLA/solvent casting	Packed with the sealed films	Thymol EO (10% w/w) Kesum EO (10% w/w) Curry EO (10% w/w)	Qualitative observations showed that product could be preserved in the active packaging until 15 days of storage.		WVP (23 °C, 58% RH): Control = 38 × 10^{-6} Active film = 34-35 × 10^{-6}	Mohamad et al. (2020)
Chicken meat	Potato Starch:Zein (sorbitol and [bmim] Cl as plasticizers)/ solvent casting	Wrapped in films/4 and 25 °C	Sorghum bran extract (25%)	Active packaging extended the shelf life by 2–4 and 10–15 days at 25 °C and 4 °C, respectively, and caused lower changes in the physicochemical parameters (pH, color, weight loss, and TBA value) compared to control packaging.			Tyagi et al. (2023)
Chicken breast	PLA-(WPC:Pullulan) bilayers/solvent casting	Covered with films/ 4 and 10 °C	*Listeria* phage A511 (embedded in the WPC: pullulan matrix) PLA-(WPC:pullulan) bilayers with thickness ratios of 70/30%, 50/50%, 30/70%, and 100%	Active packaging with the phage showed antimicrobial activity against *Listeria monocytogenes*. Active packaging increased the shelf-life Maintaining similar properties.	YM: Control = 34-227 Active film = 65-224 TS: Control = 3-9 Active film = 3-9 E: Control = 159-237 Active film = 147-180	WVP (25 °C): Control = 19-94 × 10^{-2} Active film = 20-110 × 10^{-2}	Kamali et al. (2022)
Fresh minced chicken	PLA coated Chitosan or Chitosan:Sodium Caseinate (1:1)/rod coater Chitosan (1% w/v) coating solution Chitosan (2% w/v): Sodium Caseinate (4% w/v) in ratio of 1:1 coating solution	Covered by the film, then packed in tray with modified atmosphere (80% CO_2, 20% N_2)/4 °C	Rosemary EO (1 and 2% w/w) in coating solution	Active packaging reduced meat oxidation during storage in anaerobic modified atmosphere conditions, maintained MDA and color up to 14 days, and decreased heptanal and ethanol concentration. The results were supported by TBARS analysis.	YM: Control = 1133 Active film = 1323-2073 TS: Control = 93 Active film = 140-160 E: Control = 0.6 Active film = 0.2-0.4	WVP (20 °C, 85% RH): Control = 70 × 10^{-13} Active film = 50-70 × 10^{-13}	Fiore et al. (2021)
Fresh minced chicken	PVOH: Carboxymethyl cellulose (citric acid as crosslinker; glycerol as plasticizer)/solvent casting	Packed in films/ 2–4 °C	Aloe vera extract	Active packaging delayed lipid peroxidation and microbial growth.	TS[1]: Control = ~8-14 Active film = ~10-16 E[1]: Control = ~30-140 Active film = ~30-40	WVP (N.S): Control = 46-70 Active film = 26-50	Kanatt and Makwana (2020)
Minced chicken	PLA film (PEG as plasticizer)/melt processing and	Wrapped with films/4 °C	Bimetallic Ag–Cu NPs Cinnamon EO PLA:Ag-Cu NPs (98/2 and 96/4)	Active packaging with Ag–Cu NPs:Cinnamon EO showed maximum		WVP (23 °C, 50% RH): Control = 27 Active film =	Ahmed et al. (2018)

(continued on next page)

Table 2 (*continued*)

Product	Material/Production method	Packaging technology/Storage temperature	Active compound	Key highlights from active packaging application	Mechanical properties YM (MPa) TS (MPa) E (%)	Barrier properties WVP [g·mm/(m^2·day·atm)] OP [cm^3·mm/(m^2·day·atm)]	Reference
	compression molding		PLA:Cinnamon EO (2:1 ratio) PLA:Cinnamon EO:Ag-Cu NPs (64/32/4)	antibacterial activity for 21 days.		16-40 OP (23 °C, 50% RH): Control = 23 Active film = 14-32	
Minced chicken	Starch:Gelatin (2:1) (glycerol as plasticizer)/solvent casting	Packed in films/ 2–4 °C	Lime juice (3%)	Active packaging provided a longer shelf life (12 days) with improved microbiological quality and lower rancidity levels compared to products packaged with control films (2 days).	TS: Control = 48 Active film = 55 E: Control = 7.9 Active film = 5.9		Kanatt (2020a)
Minced chicken	PVOH:Gelatin (glycerol used as plasticizer)/solvent casting	Packed in films, sealed/2–4 °C	Amaranthus leaf extract (5% v/v)	Samples packed in control films had a shelf life of only 3 days while those in active films were spoiled after 12 days.	TS: Control = 16 Active film = 19 E: Control = 129 Active film = 105	WVTR[2] (N.S.) [g/(m^2.day)]: Control = 28 × 10^2 Active film = 20 × 10^2 OTR[2] (N.S.) [ml/(m^2. day)]: Control = 17 × 10^{-1} Active film = 17 × 10^{-1}	Kanatt (2020b)
Fresh beef fillets	PLA-PVOH-PLA multilayer films/ compression molding PLA film (PEG as plasticizer)/melt processing and compression molding PVOH film with Carvacrol/solvent casting PVOH film with Ferulic acid/melt processing and compression molding	Packed in thermo-sealed bags/5 °C	Carvacrol (~10% w/w in PVOH) Ferulic acid (~2% w/w in PVOH)	Active multilayer packaging controlled the microbial growth for 17 days compared to the 3 days of the control packaging.	YM Control one layer = 54 Control multilayer = 1038 Active film one layer = 40-68 Active film multilayer = 1024-1111 TS: Control one layer = 44 Control multilayer = 33 Active film one layer = 23-71 Active film multilayer = 25-34 E: Control one layer = 34 Control multilayer = 97 Active film one layer = 58-140 Active film multilayer = 8-48	WVP (23 °C, 50% RH): Control one layer = 71 × 10^6 Control multilayer = 58 × 10^6 Active film one layer = 600-2800 × 10^6 Active film multilayer = 45-54 × 10^6 OP (23 °C, 50% RH): Control one layer = 49 × 10^2 Control multilayer = 60 × 10^2 Active film one layer = 15-39 × 10^2 Active film multilayer = 1300-4400 × 10^2	Andrade et al. (2022)
Fresh beef	PLA film/extrusion-casting Grafting of PLA with active compounds by coating	Packed in PLA bags sealed with a heat sealer/4 °C	Nisin−g−PLA film (5.34 μg of protein/cm^2 on the surface ε-polylysine−g−PLA film (3.04 μg of protein/cm^2 on the surface)	TVC of the control sample exceeded 7 log CFU/g after 11 days of cold storage versus 15 days for the active films.			Huang et al. (2020)
Fresh beef	PLA/melt mixing and blow film extrusion	Vacuum packaged with the films/4 °C	Green tea extract (2 and 4%) Rosemary extract (2 and 4%) A mix of green tea extract	Active packaging inhibited the formation of MDA content for 11 days, indicating a decrease in the primary oxidation.	YM: Control = 184 Active film = 174-229 TS: Control = 16	WVP (21 °C, 0%RH): Control = 48 × 10^{-3} Active film = 32-86 × 10^{-3}	Andrade, Barbosa, et al. (2023)

(*continued on next page*)

Table 2 (*continued*)

Product	Material/Production method	Packaging technology/Storage temperature	Active compound	Key highlights from active packaging application	Mechanical properties YM (MPa) TS (MPa) E (%)	Barrier properties WVP [g·mm/(m^2·day·atm)] OP [cm^3·mm/(m^2·day·atm)]	Reference
			(2%) and rosemary extract (2%)	The best results were observed for packaging with 4% green tea extract.	Active film = 14-16 E: Control = 433 Active film = 263-442	OP (23 °C): Control = 36 Active film = 43-57	
Fresh beef	PVOH (glycerol as plasticizer)/solvent casting	Wrapped in films/4 °C	Hybrid levan:Ag/AgCl NPs (0.5, 1 and 2%)	Active packaging showed a significant inhibitory effect against tested bacteria. The highest concentration of active compound was more efficient.	TS[1]: Control = ~5 Active film = ~6-9 E[1]: Control = ~150 Active film = ~40-80		Haddar et al. (2021)
Fresh beef meat	PLA/single screw extruder	Vacuum packaged and protected from the light/4 °C	Pomegranate peel and pomegranate peel extract (3%)	Active packaging prevented lipid oxidation and presented antimicrobial activity against *Staphylococcus aureus* during storage.	TS[1]: Control = ~38 Active film = ~15-20 E[1]: Control = ~3.5 Active film = ~5.5–11.5	WVTR[2] (23 °C) [g/(m^2.h)]: Control = 1.99 Active film = 1.94	Andrade, Rodrigues, et al. (2023)
Beef	PLA/compression melting Coating by immersion	Placed into films and sealed/7 °C	Clove EO-Chitosan emulsion (0.75% v/v) Argan EO-Chitosan emulsion (0.75% v/v)	Active packaging delayed the spoilage.		OTR[2] (23 °C, 50% RH) [ml/(m2. day)]: Control = 48 × 10^1 Active film = 42-213	Stoleru et al. (2021)
Rump steaks	Corn Starch:Gelatin film (glycerol as plasticizer)/solvent casting	Packed in PS trays, and covered with two pieces of the biodegradable films, then hermetically sealed with glue/cold	Corn stigma extract (15 and 25% w/v)	Active packaging reduced mesophilic and psychotropic microorganisms after 3 days of storage. pH levels and TBARS values decreased with extract.			Boeira et al. (2021)
Ground beef	Cassava Starch film (glycerol as plasticizer)/solvent casting	Packed with films/4 °C	Oregano EO (2% w/v) Pumpkin residue extract (3% w/v)	Active packaging incorporated oregano EO demonstrated antimicrobial activity against mesophilic bacteria, coliforms, and Salmonella as well as antioxidant activity. Active packaging incorporated oregano EO kept the pH at low values until the 6th day of storage.		WVP (25 °C, 75% RH): Control = 97 × 10^1 Active film = 229 × 10^1	Caetano et al. (2017)
Ground beef	PLA/solvent casting	Packed in PLA films and then completely covered with permeable PE bags/4 °C	*Origanum majorana* EO (1% and 1.5% v/v) ZnO$_2$ NPs (1% w/v)	Active packaging with 1.5% *O. majorana* EO extended shelf life and led to better sensorial properties.	YM: Control = 1.5 Active film = 0.2-0.7 TS: Control = 16 Active film = 4-20 E: Control = 52 Active film = 39-76	WVP (20 °C, 0% RH): Control = 28 × 10^2 Active film = 32-138 × 10^2	Negahdari et al. (2021)
Pork meat	Cassava Starch-(PLA:PHBV) bilayer/compression molding Starch:Gellan Gum (90:10) for cassava starch film (glycerol as plasticizer)/melt	Vacuum-packed in heat-sealed bags/5 °C	Ferulic 2% (w/w) p-coumaric 2% (w/w) Protocatechuic acid 2% (w/w)	Active packaging reduced the lipid oxidation and microbial counts (mainly lactic acid bacteria) during storage.	YM: Control = 834 Active film = 633-822 TS: Control = 12 Active film = 8-9	WVP (25 °C, 53% RH): Control = 28 × 10^2 Active film = 10-13 × 10^2 OP (25 °C, 53% RH):	Hernández-García et al. (2022)

(*continued on next page*)

Table 2 (*continued*)

Product	Material/Production method	Packaging technology/Storage temperature	Active compound	Key highlights from active packaging application	Mechanical properties YM (MPa) TS (MPa) E (%)	Barrier properties WVP [g·mm/(m^2·day·atm)] OP [cm^3·mm/(m^2·day·atm)]	Reference
	processing and compression molding PLA:PHBV film (75:25)/melt processing and compression molding				E: Control = 2 Active film = 2-3	Control = 81 × 10^8 Active film = 54-67 × 10^8	
Pork	PBAT/solvent casting	Wrapped/4 °C	Ag-TiO_2 NPs (1 and 2 %)	Active packaging decreased the aerobic plate count, sensory score decline, drip loss, and water activity. Active packaging slowed the increase in pH value, and total TVBN during storage and extended the shelf life by 12–15 days by inhibiting surface microbial growth.			Zhang et al. (2021)
Chilled pork meat	(Wheat Starch:Pea Starch (50:50)): Chitosan (glycerol as plasticizer)/solvent casting	Wrapped/4 °C	*Portulaca oleracea* extract (0.15, 0.30, and 0.45% of the solution)	Active packaging was effective at controlling shelf-life during 16 days of storage compared to 6 days of shelf life of product packaged control film and PE film.	TS[1]: Control = ~35 Active film = ~15-20 E[1]: Control = ~135 Active film = ~170-190	WVP (97% RH): Control = 11 × 10^{10} Active film = 12-18 × 10^{10}	Fan et al. (2023)
Raw sliced pork	PLA:Wood Sawdust (95:5)/blown extrusion Diffusion coating	Packed in direct contact with the active film and placed in a tray/4 °C	Pediocin PA-1/AcH (2.75 μg protein/cm^2 film surface)	Active packaging inhibited *Listeria monocytogenes* on raw sliced pork.	TS: Control = 8 Active film = 7-10 E: Control = 5 Active film = 4-5		Woraprayote et al. (2013)
Pork sirloin boneless steaks	PBAT:TPS film (30:70 or 40:60)/blown extrusion	Placed between PBAT:TPS films and packed in vacuum bags (OPA-LLDPE)/4 °C.	Sodium nitrite (1–5%)	Active packaging reduced TVC, lactic acid bacteria, yeast, and molds, and stabilized lipid components.	YM[1]: Control = ~25-33 Active film = ~17-27 TS[1]: Control = ~5-8 Active film = ~4-8 E[1]: Control = ~13-16 Active film = ~8-16	WVP[1] (25 °C, 50% RH): Control = ~260-290 Active film = ~310-450 OP[1] (N.S): Control = ~400-600 Active film = ~1100-1.2	Katekhong et al. (2022)
Pork collar	PBAT:TPS (60:40)/blown single-screw extruder	Placed between films, heat-sealed into packages/4 °C	Nisin (0, 3, 6 and 9% w/w) Nisin:EDTA (3 and 6% w/w)	Active packaging with Nisin:EDTA effectively inhibited lipid degradation and microbial growth, thus stabilizing redness and delayed meat discoloration.	TS[1]: Control = ~15 Active film = ~2-10 E[1]: Control = ~900 Active film = ~150-650	WVP[1] (25 °C, 53% RH): Control = ~21 × 10^1 Active film = ~15-21 × 10^1 OP (23 °C, 50% RH): Control = 17 Active film = 17-21	Leelaphiwat et al. (2022)
Ground pork meat	PBA:TPS (60:40)/melt processing and blown extrusion	Packed in three side-sealed bags - vacuum packed in nylon bags/4 °C	ZnO NPs (1–5%)	Active packaging reduced lipid oxidation and delayed microbial growth, resulting in a lower TVC, lactic acid bacteria and yeast and mold.	TS[1]: Control = ~12 Active film = ~7-10 E[1]: Control = ~480 Active film = ~375-480	WVP (25 °C, 50% RH): Control = 13 Active film = 15-20 OP (23 °C, 50% RH): Control = 28	Phothisarattana et al. (2022)

(*continued on next page*)

Table 2 (*continued*)

Product	Material/Production method	Packaging technology/Storage temperature	Active compound	Key highlights from active packaging application	Mechanical properties YM (MPa) TS (MPa) E (%)	Barrier properties WVP $[g\cdot mm/(m^2\cdot day\cdot atm)]$ OP $[cm^3\cdot mm/(m^2\cdot day\cdot atm)]$	Reference
						Active film = 33-58	
Minced pork	Banana Starch film/solvent casting	Placed on a PS tray and covered by the films	Banana peel extract	Active packaging decreased the TBARS value.	TS: Control = 31 Active film = 4-5 E: Control = 15 Active film = 10-12	WVP (25 °C): Control = 33 × 10^9 Active film = 84-96 × 10^9	Taweechat et al. (2021)
Fresh fish fillets	PLA film (glycerol as plasticizer)/solvent casting	Wrapped with films/4 °C	ZnO NPs (1.5% w/w) *Zataria multiflora Boiss* EO (0.5, 1, 1.5% w/w) *Menthe piperita* L. EO (0.5, 1, 1.5% w/w)	Active packaging significantly increased the shelf life from 8 to 16 days by decreasing microbial growth and reaching the lowest TBARS and TVBN values.			Heydari-Majd et al. (2019)
Fish fillets	PBAT film/melt extrusion	Wrapped with films and heat-sealed/7 °C	Oregano EO (2.5, 5.0, 7.5 and 10.0% w/w)	Active packaging decreased total coliforms, *Staphylococcus aureus*, and psychotropic microorganisms. All active formulations (except for 2.5%) were able to extend the shelf life up to 10 days.	YM[1]: Control = ~47 Active film = ~42.5–48.5 TS[1]: Control = ~15.75 Active film = ~13.75–17.25 E[1]: Control = ~440 Active film = ~350-375	WVP (22.4 °C, 71.3% RH): Control = 92 × 10^3 Active film = 101-114 × 10^3	Cardoso et al. (2017)
Fish fillets	Starch (glycerol as plasticizer)/solvent casting	Packed with the sealed films/4 °C	Oregano EO (0, 4, 4.5, 5, 6 and 7% w/w)	Active packaging with 4.5% oregano EO showed greater resistance, less oxidation, and less microbiological growth in 6 days of storage compared to control packaging.	TS: Control = 2 Active film = 3-5 E: Control = 138 Active film = 138-189	WVP (75% RH): Control = 89 × 10^1 Active film = 0.37-0.6 × 10^3	Martins et al. (2021)
Fresh grouper fillets	PLA/extrusion casting – laminating	Covered with the film/4 or 25 °C	Chitosan (0.5% w/w) EDTA (20 mM):Nisin (0.02% w/w) Chitosan (0.5% w/w): EDTA (20 mM):Nisin (0.01 or 0.02% w/w)	Active packaging with chitosan, EDTA, and nisin effectively reduced the mesophilic, coliform, and spoilage bacteria counts, as well as the TVBN content during storage at 4 and 25 °C, indicating better preservative efficacy compared to control films and other active packaging alternatives.	TS: Control = 14 Active film = 5-6 E: Control = 215 Active film = 28-48	WVP (20 °C, 50% RH): Control = 53 Active film = 60-86	Chang et al. (2021)
Grass carp fillets	PLA/extrusion Grafting of PLA with active compounds by coating	Packed in films and sealed on both sides/4 °C	Chitosan-*g*-PLA Lysozyme-*g*-PLA	Active packaging decreased the growth of bacteria (chitosan-incorporated packaging was more effective than lysozyme-incorporated).			Zhang et al. (2022)
Pangasius fish fillets	PLA:Wood Sawdust (95:5)/blown extrusion Diffusion coating	Packed in direct contact with the active film and placed in a tray/4 °C	Bacteriocin 7293 (19.54 μg protein/cm^2 film surface)	Active packaging inhibited the growth of target microorganisms by about 2–5 log CFU/cm^2, depending on bacterial strains, compared with control packaging.			Woraprayote et al. (2018)
Pufferfish fillets	PLA:PHA/extrusion casting	Packed with films and sealed/4 °C.	Oregano EO (4% w/w) Oregano EO:MMT (4% w/w)	Active packaging with Oregano EO:MMT showed the slightest quality difference on the 8th day of storage, extending shelf life by	TS: Control = 39 Active film = 32-36 E: Control = 23	WVP (37.8 °C, 100% RH): Control = 15 × 10^{-4} Active film =	Zheng et al. (2022)

(*continued on next page*)

Table 2 (*continued*)

Product	Material/Production method	Packaging technology/Storage temperature	Active compound	Key highlights from active packaging application	Mechanical properties YM (MPa) TS (MPa) E (%)	Barrier properties WVP [g·mm/(m^2·day·atm)] OP [cm^3·mm/(m^2·day·atm)]	Reference
				2–3 days compared to control packaging.	Active film = 64 -66	16-18 × 10^{-4} OP (23 °C, 50% RH): Control = 23 × 10^1 Active film = 26-29 × 10^1	
Fresh catfish	PLA-Gelatin bilayer/ hot press PLA/compression molding Gelatin (glycerol as plasticizer)/solvent casting	Packed in the bags, heat-sealed/4 °C	Epigallocatechin gallate (3, 6, 9 and 12% w/w) in gelatin solution	Active packaging with 12% epigallocatechin reduced psychrophilic bacteria count, weight loss, peroxide value, and TBARS value along with higher docosahexaenoic acid (C22:6 n-3) content. No difference in overall likeness score was found among all the samples packaged in different bags after 7 days of storage.	YM Control = 1777 Active film = 1596-1770 TS: Control = 26 Active film = 20-24 E: Control = 1.5 Active film = 1.2-1.4	WVP (38 °C, 90% RH): Control = 0.18 Active film = 0.18-0.19	Nilsuwan et al. (2020)
Fresh rainbow trout	PLA (Tween 80 as emulsifier)/solvent casting	Wrapped between two films and then packed aerobically in a LDPE sealed bag/4 °C	Thyme (10% w/w) Rosemary (10% w/w) Oregano EOs (10% w/w)	Active packaging resulted in the retardation of the lipid oxidation and the considerable increase in the shelf-life.	YM: Control = 126 Active film = 37-49 TS: Control = 20 Active film = 14-15 E: Control = 368 Active film = 348-358	WVTR[2] (23 °C, 90% RH) [g/(m^2.24h)]: Control = 38 Active film = 35-38 OTR[2] (23 °C, 0% RH): Control = 87 × 10^1 Active film = 87-94 × 10^1	Zeid et al. (2019)
Japanese sea bass	PLA-(Gelatin: Alginate) bilayer film by coating PLA/melt extrusion Gelatin (10%): Sodium Alginate (2%) coating solution	Packed and heat sealed into films/ 4 °C	1% of cinnamaldehyde or thymol in β-CD molecular inclusion complexes dispersed in the coating solution	Active packaging effectively inhibited the growth of microorganisms, such as Pseudomonas spp. and H$_2$S-producing Shewanella, and reduced the formation of TVBN and TBARS. The best results were observed for active packaging with thymol.	TS: Control = 44 Active film = 31-34 E: Control = 3.7 Active film = 5.1–6.8	WVP (23 °C, 50%RH): Control = 69 × 10^{-2} Active film = 73-82 × 10^{-2} OP (23 °C, 0% RH): Control = 21 × 10^1 Active film = 20-104 × 10^1	Chen, Li, et al. (2022)
Indian white prawn	PLA (PVA as plasticizer and PEG as compatibilizer)/ melt processing and compression - solvent casting	Packed in heat-sealed pouches/ 2 °C	Nanochitosan (0.5, 1 and 2% w/w)	Active packaging with 1 and 2% of nanochitosan reduced microbial growth. The quality parameters of products with active packaging were acceptable until 15 days of storage.	TS: Control = 43 Active film = 16-36 E: Control = 3.66 Active film = 2.10–3.06	WVTR[2] (N.S.) [g/(m^2.24 h)]: Control = 20 Active film = 5 -7 OTR[2] (23 °C) [ml/(m^2. day)]: Control = 48 × 10^1 Active film = 28-213 × 10^1	Fathima et al. (2018)
Large yellow croaker	PLA/extrusion Grafting of PLA with chitosan by coating	Packaged in PLA films/4 °C	Chitosan-*g*-PLA (5.44–8.63 μg of chitosan/cm^2 on the surface) Different MW of chitosan was used.	Active packaging presented lower values of total viable counts, TVBN, TBA, pH, and drip loss. Active packaging delayed the decay of fish fillets for 1–4 days.	TS: Control = 62 Active film = 57-61 E: Control = 114 Active film = 126-151	WVP (23 °C, 50% RH): Control = 58 × 10^{-6} Active film = 43-48 × 10^{-6} OP (23 °C, 50% RH): Control = 19 × 10^1 Active film = 13-16 × 10^1	Hao et al. (2023)

(*continued on next page*)

Table 2 (*continued*)

Product	Material/Production method	Packaging technology/Storage temperature	Active compound	Key highlights from active packaging application	Mechanical properties YM (MPa) TS (MPa) E (%)	Barrier properties WVP [g·mm/(m^2·day·atm)] OP [cm^3·mm/(m^2·day·atm)]	Reference
Sea bream	PBAT/solvent casting	Wrapped in the films and then wrapped using a Parafilm/4 °C	Ag-MMT (2, 3 and 5% w/w)	Active packaging effectively preserved freshness and quality, and increased shelf life up to 15 days.		WVP[1] (N.S.): Control = ~28 × 10^9 Active film = ~11-15 × 10^9 OP[1] (23 °C, 0% RH): Control = ~50 × 10^1 Active film = ~20-28 × 10^1	Seray et al. (2022)
Salmon	PLA:PHB (3:1) (mono-caprylin glycerate and glycerol monolaurate as plasticizer)/extrusion casting	Packed and sealed at atmosphere/4 °C.	Cinnamaldehyde (5%)	Active packaging using glycerol monolaurate as a plasticizer decreased the microbial growth, TVBN and TBA values during 17 days of storage.	TS: Control = 31 Active film = 30-44 E: Control = 14 Active film = 6-44	WVTR[2] (37.8 °C, 10–50% RH) [g/(m2. day)]: Control = 22 Active film = 3-78 OP (23 °C, 50% RH): Control = 66 × 10^2 Active film = 82-86 × 10^2	Ma et al. (2018)
Pacific white shrimp	PBAT:PLA films (60:40)/blown extrusion	Placed between films and heat sealed /4 °C.	Carvacrol EO (3 and 6%) Citral EO (3 and 6%) α-terpineol EOs (3 and 6%)	Active packaging inhibited quality deterioration, including microbial growth, lipid oxidation, and textural change. Active packaging stabilized protein conformation in muscle tissues, leading to delayed drip loss and retained adhesion between shrimp cephalothorax and abdomen and prevented melanosis.	YM: Control = 224 Active film = 219-243 TS: Control = 21.0 Active film = 10-28 E: Control = 263 Active film = 56-315	WVP (25 °C, 53% RH): Control = 10 × 10^1 Active film = 8-12 × 10^1 OP (23 °C, 50% RH): Control = 30 Active film = 39-54	Laorenza and Harnkarnsujarit (2021)
Minced squab	PLA (glycerol as plasticizer)/solvent casting	Covered with PLA films, transferred to bags/4 °C	*Cinnamomum verum* EO (0, 0.3, 0.6, and 0.9 %)	Products packed with active film using 0.6 and 0.9% of *Cinnamomum verum* EO presented lower *Eschericia coli* and *Listeria monocytogenes* counts than the control. Active packaging led to lower TVBN and TBARS values, as well as minor changes in the sensorial characteristics of the products.			Khanjari et al. (2023)

Notes [1]: The value estimated from the figure, [2] Transmission rate.

Table Abbreviations: PLA: Polylactic acid, PEG: Polyethylene glycol, NPs: nanoparticles, PVOH: polyvinyl alcohol, PBAT: Polybutylene adipate-co-terephthalate, TPS: thermoplastic starch, PHA: Polyhydroxyalkanoates, PHB: Poly(hydroxybutyrate), PHBV: Poly(3-hydroxybutyrate-co-3-hydroxyvalerate), PCL: Polycaprolactone, EO: essential oil, Ag–Cu: Silver–copper, [bmim]Cl: 1-butyl-3-methylimida-zolium chloride, β-CD: β-cyclodextrin, EDTA: ethylenediaminetetraacetic acid, Ag: silver, MDA: malonaldehyde, TBARS: thiobarbituric acid reactive substances, TBA: thiobarbituric acid, TVBN: volatile basic nitrogen, TVC: Total viable count, MMT: montmorillonite, RH: relative humidity, TS: Tensile strength, E: elongation at break, YM: Young's modulus, WVP: water vapor permeability, WVTR: Water vapor transmission rate, OP: oxygen permeability, OTR: Oxygen transmission rate, log CFU/g: logarithms of the number of colony-forming units per gram, N.S.: Conditions are not specified.

materials. Recently, a film based on starch and acacia gum with sepiolite clay as active material was shown to successfully absorb ethylene (Upadhyay et al., 2022).

Among the active releasing systems, those loaded with antioxidants and antimicrobials are the most reported. These solutions may provide synergies and retard the oxidation of food components, thereby extending shelf life. These compounds are normally released in the headspace or migrate into the food matrix. The mechanism of action of the antimicrobial compound can vary and will be influenced by several factors such as the material characteristics (chemical composition, solubility, diffusion properties, size, etc.) and the type of microorganism (bacteria – Gram positive or Gram negative, fungi or yeast).

Table 3
Recent research articles on bio-based intelligent packaging of meat and fish, using natural dyes and color indicators.

Natural Dyes/Pigments	Bio-based Binders/matrices	External packaging materials and properties	Main Spoilage Metabolite	Food Application	Reference
Ipomoea coccinea extract	PVOH/Guar gum	Transparent PP tray	No metabolite (color change related with pH)	Chicken fillets	Akhila et al. (2023)
Black carrot anthocyanin	Cellulose Acetate film (4 cm^2)	Validated in Petri dish covered with PVC	Aerobic psychotropic bacterial count	Chicken breast	Franco et al. (2021)
Curcumin	Chitosan/Polyethylene oxide nanofiber	Validated in Petri dish	TVBN	Chicken breast	Yildiz et al. (2021)
Butterfly pea flower anthocyanin	N-glutaryl Chitosan film	Plastic container (no description)	TVBN	Chicken breast	Anugrah et al. (2023)
Black chokeberry extract	Arrowhead Starch and κ-Carrageenan films	Airtight plastic box (no description)	TVBN	Chicken wings	Wang et al. (2023)
Anthocyanin rich grape skin powder	κ-Carrageenan and Hydroxypropyl methylcellulose blend film	Validated in Petri dish	TVBN	Pork meat	Chi et al. (2020)
Roselle anthocyanin	Starch/PVOH film (2 × 2 cm)	Packing box (20 × 10 × 6 cm) (no details)	TVBN	Pork meat	Zhang et al. (2019)
Red cabbage anthocyanin	PVOH/Chitosan film	Food partially wrapped with PVOH/CH film and put in Petri dish	No metabolite (only color change of films attached to pork surfaces)	Pork slices	Vo et al. (2019)
Saffron petal and barberry anthocyanins	Gelatin/Chitin nanofiber films	PET box	TVBN	Fish fillet	Khezerlou et al. (2023)
Red cabbage extract (RCE)	Gelatin, Carboxymethyl cellulose and Chitosan films (both monolayer and multilayer films)	Petri plates	TVBN	Tilapia fish fillets	(Zam et al., 2022)
Curcumin/Anthocyanin	Starch/PVOH film	PET trays (no details)	TVBN	Fish (Bighead carp)	Chen, Zhang et al. (2020)
Alizarin	Cellulose Acetate nanofiber	Validated in sterile jar	TVBN	Rainbow trout fish	Aghaei et al. (2018)
Beet root, elderberry, blueberry, green tea and yerba mate extracts	Furcellaran film	PET trays with transparent covers	TVBN	Atlantic mackerel fillet	Jamróz et al. (2019)
Red poppy anthocyanins (a new pigment)	Chitosan	Rectangular package (no description)	Ammonia	Shrimp	Tavassoli et al. (2023)
Amaranthus leaf extract	PVO/Gelatin film	PVOH Gelatin film pouches	TVBN	Fish, chicken and meat	Kanatt (2020a)
Curcumin	κ-Carrageenan film	Validated in Petri dish	TVBN	Shrimp and pork meat	Liu et al. (2018)

Table Abbreviations: PET: Polyethylene terephthalate, TVBN: Total volatile basic nitrogen, PVOH: Polyvinyl alcohol, PP: Polypropylene, PVC: polyvinyl chloride.

In the fresh meat and fish domain, most of the research has focused on the incorporation of the active material into the packaging matrix. Table 2 summarizes bioplastic-specific active packaging systems including the type of bioplastic, processing and conversion method, film's technological properties as well as incorporated active compounds, intended food products, and key findings on product quality and shelf-life.

Among the active materials used, inorganic materials (some of them in the nanoform) and natural compounds (e.g., plants extract and essential oils) are the most popular, but also enzymes, polysaccharides, and organic acids have been tested.

Several studies are also available where the metabolites produced during storage have been used as a target monitoring of the freshness and quality of meat and seafood. Table 3 gives an overview of current literature for intelligent packaging of meat and fish based on using natural dyes as color-changing indicators directly immobilized into bio-based films or bio-based binders which are mostly applied after lamination.

Dyes/natural colorants are used as a main part of intelligent packaging based on colorimetric transition properties sensitive to changes in the food (pH, volatile spoilage metabolites) or environment (elevated temperature, UV radiation, and humidity). The color changes then promptly indicate food freshness and spoilage. Due to their non-toxic nature, research has shifted to the use of natural dyes or pigments (e.g., anthocyanins and curcumin) in bio-based binders (Bhargava et al., 2020).

When it comes to more details on natural pigments/dyes, anthocyanins are commonly used compounds contributing to color changes (red, orange, blue, and purple) due to modification of the chemical structure of phenolic substances in anthocyanin due to pH variations (Bhargava et al., 2020; Latos-Brozio & Masek, 2020). For example, roselle anthocyanins have been applied to monitor pork freshness in intelligent packaging based on starch, PVOH and chitosan films(Zhang et al., 2019). Curcumin, a major yellow pigment extracted from turmeric, also has a pH responsive property, and is used with biocompatible and biodegradable polymers such as chitosan (Yildiz et al., 2021) and carrageenan (Liu et al., 2018) in intelligent packaging. However, in this case, the color change may not be very distinguishable in the pH range where food spoilage occurs, as the range is from bright yellow at pH 2 to dark red at pH 11 (Yildiz et al., 2021). Latos-Brozio and Masek (2020) produced PLA and PHB with natural colorants using extrusion (160 °C for PHB and 180 °C for PLA) and reported that natural dyes of ß-carotene, curcumin and lutein showed a clear color change under the influence of UV radiation, elevated storage temperature and weathering.

Most of the bio-based intelligent packaging studies using natural colorants with bio-based binders or matrices have been conducted in a small scale, using petri dishes and jars, still far from realistic conditions (i.e. vacuum or MAP) for meat and fish packaging. However, several studies with petroleum-derived materials (PE, PET, PA/PE), have demonstrated the potential of these systems (Karaca et al., 2023; Obaidi et al., 2022).

5.2. *Commercial examples of bioplastic packaging in meat and fish applications*

Finding a balance between the sustainability of the packaging and product quality is a challenge. Substitution of fossil-based plastic (Table 2S) with bioplastic is still at its infancy, in meat and fish applications. When it comes to bioplastic, beverage bottles, and compostable shopping bags have been so far the most common market products.

However, with consumers becoming more conscious of sustainability, the need to address environmental concerns and minimize the ecological impact of packaging materials has led to increased exploration of bioplastic alternatives for diverse applications in the food sector. In this context, findings have demonstrated that bioplastics can have comparable material properties as conventional plastics but have additional benefits that are reduced carbon footprint or compostability as an additional waste management option. However, food needs, required storage conditions, and material functionalities should be holistically considered when designing bioplastic packaging. These are the key factors driving the brands to launch a range of bioplastic-based packaging and tailoring them for the preservation of fresh meat and fish (Table 4).

Coopbox Group produces Naturabox®, a packaging solution made from PLA sourced from Nature Works. PLA is derived from renewable sources and undergoes complete degradation, resulting in carbon dioxide and water. Ecovio® PS1606 from BASF, which is composed of Ecoflex® and PLA made of more than 70% renewable sources, is a compostable packaging solution for fresh meat products in the form of bioplastic and/or coating on paper or paperboard through coextrusion coating. The specific environment, including climate, microorganisms, and substrate, is a factor in the biodegradation of Ecovio® PS1606. Comcoplast Natural Box, an organic biodegradable tray made of 100% PLA, is intended to be used for fresh meat. Anbio Joint Stock Company manufactures 100% compostable meat containers that decompose in 6–12 months into humus, water, and CO_2. PLANTIC™ derived from starch, produces laminated films and trays for meat, fish, and poultry by Plantic Technologies Limited/Kuraray Co. Ltd. Pak & Vac offers an innovative solution with pads made from virgin cellulose for fresh meat and fish. These packaging solutions, ranging from PLA and starch-based materials to cellulose-based innovations, reflect a concerted effort by the meat and fish industries to contribute to the use of more sustainable packaging materials. However, increased innovation in the production of bioplastics with improved technological properties is needed to foster the development of additional commercial applications.

6. Safety of bioplastics used as food contact material

As food contact material, bioplastic packaging for meat and fish needs to demonstrate their safety. They should not transfer any components in the food, which could be harmful to our health, or change the product quality. Furthermore, the safety of the material should also be considered after its use, as it should not decompose in ways that would harm the environment and the ecosystem.

In terms of the chemical migration of substances from food contact material, the EU Commission through Regulation (EU) No. 10/2011 (European Commission, 2011) has established restrictions for the use of substances and mixtures of compounds in plastic FCM materials. Migration tests should be performed based on the type of food and the foreseen intended use and represent worst-case scenarios. While the ‘overall migration limit’ means the maximum permitted amount of non-volatile substances released from a material or article into food simulants, the ‘specific migration limit’ refers to the maximum permitted amount of a given substance released from a material or article into food or official food simulants. Considering the different properties of meat and fish, it is clear that almost all simulants may be needed for migration testing, to cover the product spectrum.

Several migration studies have been performed, either directly using the food matrix (Soares Silva et al., 2023), or food simulants (Fathima et al., 2018; Woraprayote et al., 2018; Zeid et al., 2019), investigating different bioplastic packaging materials. For example, for bio-based and biodegradable PLA-based composite film intended for fish products, the simulants used were water, acetic acid 3% (w/v), ethanol 10% (v/v), and isooctane (Woraprayote et al., 2018), the overall migration rate was proven to be within the limit for food contact applications.

Since biopolymers are in general less stable and have a lower diffusion barrier than conventional polymers, additives may be used to improve their properties, making migration testing even more relevant. Nevertheless, few studies concerning the safety assessment of food packaging made of biodegradable polymers have yet to be reported, and overall and specific migration testing against all potentially harmful migrating substances (nanofillers, plasticizers, antimicrobial additives, etc.) must be investigated to ensure their market (Scarfato et al., 2017).

In addition to potentially harmful compounds, it is also important to provide safety data on nanotechnology applications in biopolymer-based packaging which is considered a promising approach to design active and intelligent packaging. Indeed, the incorporation of nanoparticles or shelf life extending functionalities in bio-based films is considered capable of transforming the entire sector, however, within the regulatory framework ensuring food safety (Adeyeye, 2019; European Commission, 2009). So far, most overall migration experiments have been performed (Doineau et al., 2022) for bionanocomposites, accompanied by some targeted metal migration tests (Kao et al., 2018).

The complex mixture of intentionally (IAS) and non-intentionally added substances (NIAS) which could be present in a food contact material underlines the challenges in packaging migration studies. In many cases, the amount of food contaminants present in the migration solution can pose a significant barrier to their identification, or even detection, depending on the sample matrix. That is particularly true for NIAS screening when non-targeted analysis is executed (Riboni et al., 2023). A potential increase in migration rates in recycled and reused fossil-based food contact materials can also be of concern for bioplastic packaging (Ciano et al., 2023).

7. Consumer perception of bioplastic packaging

A systematic literature review was carried out to understand consumer beliefs regarding bioplastic food packaging. We searched for articles across three research engines (Scopus, Web of Science, and Wiley) using the string: (ALL (“bio-based” OR “biobased” OR “biodegradable” OR “compostable” OR “bioplastic”) AND ALL (“packaging”) AND ALL (“consumer”)). We searched for articles published until August 2023. In total, and after removing duplicates, 1223 articles were identified. In the first stage, an initial assessment of inclusion was performed by reading the abstract of each article. At this stage, review papers and studies that did not involve any primary data collection with individuals were excluded. This exercise resulted in 92 articles. Those articles were then read carefully to assess their relevance (i.e., studying consumer responses to bio-based food packaging). A descriptive analysis of the body of literature on consumer responses to bio-based food packaging resulted in 41 articles, and revealed a steadily growing interest over the years, with most (80%) of the studies being published since (including) 2020, and the first paper published in 2012 (Koutsimanis et al., 2012). Studies have assessed measures such as knowledge (Filho et al., 2022), perceptions and attitudes (Herrmann et al., 2022), implicit attitudes (Koenig-Lewis et al., 2022), recycling behavior (Zwicker et al., 2023), buying intentions (Koenig-Lewis et al., 2022), and willingness to pay (Wensing et al., 2020). The majority of the consumer research work on bioplastic packaging approached packaging as a general application, without a focus on meat and fish applications. Among the articles reviewed, one study (Zakowska-Biemans et al., 2016) specifically focused on processed meat, while one study examined seafood (Almeida et al., 2023). Almeida et al. (2023) revealed that consumers express concerns regarding excessive packaging for seafood products, leading some to refrain from purchasing seafood due to this issue. Consequently, consumers exhibit a strong willingness to pay more for seafood packaged in an environmentally sustainable manner, including the use of compostable packaging, as demonstrated in their research. Additionally, Zakowska-Biemans et al. (2016) found that consumers are willing to pay a premium for biodegradable packaging. These findings contribute to the broader body of research which consistently highlights the positive impact of bio-based and/or biodegradable food packaging on consumer

Table 4
Some examples of commercial bioplastics packaging applications intended for fresh meat and fish.

Bioplastic	Product group	Application	Commercial name	Supplier	Competitive performance	Bio-based content (%) and resource	Biodegradablity or Compostability claim
Bio-based and non-biodegradable							
Biopolymer	Meat and fish	Foam tray	Nature® [a]	ProAmpac		Renewable resources up to 100%	
PS	Meat products	Trays	Styrolution® PS ECO - BC100 [b]	INEOS Styrolution		Renewable resources up to 100%	
TPSB copolymers	Meat products	Flexible films, Trays	STYROLUX® ECO STYROFLEX® ECO [c]	INEOS Styrolution		≥60% from renewable resources	
Bio-PE and Bio-EVA	Meat products	Film	I'm green™ [d]	FKuR		Renewable resource (sugar cane)	
Bioplastic	Meat, fish and poultry	Films, paper composite	Green Choice [e]	Wipak Group		Varying renewable resources (crude tall oil or used cooking oils)	
Bio-based and biodegradable							
PLA	Fresh meat, fish	Trays	Naturalbox® [f]	Coopbox group	Similar performance with EPS for fresh red meat packaging	Renewable resource	Compostable (N.D.)
PLA	Fresh meat	Trays	Organic trays - Natural Box [g]	Comcoplast UK Limited		100% from renewable resource	Biodegradable (N.D.)
PLA	Meat	Trays, containers	AnEco's [h]	Anbio Joint Stock Company		Renewable resources (corn starch, cassava, sugar cane)	Compostable (based on TUV Compost, BPI compostable, Seedling, OK Compost international certificates)
PBAT/PLA blend	Meat and fish	Tray-container, coating	Ecovio® [i]	BASF Corporation	Take the same load as its PE counterpart	Variable bio-based content	Biodegradable and compostable (OK Compost, OK biodegradable, EN 13432, ASTM 6400, AS 4736, CIC, GreenPla, CAN/BNQ 0017–088)
PLA/bio-based copolyester blend	Fresh meat and fish	Films, coatings for paper-based	Ecovio® PS1606 [j]	BASF Corporation	High toughness Excellent welding Good adhesion to cellulose (extrusion coating of paper and board) Barrier for fat, liquids, aromas, and mineral oils, and relatively low water vapor	70% > from renewable resources according to ASTM D 6866	Biodegradable and compostable (ASTM D6400 and DIN EN 13432)
Expanded PLA	Meat and fish	Foam tray	BioFoam® [k]	BEWI	Strong resemblance with EPS based on mechanical properties	>85% from renewable resource	Biodegradable and compostable (EN 13432)
Bioplastic	Meat products	Tray and lid	Mater-Bi® [l]	NovaMont	Good mechanical performance	Renewable resource (non-genetically modified corn starch and vegetable oils)	Biodegradable and compostable (OK Compost in accordance with Standard UNI EN 13432, OK biodegradable, CIC, BPI)
PLA, PLA and Mater-Bi®	Meat and fish	Tray and film	MQ Bio [m]	Petruzalek	Good mechanical performance Impermeable to gases	Renewable resources (corn, beet, and sugar cane)	Biodegradable and compostable (CIC, TUV Austria, EN 13432 standard)
Bioplastic	Meat products (red meat, pork, seafood, poultry)	Pouch, vacuum pouch	Comvac™ [n]	Grounded	High oxygen and water vapor barrier	Renewable resource	Biodegradable and compostable (OK Compost, BPI – ASTM D6400 or D6868, BSC, ABA)
Bioplastic	Poultry, seafood	Pouch, vacuum pouch	Plantcell™ [o]	Grounded	High oxygen and water vapor barrier	Renewable resources (eucalyptus and cassava root)	Compostable (OK Compost, ABA)
Starch-based	Fresh red meat, seafood	Laminated films, trays, pouches	PLANTIC™ [p]	Plantic Technologies Limited/Kuraray Co.Ltd	High gas barrier (good oxygen barrier compared to LDPE)	Renewable resource up to 80% (plant-based sources)	Biodegradable and compostable (OK Compost, OK biodegradable)

(continued on next page)

Table 4 (*continued*)

Bioplastic	Product group	Application	Commercial name	Supplier	Competitive performance	Bio-based content (%) and resource	Biodegradablity or Compostability claim
Fossil-based and biodegradable							
PBAT	Meat	Flexible film	Ecoflex® [q]	BASF Corporation	Elastic Water resistant Tear resistant Printable Weldable		Biodegradable and compostable (ASTM D6400 and DIN EN 13432, GreenPla)
PVOH	Meat product	Barrier films (Flexible and Rigid Packaging)	Kuraray Poval™ [r]	Kuraray Co.Ltd	Water soluble High tensile strength and elastic		Biodegradable (N.D.)
Hydrophobic (less hydrophilic) PVOH	Meat product	Barrier films (Flexible and Rigid Packaging)	Exceval™ [s]	Kuraray Co.Ltd	Water soluble Excellent barrier against oxygen and grease		Biodegradable (N.D.)
PVOH	Meat product	Smokable casings	Mowiflex™ [t]	Kuraray Co.Ltd	Water soluble high tensile strength		Biodegradable (N.D.)
Thermoplastic	Meat products	Bag, film	Biogenpol BG8800 [u]	Marco Polo International	–		Biodegradable and compostable (N.D.)

Abbreviations: PS: Polystyrene, TPSB: Thermoplastic styrene-butadiene copolymers, Bio-PE: bio-based Polyethylene, Bio-EVA: bio-based Ethylene vinyl alcohol, PLA: Poly(lactic acid), PBAT: Polybutylene adipate terephthalate, PVOH: Polyvinyl alcohol, PE: Polyethylene, LDPE: Low density polyethylene, PVA: Polyvinyl acetate; N.D: Non-defined.

[a] Nature® ProAmpac. https://www.proampac.com/en-us/meat-packing/. Accessed October 15, 2023.

[b] Styrolution® PS ECO - BC100, https://styrolution-eco.com/styrolution%C2%AE-ps-eco.html#product. Accessed November 4, 2023

[c] STYROLUX® ECO, STYROFLEX® ECO. https://styrolution-eco.com/styrolux%C2%AE-eco.html. Accessed November 4, 2023

[d] I'm green™. https://fkur.com/en/bioplastics/im-green-polyethylene/. Accessed November 4, 2023

[e] Green Choice. https://wipak.com/food-packaging/meat-fish-poultry-packaging-solutions/fish-and-seafood/. Accessed October 15, 2023.

[f] Naturalbox®. https://www.bulpro2004.com/media/NaturalBox_ITA-ENG_web.pdf. Accessed October 15, 2023.

[g] Organic trays - Natural Box. https://www.comcoplast.com/en/bio-schalen/. Accessed October 15, 2023.

[h] AnEco's. https://aneco.com.vn/aneco-compostable-en/. Accessed October 15, 2023.

[i] Ecovio®. https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecovio.html. Accessed October 15, 2023.

[j] Ecovio® PS1606. https://www.basf.com/us/documents/en/general-business-topics/dispersions/PrintingPackaging/2016_BASF_ecovioPS1606_Brochure_LRes.pdf. Accessed October 15, 2023.

[k] BioFoam®. https://bewi.com/products/biofoam/. Accessed October 15, 2023.

[l] Mater-Bi®. https://www.novamont.com/eng/mater-bi. Accessed October 15, 2023.

[m] MQ Bio. https://www.petruzalek.com/sustainable-ready-meal-packaging/cold-ready-meals-containers/mq-bio/. Accessed October 15, 2023.

[n] Comvac™. https://groundedpackaging.co/products/vacuum-bag. Accessed October 15, 2023.

[o] Plantcell™. https://groundedpackaging.co/products/compostable-stand-up-pouch-plantmade/customize. Accessed October 15, 2023.

[p] PLANTIC™. https://www.kuraray.com/products/plantic. Accessed October 15, 2023.

[q] Ecoflex®. https://plastics-rubber.basf.com/global/en/performance_polymers/products/ecoflex.html. Accessed October 15, 2023.

[r] Kuraray Poval™. https://www.kuraray-poval.com/products/kuraray-poval. Accessed October 15, 2023.

[s] Exceval™. https://www.kuraray-poval.com/products/exceval. Accessed October 15, 2023.

[t] Mowiflex™. https://www.kuraray-poval.com/fileadmin/technical_information/brochures/mowiflex/mowiflex_general_information_combining_strengths_of_thermoplastics_and_pvoh.pdf. Accessed October 15, 2023.

[u] Biogenpol BG8800. https://www.matweb.com/search/datasheettext.aspx?matguid=1385d8dd1b34448482f533b0df5972ef. Accessed October 15, 2023.

perceptions and purchasing intentions.

The use of bioplastics in fresh fish and meat applications is still rare. Most consumer behavior perspectives are still sought in regard to measuring their willingness to pay, and overall understanding of bioplastic food packaging. This is in line with the general interest of the scientific community in understanding the market potential for bio-based packaging. It is important to note that most of the studies are survey-based or involve hypothetical examples, as studies testing actual product packaging and direct consumer experiences are not widely available. Furthermore, market-related and culture-related conditions are factors that may impact consumer response to bio-based packaging, limiting the generalizability of the current findings to other contexts.

8. Challenges and opportunities for end-of-life scenario of bioplastic meat and fish packaging

The sustainability and economic viability of bioplastic packaging materials can be improved by increasing their production rate, as with higher supply chain volumes, it is also possible to roll out effective waste management strategies (Fredi & Dorigato, 2021). Although according to life-cycle-assessment evaluations, mechanical recycling is the highest impact waste management strategy to reduce carbon emissions, the best end-of-life scenario for bioplastics is material-specific, as it depends on market share and volumes, processing structure, and available collection sites (Fredi & Dorigato, 2021). Bioplastic packaging material used for food is frequently disposed of with organic waste. This makes recycling impractical and costly, due to the expensive cleaning and separation steps when compared to post-industrial waste (Wojnowska-Baryła et al., 2020). The main advantages and disadvantages of various possible bioplastic waste management approaches with a focus on post-consumer food packaging are interpretatively summarized in Table 5, based on the state of the art. Landfilling of bioplastics together with other municipal solid waste is also considered another end-of-life option, and it is accepted as a cost-effective, simple, and suitable way for plastics that are not currently recyclable or compostable, or for which such facilities are not available. However, it is very critical to emphasize that disposal of plastics into landfill is an unsustainable management strategy and contaminates the world through different means, namely contaminating surface water and groundwater resources and air pollution (Rosenboom et al., 2022), and under the five-step waste hierarchy set by EU Waste Framework Directive, EU highlights that "ending waste to landfill should be the last resort" (EU Water Framework, 2023). To reduce or

Table 5
Summary of the main advantages and disadvantages of various bioplastic waste management approaches with a focus on post-consumer food packaging.

Waste management method		Biodegradable bioplastics		Non-biodegradable bioplastics	
		Advantages	Disadvantages	Advantages	Disadvantages
Recycling	**Mechanical**	A more sustainable end-of-life scenario for clean post-consumer food packaging	Requires clean waste streams (not easy for post-consumer waste, mixed plastic waste, and bioplastics contaminated or collected with organic frame/food waste)	Can be recycled in established recycling streams (bio-PE and PE in the same recycling stream)	Has higher rejection rates due to the sorting of mixed plastic waste and organic/food waste
		Lower greenhouse gas emissions than other bioplastic waste management options	Requires high cleaning, separation, and sorting costs (also capital and labor intensive)	Reduces plastic waste accumulation in landfills	Can contaminate the recycling stream and lower the quality of their fossil-based counterparts if their physical properties are not robust during recycling
		Simple process with potential high purity recycled material	Can be degraded during processing		
	Chemical	Forms new plastics or building blocks for alternative polymers, resulting in identical mechanical properties to their virgin material	Not appropriate for all bioplastics. Requires complex chemical processes (molecules are broken down into monomers, separated from contaminants, and then fed into the polymerization process)	Similar benefits stated for biodegradable bioplastic waste	Similar concerns stated for biodegradable bioplastic waste
		Has more tolerance to greater feedstock variability and contaminants compared to mechanical recycling	The quality of the recycled materials depends on the purity of the feedstock		
		Can be integrated into the conventional plastic waste stream	Needs investment for separate recycling facilities, need for large and viable plants to be cost-effective and to tackle post-consumer waste (capital intensive)		
		Can handle post-consumer waste shortly			
Biodegradation	**Composting (Organic recycling)**	An alternative for materials that are usually not recycled when collected or contaminated with organic waste/bio-waste (bioplastics can degrade during the composting of organic fraction of municipal waste)	Requires longer time (can take several months, especially under mesophilic composting conditions) and careful separation from non-degradable plastics		Should be separated from collected waste. Otherwise, non-compostable items end up mixed with organics and contaminate the compost.
		Final products/compost are used for other purposes (gardening, fertilizers, etc.)	Requires extra attention for food waste contaminated parts (closed vessel composting)		
		Home composting uses less energy (temperature <35–40 °C)	Requires large area and continuous aeration in industrial composting		
		May provide more beneficial options when coupled with anaerobic digestion (higher degradation rates)	Incomplete composting resulted in the accumulation of small fragments e.g., microplastics in compost and their unintentional release into the environment, as well as uncontrolled CO_2 emissions (due to the uncontrolled waste decomposition)		
			Higher global warming potential due to the high industrial composting costs and transportation		
	Anaerobic digestion	Can be a key solution for biowaste management when treated together with food waste and municipal organic waste, making sorting easier at the consumer level.	Requires efficient sorting from other non-biodegradable plastics due to their detrimental effects on the entire process		Improper processes for non-biodegradable bioplastics; should be separated from the collected waste. Otherwise, they can contaminate the digestion process, and impede the production of methane from food waste.
		Protein-rich waste (i.e. food) rich in nitrogen could be co-digested with biodegradable plastics increasing the C/N ratio leading to a more efficient and stable digestion process.	May not be fit for all the biodegradable plastics that have lower C/N ratios or are organic waste-free as they may not provide the necessary carbon source for the microorganisms to effectively break down the organic matter.		
		Potential to increase the efficiency of composting (combined anaerobic digestion and composting treatment of bioplastic collected with organic municipal waste)	The presence of slow-growth microorganisms or fewer enzymes, and the absence of desirable microorganisms or thermophilic conditions that are needed for certain bioplastics can result in low degradation during digestion;		

(*continued on next page*)

Table 5 (continued)

Waste management method	Biodegradable bioplastics		Non-biodegradable bioplastics	
	Advantages	Disadvantages	Advantages	Disadvantages
		thereafter the residual compost needs to undergo aerobic process for complete degradation.		
	Potentially not contribute to an increase in atmospheric CO_2 levels as CO_2 produced in this process is part of the short-term carbon cycle.	Produces methane, which if not properly captured for energy production, can escape into the atmosphere and contribute to global warming		
	The carbon is converted into biogas (a mixture of methane and CO_2) as an energy source.	Standard specifications, test schemes, and certifications for biodegradation of bioplastics in anaerobic digestion systems are lacking.		
Incineration	Can be the source of mono-combustion or co-combustion with municipal solid waste in incinerator plants to produce combined heat and electricity	The release of potentially hazardous emissions and toxins into the environment if incineration is at too low temperatures.	Destruction of hazardous components	Air pollution and residual ash
	CO2 that is emitted can be considered as net neutral.	Loss of the major value of resources/materials	Energy recovery and non-degradable plastic volume reduction	Non-renewable energy source with inefficient energy recovery rates (the loss of valuable resources/materials that could be otherwise recycled)
		Even though the produced CO_2 can be absorbed by the plants used to produce the bioplastics, it still contributes to the overall CO_2 concentration in the atmosphere.		

avoid landfilling, landfill bans, and taxes are planned to be implemented at the EU level. In light of the proven unwanted outcomes of landfilling plastics and planned waste management strategies toward sustainability, landfilling is not considered an optimal approach in this review. Table 5 lists main advantages and disadvantages of the various management approaches to bioplastic, based on current literature (Ali et al., 2023; Bandini et al., 2022; Battista et al., 2021; Calabrò & Grosso, 2018; Dilkes-Hoffman et al., 2019; Fredi & Dorigato, 2021; Gadaleta et al., 2022a, 2022b, 2023; Kosheleva et al., 2023; Kumar et al., 2023; Paul-Pont et al., 2023; Wojnowska-Baryła et al., 2020).

The collection of post-consumer waste requires a detailed classification, especially for bioplastics; this is not current practice, because a very low share of household packaging waste is made of bioplastics (Sadeleer, 2018). In addition to the collection, sorting is critical for post-consumer management steps such as recycling. Only with an effective collection and sorting strategy, it will be possible to obtain cost-effective, high quality, and pure recycled secondary materials (Pandey et al., 2015). However, the presence of many different layers (bioplastic itself) or various compounds (additives including printing, filler, etc.) or food waste-contaminated surfaces will make the separation step an insurmountable challenge, due to costs and effects on final quality (Soroudi & Jakubowicz, 2013).

Recycling of bioplastics can be conducted in closed loops together with fossil-based counterparts. For example, it is possible to recycle bio-PE in the PE stream (Wojnowska-Baryła et al., 2020). For recycling, post-consumer bioplastic or plastic waste contaminated food scraps need to be washed and decontaminated (Calabrò & Grosso, 2018). Composting can complement recycling and may be a preferred solution when recycling cannot or no longer be applied; for example, bioplastic is heavily contaminated with food such as in the case of oil-rich meat and fish. However, great care has to be taken to ensure the absence of various impurities (e.g., conventional plastics or other additives) in the collected biowaste for composting, as the current reality is that composting and anaerobic digestion are only feasible for clean biodegradable plastics due to poor organic collection systems, limited facilities, and the inability of existing facilities (Dilkes-Hoffman et al., 2019) and needs to be adjusted to ensure the required degradation rate of bioplastics (Gadaleta et al., 2023).

Some bioplastics may biodegrade very quickly in one environment but over many years (or not at all) in a different environment. Hence, it is very important to define the timeframe and environmental conditions (media, temperature, humidity etc.) when describing and defining biodegradation of biodegradable bioplastic. In this context, following the testing protocols developed by standards such as ASTM D6400 and EN 13432 can provide a foundation for a structured database, and improve consistency, reliability, and reproducibility of the test results across the test laboratories, even though standardization processes exist at national, continental, and international levels and they do not require the same biodegradation within the same time frame. The biodegradation rate of biodegradable bioplastics including PLA is viable only under specific conditions such as industrial composting setting at thermophilic conditions as it is low if not in the ideal environment (Niaounakis, 2019).

Methane is produced as a bioenergy source from anaerobic digestion of bioplastics in addition to biowaste. Gadaleta, De Gisi, Picuno, et al. (2022) reported that the presence of cellulose acetate as a bioplastic food packaging material during combined anaerobic digestion and composting treatment of organic municipal waste increased the methane yield (app. 4.5%) without toxic effects. This finding has raised interest in evaluating means to treat bioplastics in conventional anaerobic digesters for food waste. The combined systems including anaerobic digestion and composting for bioplastics contaminated with food waste or disposed/collected with organic fractions of municipal solid waste should be verified to clarify the fate of these materials along the treatment chain (Battista et al., 2021). Peng et al. (2022) and Kosheleva et al. (2023) showed that PBAT/PLA blend and cellulose-based bioplastics can be co-digested with food waste. Emissions must be managed, including methane emissions, as they will lead to adverse effects on the environment (Gadaleta, De Gisi, Todaro, & Notarnicola, 2022; Niaounakis, 2019). Incomplete degradation of bioplastic waste during anaerobic digestion and composting leads to problems with the quality of the final compost produced. Lu et al. (2022) showed that anaerobic digestion of the PLA fragments with food waste produced irregular cracking and tiny daughter particles (PLA microparticles), increased the oxygen-containing functional groups, and dissolved organic matter.

The energy from bioplastics can be also recovered by combustion and incineration at the end-of-life (Van Den Oever et al., 2017); however, this should be a least preferred practice to recycling, as the latter will result in higher CO_2 savings (Berger et al., 2023).

Developing cost-effective and technologically viable/efficient waste management systems and end markets for post-consumer bioplastic should be prioritized. Even if both biodegradable and compostable plastics can be degraded to biomass, CO_2, and water, many consumers may be unaware that the conditions in home composters and the open environment differ significantly from those in industrial composting plants. Clear instructions are needed at the consumer level to enhance waste management by preventing contamination of recycling or composting streams by unfitting materials (Paul-Pont et al., 2023).

9. Conclusion and outlook

Bioplastics designed for food packaging are increasingly in focus, due to their potential to lower our carbon footprint. In this work, it is advocated that among all foods, fresh meat and fish stand out as a category well suited to an early implementation of bioplastic packaging solutions, due to the perishable nature and susceptibility to spoilage of these food products. This work uniquely provides a holistic view of food packaging and clearly demonstrates the importance of focusing on the food/package interface. Indeed, it is demonstrated that given their high market value and short shelf life, the choice of the best package will significantly decrease the carbon footprint of the product. As both consumers and packaging practitioners positively perceive biodegradable bioplastics, it should be possible to implement the use of these materials in fresh meat and fish, despite the challenges in terms of scalability, limited availability, and higher costs when compared to conventional fossil-based packaging materials. A better awareness of the technological properties of these materials, including factors such as permeability (water vapor, O_2, and/or CO_2), mechanical strength and elasticity, in relation to the food that they have to protect is necessary, to ensure rapid uptake. In the fresh meat and fish category, the potential of well-suited end-of-life scenarios which include industrial composting may help realizing the full potential of bioplastics, especially amongst certified industrially compostable materials such as PLA and PHA. Indeed, meat or fish contaminated packaging waste can be composted avoiding costly cleaning process of plastics from contamination that is needed for mechanical recycling, and diverting waste from landfill. Current data indeed suggest that composting bioplastic contaminated with these foods may be the most viable and climate friendly solution.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author statement

IUU and ES: conceptualization and methodology. IUU, ES, HC, EO, EE, RMM, FO, MN, MAC, KYP, ZA, DKAU, CK, and PC: writing - original draft. IUU, CER, BMM, and MC: writing - review & editing. All authors contributed to the article and approved the submitted version.

Data availability

Data will be made available on request.

Acknowledgments

This publication is based upon work from COST Action “CA19124 Circul-a-bility” (circul-a-bility.org), supported by COST (European Cooperation in Science and Technology).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tifs.2024.104660.

References

Adeyeye, S. A. O. (2019). Food packaging and nanotechnology: Safeguarding consumer health and safety. *Nutrition & Food Science, 49*(6), 1164–1179. https://doi.org/10.1108/NFS-01-2019-0020

Aghaei, Z., Emadzadeh, B., Ghorani, B., & Kadkhodaee, R. (2018). Cellulose acetate nanofibres containing alizarin as a halochromic sensor for the qualitative assessment of rainbow trout fish spoilage. *Food and Bioprocess Technology, 11*(5). https://doi.org/10.1007/s11947-017-2046-5

Ahmed, J., Arfat, Y. A., Bher, A., Mulla, M., Jacob, H., & Auras, R. (2018). Active chicken meat packaging based on polylactide films and bimetallic Ag–Cu nanoparticles and essential oil. *Journal of Food Science, 83*(5). https://doi.org/10.1111/1750-3841.14121

Akhila, K., Sultana, A., Ramakanth, D., & Gaikwad, K. K. (2023). Monitoring freshness of chicken using intelligent pH indicator packaging film composed of polyvinyl alcohol/guar gum integrated with Ipomoea coccinea extract. *Food Bioscience, 52*. https://doi.org/10.1016/j.fbio.2023.102397

Ali, W., Ali, H., Souissi, S., & Zinck, P. (2023). Are bioplastics an ecofriendly alternative to fossil fuel plastics? *Environmental Chemistry Letters*, 1–12. https://doi.org/10.1007/s10311-023-01601-6

Almeida, C., Laso, J., de Sousa, D. B., Cooney, R., Quinteiro, P., Rowan, N., Dias, A. C., Clifford, E., Reboredo, R. G., Margallo, M., Nunes, M. L., & Marques, A. (2023). Seafood consumers engagement in reducing environmental impacts from packaging. *Science of the Total Environment, 863*. https://doi.org/10.1016/j.scitotenv.2022.160846

Andrade, M. A., Barbosa, C. H., Cerqueira, M. A., Azevedo, A. G., Barros, C., Machado, A. V., Coelho, A., Furtado, R., Correia, C. B., Saraiva, M., Vilarinho, F., Silva, A. S., & Ramos, F. (2023). PLA films loaded with green tea and rosemary polyphenolic extracts as an active packaging for almond and beef. *Food Packaging and Shelf Life, 36*, Article 101041. https://doi.org/10.1016/j.fpsl.2023.101041

Andrade, J., González-Martínez, C., & Chiralt, A. (2022). Antimicrobial PLA-PVA multilayer films containing phenolic compounds. *Food Chemistry, 375*. https://doi.org/10.1016/j.foodchem.2021.131861

Andrade, M. A., Rodrigues, P. V., Barros, C., Cruz, V., Machado, A. V., Barbosa, C. H., … Silva, A. S. (2023). Extending high fatty foods shelf-life protecting from lipid oxidation and microbiological contamination: An approach using active packaging with pomegranate extract. *Coatings, 13*(1), 93. https://doi.org/10.3390/coatings13010093

Anugrah, D. S. B., Delarosa, G., Wangker, P., Pramitasari, R., & Subali, D. (2023). Utilising N-glutaryl chitosan-based film with butterfly pea flower anthocyanin as a freshness indicator of chicken breast. *Packaging Technology and Science*. https://doi.org/10.1002/pts.2736

Auras, R., Harte, B., & Selke, S. (2004). An overview of polylactides as packaging materials. *Macromolecular Bioscience, 4*(9), 835–864. https://doi.org/10.1002/mabi.200400043

Azevedo, A. G., Barros, C., Miranda, S., Machado, A. V., Castro, O., Silva, B., … Cerqueira, M. A. (2022). Active flexible films for food packaging: A review. *Polymers, 14*(12), 2442. https://doi.org/10.3390/polym14122442

Bandini, F., Taskin, E., Bellotti, G., Vaccari, F., Misci, C., Guerrieri, M. C., … Puglisi, E. (2022). The treatment of the organic fraction of municipal solid waste (OFMSW) as a possible source of micro-and nano-plastics and bioplastics in agroecosystems: A review. *Chemical and Biological Technologies in Agriculture, 9*(1), 1–17. https://doi.org/10.1186/s40538-021-00269-w

Bangar, S. P., Whiteside, W. S., Ashogbon, A. O., & Kumar, M. (2021). Recent advances in thermoplastic starches for food packaging: A review. *Food Packaging and Shelf Life, 30*, Article 100743. https://doi.org/10.1016/j.fpsl.2021.100743

Battista, F., Frison, N., & Bolzonella, D. (2021). Can bioplastics be treated in conventional anaerobic digesters for food waste treatment? *Environmental Technology & Innovation, 22*. https://doi.org/10.1016/j.eti.2021.101393

Berger, N. J., Masri, M. A., Brück, T., Garbe, D., Pfeifer, C., & Lindorfer, J. (2023). Utilizing a CHP power plant's energy and CO2 emissions for the manufacture of affordable and carbon neutral algae bioplastic for re-useable packaging. *Industrial & Engineering Chemistry Research, 62*(18), 7275–7296. https://doi.org/10.1021/acs.iecr.3c00590

Bhagwat, G., Gray, K., Wilson, S. P., Muniyasamy, S., Vincent, S. G. T., Bush, R., & Palanisami, T. (2020). Benchmarking bioplastics: A natural step towards a sustainable future. *Journal of Polymers and the Environment, 28*, 3055–3075. https://doi.org/10.1007/s10924-020-01830-8

Bhargava, N., Sharanagat, V. S., Mor, R. S., & Kumar, K. (2020). Active and intelligent biodegradable packaging films using food and food waste-derived bioactive compounds: A review. *Trends in Food Science & Technology, 105*, 385–401. https://doi.org/10.1016/j.tifs.2020.09.015

Bher, A., Cho, Y., & Auras, R. (2023). Boosting degradation of biodegradable polymers. *Macromolecular Rapid Communications, 44*(5), Article 2200769. https://doi.org/10.1002/marc.202200769

Bher, A., Unalan, I. U., Auras, R., Rubino, M., & Schvezov, C. E. (2019). Graphene modifies the biodegradation of poly(lactic acid)-thermoplastic cassava starch reactive blend films. *Polymer Degradation and Stability, 164*, 187–197. https://doi.org/10.1016/j.polymdegradstab.2019.04.014

Boeira, C. P., Alves, J., dos, S., Flores, D. C. B., de Moura, M. R., Melo, P. T. S., & da Rosa, C. S. (2021). Antioxidant and antimicrobial effect of an innovative active film containing corn stigma residue extract for refrigerated meat conservation. *Journal of Food Processing and Preservation, 45*(9). https://doi.org/10.1111/jfpp.15721

Caetano, K., dos, S., Hessel, C. T., Tondo, E. C., Flôres, S. H., & Cladera-Olivera, F. (2017). Application of active cassava starch films incorporated with oregano essential oil and pumpkin residue extract on ground beef. *Journal of Food Safety, 37*(4). https://doi.org/10.1111/jfs.12355

Calabrò, P. S., & Grosso, M. (2018). Bioplastics and waste management. *Waste Management, 78*, 800–801. https://doi.org/10.1016/j.wasman.2018.06.054

Cano, A. I., Cháfer, M., Chiralt, A., & González-Martínez, C. (2016). Biodegradation behavior of starch-PVA films as affected by the incorporation of different antimicrobials. *Polymer Degradation and Stability, 132*, 11–20. https://doi.org/10.1016/j.polymdegradstab.2016.04.014

Cardoso, L. G., Pereira Santos, J. C., Camilloto, G. P., Miranda, A. L., Druzian, J. I., & Guimarães, A. G. (2017). Development of active films poly (butylene adipate co-terephthalate) – PBAT incorporated with oregano essential oil and application in fish fillet preservation. *Industrial Crops and Products, 108*. https://doi.org/10.1016/j.indcrop.2017.06.058

Chang, S. H., Chen, Y. J., Tseng, H. J., Hsiao, H. I., Chai, H. J., Shang, K. C., Pan, C. L., & Tsai, G. J. (2021). Applications of Nisin and EDTA in food packaging for improving fabricated chitosan-polylactate plastic film performance and fish fillet preservation. *Membranes, 11*(11). https://doi.org/10.3390/membranes11110852

Chen, Q., Auras, R., Kirkensgaard, J. J. K., & Uysal-Unalan, I. (2023). Modulating barrier properties of stereocomplex polylactide: The polymorphism mechanism and its relationship with rigid amorphous fraction. *ACS Applied Materials & Interfaces, 15*(42), 49678–49688.

Chen, Q., Auras, R., & Uysal-Unalan, I. (2022). Role of stereocomplex in advancing mass transport and thermomechanical properties of polylactide. *Green Chemistry, 24*(9), 3416–3432.

Chen, J., Li, Y., Wang, Y., Yakubu, S., Tang, H., & Li, L. (2022). Active polylactic acid/tilapia fish gelatin-sodium alginate bilayer films: Application in preservation of Japanese sea bass (Lateolabrax japonicus). *Food Packaging and Shelf Life, 33*, Article 100915. https://doi.org/10.1016/j.fpsl.2022.100915

Chen, H. Z., Zhang, M., Bhandari, B., & Yang, C. H. (2020). Novel pH-sensitive films containing curcumin and anthocyanins to monitor fish freshness. *Food Hydrocolloids, 100*. https://doi.org/10.1016/j.foodhyd.2019.105438

Chi, W., Cao, L., Sun, G., Meng, F., Zhang, C., Li, J., & Wang, L. (2020). Developing a highly pH-sensitive κ-carrageenan-based intelligent film incorporating grape skin powder via a cleaner process. *Journal of Cleaner Production, 244*. https://doi.org/10.1016/j.jclepro.2019.118862

Chiellini, E., Corti, A., D'Antone, S., & Solaro, R. (2003). Biodegradation of poly (vinyl alcohol) based materials. *Progress in Polymer Science, 28*(6), 963–1014. https://doi.org/10.1016/S0079-6700(02)00149-1

Ciano, S., Di Mario, M., Goscinny, S., & Van Hoeck, E. (2023). Towards less plastic in food contact materials: An in-depth overview of the Belgian market. *Foods, 12*(14). https://doi.org/10.3390/foods12142737

Coppola, D., Lauritano, C., Palma Esposito, F., Riccio, G., Rizzo, C., & de Pascale, D. (2021). Fish waste: From problem to valuable resource. *Marine Drugs, 19*(2), 116. https://doi.org/10.3390/MD19020116

Corres, M.Á., Mayor, Á., Sangroniz, A., del Río, J., Iriarte, M., & Etxeberria, A. (2020). Blends based on biodegradable poly(caprolactone) with outstanding barrier properties for packaging applications: The role of free volume and interactions. *European Polymer Journal, 135*. https://doi.org/10.1016/j.eurpolymj.2020.109869

Costa, A., Encarnação, T., Tavares, R., Todo Bom, T., & Mateus, A. (2023). Bioplastics: Innovation for green transition. *Polymers, 15*(3), 517. https://doi.org/10.3390/polym15030517

Cruz, R. M., Krauter, V., Krauter, S., Agriopoulou, S., Weinrich, R., Herbes, C., … Varzakas, T. (2022). Bioplastics for food packaging: Environmental impact, trends and regulatory aspects. *Foods, 11*(19), 3087. https://doi.org/10.3390/foods11193087

Dörnyei, K. R., Uysal-Unalan, I., Krauter, V., Weinrich, R., Incarnato, L., Karlovits, I., Colelli, G., Chrysochou, P., Fenech, M. C., Pettersen, M. K., Arranz, E., Marcos, B., Frigerio, V., Apicella, A., Yildirim, S., Poças, F., Dekker, M., Johanna, L., Coma, V., & Corredig, M. (2023). Sustainable food packaging: An updated definition following a holistic approach. *Frontiers in Sustainable Food Systems, 7*. https://doi.org/10.3389/fsufs.2023.1119052

Dammak, M., Fourati, Y., Tarrés, Q., Delgado-Aguilar, M., Mutjé, P., & Boufi, S. (2020). Blends of PBAT with plasticized starch for packaging applications: Mechanical properties, rheological behaviour and biodegradability. *Industrial Crops and Products, 144*. https://doi.org/10.1016/j.indcrop.2019.112061

Dawson, P. L., Han, I. Y., Voller, L. M., Clardy, C. B., Martinez, R. M., & Acton, J. C. (1995). Film oxygen transmission rate effects on ground chicken meat quality. *Poultry Science, 74*(8), 1381–1387. https://doi.org/10.3382/ps.0741381

Day, B. P. F. (2003). *Novel MAP applications for fresh-prepared produce. Novel food packaging techniques* (pp. 189–207). https://doi.org/10.1533/9781855737020.2.189

Dilkes-Hoffman, L., Ashworth, P., Laycock, B., Pratt, S., & Lant, P. (2019). Public attitudes towards bioplastics – knowledge, perception and end-of-life management. *Resources, Conservation and Recycling, 151*. https://doi.org/10.1016/j.resconrec.2019.104479

Doineau, E., Rol, F., Gontard, N., & Angellier-Coussy, H. (2022). Physical-chemical and structural stability of poly(3HB-co-3HV)/(ligno-)cellulosic fibre-based biocomposites over successive dishwashing cycles. *Membranes, 12*(2). https://doi.org/10.3390/membranes12020127

Domínguez, R., Pateiro, M., Gagaoua, M., Barba, F. J., Zhang, W., & Lorenzo, J. M. (2019). A comprehensive review on lipid oxidation in meat and meat products. *Antioxidants, 8*(10), 429. https://doi.org/10.3390/antiox8100429

Enescu, D., Cerqueira, M. A., Fucinos, P., & Pastrana, L. M. (2019). Recent advances and challenges on applications of nanotechnology in food packaging. A literature review. *Food and Chemical Toxicology, 134*, Article 110814. https://doi.org/10.1016/j.fct.2019.110814

EU Water Framework. (2023). EU water framework directive. https://Environment.Ec.Europa.Eu/Topics/Waste-and-Recycling/Waste-Framework-Directive_en. (Accessed 31 October 2023).

European Bioplastics. (2023a). Bioplastics. https://docs.european-bioplastics.org/2016/publications/fs/EUBP_fs_what_are_bioplastics.pdf.

European Bioplastics. (2023b). Bioplastics market data. https://www.European-Bioplastics.Org/Market.

European Bioplastics. (2023c). Industrial composting. https://Docs.European-Bioplastics.Org/2016/Publications/Fs/EUBP_fs_industrial_composting.Pdf.

European Bioplastics. (2023d). Home composting. https://Docs.European-Bioplastics.Org/2016/Publications/Pp/EUBP_PP_Home_Composting.Pdf.

European Commission. (2009). Commission Regulation (EC) No 450/2009 of 29 May 2009 on active and intelligent materials and articles intended to come into contact with food. Off. *Official Journal of the European Union, 135*, 3–11.

European Commission. (2011). Commission Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food. *Official Journal of the European Union*.

Félix, J. S., Manzoli, J. E., Padula, M., & Monteiro, M. (2014). Evaluation of different conditions of contact for caprolactam migration from multilayer polyamide films into food simulants. *Packaging Technology and Science, 27*(6), 457–466. https://doi.org/10.1002/pts.2046

Fan, X., Zhang, B., Zhang, X., Ma, Z., & Feng, X. (2023). Incorporating Portulaca oleracea extract endows the chitosan-starch film with antioxidant capacity for chilled meat preservation. *Food Chemistry X, 18*, Article 100662. https://doi.org/10.1016/j.fochx.2023.100662

Fathima, P. E., Panda, S. K., Ashraf, P. M., Varghese, T. O., & Bindu, J. (2018). Polylactic acid/chitosan films for packaging of Indian white prawn (Fenneropenaeus indicus). *International Journal of Biological Macromolecules, 117*, 1002–1010. https://doi.org/10.1016/j.ijbiomac.2018.05.214

Filho, W. L., Barbir, J., Abubakar, I. R., Paço, A., Stasiskiene, Z., Hornbogen, M., Fendt, M. T. C., Voronova, V., & Klõga, M. (2022). Consumer attitudes and concerns with bioplastics use: An international study. *PLoS One, 17*. https://doi.org/10.1371/journal.pone.0266918

Fiore, A., Park, S., Volpe, S., Torrieri, E., & Masi, P. (2021). Active packaging based on PLA and chitosan-caseinate enriched rosemary essential oil coating for fresh minced chicken breast application. *Food Packaging and Shelf Life, 29*, Article 100708. https://doi.org/10.1016/j.fpsl.2021.100708

Folino, A., Pangallo, D., & Calabrò, P. S. (2023). Assessing bioplastics biodegradability by standard and research methods: Current trends and open issues. *Journal of Environmental Chemical Engineering, 11*(2). https://doi.org/10.1016/j.jece.2023.109424

Franco, M. R., da Cunha, L. R., & Bianchi, R. F. (2021). Janus principle applied to food safety: An active two-faced indicator label for tracking meat freshness. *Sensors and Actuators, B: Chemical, 333*. https://doi.org/10.1016/j.snb.2021.129466

Fredi, G., & Dorigato, A. (2021). Recycling of bioplastic waste: A review. *Advanced Industrial and Engineering Polymer Research, 4*(3), 159–177. https://doi.org/10.1016/j.aiepr.2021.06.006

Funabashi, M., Ninomiya, F., & Kunioka, M. (2009). Biodegradability evaluation of polymers by ISO 14855-2. *International Journal of Molecular Sciences, 10*(8), 3635–3654. https://doi.org/10.3390/ijms10083635

Gadaleta, G., De Gisi, S., Picuno, C., Heerenklage, J., Cafiero, L., Oliviero, M., Notarnicola, M., Kuchta, K., & Sorrentino, A. (2022). The influence of bio-plastics for food packaging on combined anaerobic digestion and composting treatment of organic municipal waste. *Waste Management, 144*, 87–97. https://doi.org/10.1016/j.wasman.2022.03.014

Gadaleta, G., De Gisi, S., Todaro, F., & Notarnicola, M. (2022). Carbon footprint and total cost evaluation of different bio-plastics waste treatment strategies. *Cleanroom Technology, 4*(2), 570–584. https://doi.org/10.3390/cleantechnol4020035

Gadaleta, G., Ferrara, C., De Gisi, S., Notarnicola, M., & De Feo, G. (2023). Life cycle assessment of end-of-life options for cellulose-based bioplastics when introduced into a municipal solid waste management system. *Science of the Total Environment, 871*. https://doi.org/10.1016/j.scitotenv.2023.161958

Ghasemlou, M., Barrow, C. J., & Adhikari, B. (2024). The future of bioplastics in food packaging: An industrial perspective. *Food Packaging and Shelf Life, 43*, Article 101279. https://doi.org/10.1016/j.fpsl.2024.101279

Gill, C. O. (2003). Active packaging in practice: Meat. In *Novel food packaging techniques*. https://doi.org/10.1016/B978-1-85573-675-7.50021-3

Gregory, G. L., Lopez-Vidal, E. M., & Buchard, A. (2017). Polymers from sugars: Cyclic monomer synthesis, ring-opening polymerisation, material properties and applications. *Chemical Communications, 53*(14), 2198–2217. https://doi.org/10.1039/c6cc09578j

Grujić, R., Vujadinović, D., & Savanović, D. (2017). Biopolymers as food packaging materials. *Advances in Applications of Industrial Biomaterials*, 139–160. https://doi.org/10.1007/978-3-319-62767-0_8

Haddar, A., Ben Ayed, E., Sila, A., Putaux, J.-L., Bougatef, A., & Boufi, S. (2021). Hybrid levan–Ag/AgCl nanoparticles produced by UV-irradiation: Properties, antibacterial efficiency and application in bioactive poly(vinyl alcohol) films. *RSC Advances, 11*(62), 38990–39003. https://doi.org/10.1039/D1RA07852F

Hao, Y., Zhang, M., Liu, B., Ma, W., Dong, Q., Fan, M., Wang, Y., & Li, L. (2023). Nonmigrating active antibacterial packaging: Antimicrobial mechanism against Staphylococcus Aureus and its application in large yellow croaker. *ACS Sustainable Chemistry & Engineering, 11*(16), 6220–6229. https://doi.org/10.1021/acssuschemeng.2c07273

Henchion, M., McCarthy, M., Resconi, V. C., & Troy, D. (2014). Meat consumption: Trends and quality matters. *Meat Science, 98*(3). https://doi.org/10.1016/j.meatsci.2014.06.007

Hernández-García, E., Vargas, M., & Chiralt, A. (2022). Starch-polyester bilayer films with phenolic acids for pork meat preservation. *Food Chemistry, 385*. https://doi.org/10.1016/j.foodchem.2022.132650

Herrmann, C., Rhein, S., & Sträter, K. F. (2022). Consumers' sustainability-related perception of and willingness-to-pay for food packaging alternatives. *Resources, Conservation and Recycling, 181*. https://doi.org/10.1016/j.resconrec.2022.106219

Heydari-Majd, M., Ghanbarzadeh, B., Shahidi-Noghabi, M., Najafi, M. A., & Hosseini, M. (2019). A new active nanocomposite film based on PLA/ZnO nanoparticle/essential oils for the preservation of refrigerated Otolithes ruber fillets. *Food Packaging and Shelf Life, 19*. https://doi.org/10.1016/j.fpsl.2018.12.002

Huang, Y., Wang, Y., Li, Y., Luo, C., Yang, C., Shi, W., & Li, L. (2020). Covalent immobilization of polypeptides on polylactic acid films and their application to fresh beef preservation. *Journal of Agricultural and Food Chemistry, 68*(39). https://doi.org/10.1021/acs.jafc.0c03922

Hur, S. J., Jin, S. K., Park, J. H., Jung, S. W., & Lyu, H. J. (2013). Effect of modified atmosphere packaging and vacuum packaging on quality characteristics of low grade beef during cold storage. *Asian-Australasian Journal of Animal Sciences, 26*(12). https://doi.org/10.5713/ajas.2013.13225

Iovino, R., Zullo, R., Rao, M. A., Cassar, L., & Gianfreda, L. (2008). Biodegradation of poly(lactic acid)/starch/coir biocomposites under controlled composting conditions. *Polymer Degradation and Stability, 93*(1), 147–157. https://doi.org/10.1016/j.polymdegradstab.2007.10.011

Jõgi, K., & Bhat, R. (2020). Valorization of food processing wastes and by-products for bioplastic production. *Sustainable Chemistry and Pharmacy, 18*. https://doi.org/10.1016/j.scp.2020.100326

Jamróz, E., Kulawik, P., Guzik, P., & Duda, I. (2019). The verification of intelligent properties of furcellaran films with plant extracts on the stored fresh Atlantic mackerel during storage at 2 °C. *Food Hydrocolloids, 97*. https://doi.org/10.1016/j.foodhyd.2019.105211

Jayakumar, A., Radoor, S., Siengchin, S., Shin, G. H., & Kim, J. T. (2023). Recent progress of bioplastics in their properties, standards, certifications and regulations: A review. *Science of the Total Environment, 878*, Article 163156. https://doi.org/10.1016/j.scitotenv.2023.163156

Jem, K. J., & Tan, B. (2020). The development and challenges of poly (lactic acid) and poly (glycolic acid). *Advanced Industrial and Engineering Polymer Research, 3*(2), 60–70. https://doi.org/10.1016/j.aiepr.2020.01.002

Jian, J., Xiangbin, Z., & Xianbo, H. (2020). An overview on synthesis, properties and applications of poly (butylene-adipate-co-terephthalate)–PBAT. *Advanced Industrial and Engineering Polymer Research, 3*(1), 19–26. https://doi.org/10.1016/j.aiepr.2020.01.001

Kamali, S., Yavarmanesh, M., Habibi Najafi, M. B., & Koocheki, A. (2022). Poly (lactic acid) and whey protein/pullulan composite bilayer film containing phage A511 as an anti-Listerial packaging for chicken breast at refrigerated temperatures. *Lebensmittel-Wissenschaft & Technologie, 170*, Article 114085. https://doi.org/10.1016/j.lwt.2022.114085

Kanatt, S. R. (2020a). Irradiation as a tool for modifying tapioca starch and development of an active food packaging film with irradiated starch. *Radiation Physics and Chemistry, 173*, Article 108873. https://doi.org/10.1016/j.radphyschem.2020.108873

Kanatt, S. R. (2020b). Development of active/intelligent food packaging film containing Amaranthus leaf extract for shelf life extension of chicken/fish during chilled storage. *Food Packaging and Shelf Life, 24*. https://doi.org/10.1016/j.fpsl.2020.100506

Kanatt, S. R., & Makwana, S. H. (2020). Development of active, water-resistant carboxymethyl cellulose-poly vinyl alcohol-Aloe vera packaging film. *Carbohydrate Polymers, 227*, Article 115303. https://doi.org/10.1016/j.carbpol.2019.115303

Kao, C. Y., Huang, Y. C., Chiu, S. Y., Kuo, K. L., & Hwang, P. A. (2018). Bacteriostatic effect of a calcined waste clamshell-activated plastic film for food packaging. *Materials, 11*(8). https://doi.org/10.3390/ma11081370

Karaca, I. M., Haskaraca, G., Ayhan, Z., & Gültekin, E. (2023). Development of real time-pH sensitive intelligent indicators for monitoring chicken breast freshness/spoilage using real packaging practices. *Food Research International, 173*. https://doi.org/10.1016/j.foodres.2023.113261

Karwowska, M., Łaba, S., & Szczepański, K. (2021). Food loss and waste in meat sector—why the consumption stage generates the most losses? *Sustainability, 13*(11), 6227. https://doi.org/10.3390/su13116227

Katekhong, W., Wongphan, P., Klinmalai, P., & Harnkarnsujarit, N. (2022). Thermoplastic starch blown films functionalized by plasticized nitrite blended with PBAT for superior oxygen barrier and active biodegradable meat packaging. *Food Chemistry, 374*. https://doi.org/10.1016/j.foodchem.2021.131709

Kerry, J. P. (2012). Advances in meat, poultry and seafood packaging. In *Advances in meat, poultry and seafood packaging*. https://doi.org/10.1533/9780857095718

Khanjari, A., Esmaeili, H., & Hamedi, M. (2023). Shelf life extension of minced squab using poly-lactic acid films containing Cinnamomum verum essential oil. *International Journal of Food Microbiology, 385*, Article 109982. https://doi.org/10.1016/j.ijfoodmicro.2022.109982

Khezerlou, A., Alizadeh Sani, M., Tavassoli, M., Abedi-Firoozjah, R., Ehsani, A., & McClements, D. J. (2023). Halochromic (pH-Responsive) indicators based on natural anthocyanins for monitoring fish freshness/spoilage. *Journal of Composites Science, 7*(4). https://doi.org/10.3390/jcs7040143

Kim, D., Lee, S., Lee, K., Baek, S., & Seo, J. (2017). Development of a pH indicator composed of high moisture-absorbing materials for real-time monitoring of chicken breast freshness. *Food Science and Biotechnology, 26*(1). https://doi.org/10.1007/s10068-017-0005-6

Klemeš, J. J., Fan, Y. Van, & Jiang, P. (2021). Plastics: Friends or foes? The circularity and plastic waste footprint. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 43*(13), 1549–1565. https://doi.org/10.1080/15567036.2020.1801906

Koenig-Lewis, N., Grazzini, L., & Palmer, A. (2022). Cakes in plastic: A study of implicit associations of compostable bio-based versus plastic food packaging. *Resources, Conservation and Recycling, 178*. https://doi.org/10.1016/j.resconrec.2021.105977

Kosheleva, A., Gadaleta, G., De Gisi, S., Heerenklage, J., Picuno, C., Notarnicola, M., Kuchta, K., & Sorrentino, A. (2023). Co-digestion of food waste and cellulose-based bioplastic: From batch to semi-continuous scale investigation. *Waste Management, 156*, 272–281. https://doi.org/10.1016/j.wasman.2022.11.031

Koutsimanis, G., Getter, K., Behe, B., Harte, J., & Almenar, E. (2012). Influences of packaging attributes on consumer purchase decisions for fresh produce. *Appetite, 59*(2), 270–280. https://doi.org/10.1016/j.appet.2012.05.012

Kumar, R., Sadeghi, K., Jang, J., & Seo, J. (2023). Mechanical, chemical, and bio-recycling of biodegradable plastic: A review. *Science of the Total Environment*. , Article 163446. https://doi.org/10.1016/j.scitotenv.2023.163446

Ladeira, M. M., Schoonmaker, J. P., Swanson, K. C., Duckett, S. K., Gionbelli, M. P., Rodrigues, L. M., & Teixeira, P. D. (2018). Nutrigenomics of marbling and fatty acid profile in ruminant meat. *Animal, 12*(s2), s282–s294. https://doi.org/10.1017/S1751731118001933

Laorenza, Y., & Harnkarnsujarit, N. (2021). Carvacrol, citral and α-terpineol essential oil incorporated biodegradable films for functional active packaging of Pacific white shrimp. *Food Chemistry, 363*. https://doi.org/10.1016/j.foodchem.2021.130252

Latos-Brozio, M., & Masek, A. (2020). The application of natural food colorants as indicator substances in intelligent biodegradable packaging materials. *Food and Chemical Toxicology, 135*. https://doi.org/10.1016/j.fct.2019.110975

Lee, K., Baek, S., Kim, D., & Seo, J. (2019). A freshness indicator for monitoring chicken-breast spoilage using a Tyvek® sheet and RGB color analysis. *Food Packaging and Shelf Life, 19*. https://doi.org/10.1016/j.fpsl.2018.11.016

Leelaphiwat, P., Pechprankan, C., Siripho, P., Bumbudsanpharoke, N., & Harnkarnsujarit, N. (2022). Effects of nisin and EDTA on morphology and properties of thermoplastic starch and PBAT biodegradable films for meat packaging. *Food Chemistry, 369*. https://doi.org/10.1016/j.foodchem.2021.130956

Liu, S., Guo, J., Liu, X., Yang, R., Wang, H., Sun, Y., Chen, B., & Dong, R. (2023). Detection of various microplastics in placentas, meconium, infant feces, breastmilk and infant formula: A pilot prospective study. *Science of the Total Environment, 854*, Article 158699. https://doi.org/10.1016/j.scitotenv.2022.158699

Liu, J., Wang, H., Wang, P., Guo, M., Jiang, S., Li, X., & Jiang, S. (2018). Films based on κ-carrageenan incorporated with curcumin for freshness monitoring. *Food Hydrocolloids, 83*. https://doi.org/10.1016/j.foodhyd.2018.05.012

Lorenzo, J. M., & Gómez, M. (2012). Shelf life of fresh foal meat under MAP, overwrap and vacuum packaging conditions. *Meat Science, 92*(4), 610–618. https://doi.org/10.1016/j.meatsci.2012.06.008

Lu, B., Jiang, C., Chen, Z., Li, A., Wang, W., Zhang, S., & Luo, G. (2022). Fate of polylactic acid microplastics during anaerobic digestion of kitchen waste: Insights on property changes, released dissolved organic matters, and biofilm formation. *Science of the Total Environment, 834*. https://doi.org/10.1016/j.scitotenv.2022.155108

Luo, Y., Lin, Z., & Guo, G. (2019). Biodegradation assessment of poly (lactic acid) filled with functionalized titania nanoparticles (PLA/TiO 2) under compost conditions. *Nanoscale Research Letters, 14*. https://doi.org/10.1186/s11671-019-2891-4

Ma, Y., Li, L., & Wang, Y. (2018). Development of PLA-PHB-based biodegradable active packaging and its application to salmon. *Packaging Technology and Science, 31*(11). https://doi.org/10.1002/pts.2408

Mahieu, A., Terrié, C., & Youssef, B. (2015). Thermoplastic starch films and thermoplastic starch/polycaprolactone blends with oxygen-scavenging properties: Influence of water content. *Industrial Crops and Products, 72*. https://doi.org/10.1016/j.indcrop.2014.11.037

Marchildon, K. (2011). Polyamides–still strong after seventy years. *Macromolecular Reaction Engineering, 5*(1), 22–54. https://doi.org/10.1002/mren.201000017

Martins, P. C., Bagatini, D. C., & Martins, V. G. (2021). Oregano essential oil addition in rice starch films and its effects on the chilled fish storage. *Journal of Food Science and Technology, 58*(4). https://doi.org/10.1007/s13197-020-04668-z

Marzlan, A. A., Muhialdin, B. J., Zainal Abedin, N. H., Manshoor, N., Ranjith, F. H., Anzian, A., & Meor Hussin, A. S. (2022). Incorporating torch ginger (Etlingera elatior Jack) inflorescence essential oil onto starch-based edible film towards sustainable active packaging for chicken meat. *Industrial Crops and Products, 184*, Article 115058. https://doi.org/10.1016/j.indcrop.2022.115058

Mayekar, P. C., Limsukon, W., Bher, A., & Auras, R. (2023). Breaking it down: How thermoplastic starch enhances poly(lactic acid) biodegradation in compost—A comparative analysis of reactive blends. *ACS Sustainable Chemistry & Engineering, 11*(26), 9729–9737. https://doi.org/10.1021/acssuschemeng.3c01676

McKeen, L. (2021). The effect of heat aging on the properties of sustainable polymers. *Eff. Long Term Therm. Expo. Plast. Elastomers*, 313–332.

McMillin, K. W. (2008). Where is MAP going? A review and future potential of modified atmosphere packaging for meat. *Meat Science, 80*(1), 43–65. https://doi.org/10.1016/j.meatsci.2008.05.028

Mohamad, N., Mazlan, M. M., Tawakkal, I. S. M. A., Talib, R. A., Kian, L. K., Fouad, H., & Jawaid, M. (2020). Development of active agents filled polylactic acid films for food packaging application. *International Journal of Biological Macromolecules, 163*. https://doi.org/10.1016/j.ijbiomac.2020.07.209

Nagarajan, V., Misra, M., & Mohanty, A. K. (2013). New engineered biocomposites from poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV)/poly(butylene adipate-co-terephthalate) (PBAT) blends and switchgrass: Fabrication and performance evaluation. *Industrial Crops and Products, 42*(1), 461–468. https://doi.org/10.1016/j.indcrop.2012.05.042

Negahdari, M., Partovi, R., Talebi, F., Babaei, A., & Abdulkhani, A. (2021). Preparation, characterization, and preservation performance of active polylactic acid film containing Origanum majorana essential oil and zinc oxide nanoparticles for ground meat packaging. *Journal of Food Processing and Preservation, 45*(1), Article e15013. https://doi.org/10.1111/jfpp.15013

Niaounakis, M. (2019). Recycling of biopolymers–the patent perspective. *European Polymer Journal, 114*, 464–475. https://doi.org/10.1016/j.eurpolymj.2019.02.027

Nilsen-Nygaard, J., Fernández, E. N., Radusin, T., Rotabakk, B. T., Sarfraz, J., Sharmin, N., … Pettersen, M. K. (2021). Current status of biobased and biodegradable food packaging materials: Impact on food quality and effect of innovative processing technologies. *Comprehensive Reviews in Food Science and Food Safety, 20*(2), 1333–1380. https://doi.org/10.1111/1541-4337.12715

Nilsuwan, K., Guerrero, P., de la Caba, K., Benjakul, S., & Prodpran, T. (2020). Properties and application of bilayer films based on poly (lactic acid) and fish gelatin containing epigallocatechin gallate fabricated by thermo-compression molding. *Food Hydrocolloids, 105*, Article 105792. https://doi.org/10.1016/j.foodhyd.2020.105792

Nomadolo, N., Dada, O. E., Swanepoel, A., Mokhena, T., & Muniyasamy, S. (2022). A comparative study on the aerobic biodegradation of the biopolymer blends of poly (butylene succinate), poly(butylene adipate terephthalate) and poly(lactic acid). *Polymers, 14*(9). https://doi.org/10.3390/polym14091894

Nur Hanani, Z. A., Reich, F., Tolksdorf, T., Siemen, H., & Bandick, N. (2022). Monitoring the effect of active packaging films with silver-kaolinite using different packaging systems on the quality of beef meat. *Heliyon, 8*(10), Article e11019. https://doi.org/10.1016/j.heliyon.2022.e11019

O'Sullivan, M. G., & Kerry, J. P. (2012). Sensory and quality properties of packaged fresh and processed meats. In *Advances in meat, poultry and seafood packaging*. https://doi.org/10.1533/9780857095718.1.86

Obaidi, A. Al, Karaca, I. M., Ayhan, Z., Haskaraca, G., & Gultekin, E. (2022). Fabrication and validation of CO2-sensitive indicator to monitor the freshness of poultry meat. *Food Packaging and Shelf Life, 34*, Article 100930. https://doi.org/10.1016/j.fpsl.2022.100930

Pandey, V., Jash, P., Ruj, B., & Srivastava, V. K. (2015). Sorting of plastic waste for effective recycling. *Journal of Applied Sciences and Engineering Research, 4*. https://doi.org/10.6088/ijaser.04058

Panseri, S., Martino, P. A., Cagnardi, P., Celano, G., Tedesco, D., Castrica, M., Balzaretti, C., & Chiesa, L. M. (2018). Feasibility of biodegradable based packaging used for red meat storage during shelf-life: A pilot study. *Food Chemistry, 249*, 22–29. https://doi.org/10.1016/j.foodchem.2017.12.067

Pant, A. F., Sangerlaub, S., & Muller, K. (2017). Gallic acid as an oxygen scavenger in bio-based multilayer packaging films. *Materials, 10*(5). https://doi.org/10.3390/ma10050489

Park, H., He, H., Yan, X., Liu, X., Scrutton, N. S., & Chen, G. Q. (2024). PHA is not just a bioplastic. *Biotechnology Advances, 108320*. https://doi.org/10.1016/j.biotechadv.2024.108320

Paul-Pont, I., Ghiglione, J. F., Gastaldi, E., Ter Halle, A., Huvet, A., Bruzaud, S., … Fabre, P. (2023). Discussion about suitable applications for biodegradable plastics regarding their sources, uses and end of life. *Waste Management, 157*, 242–248. https://doi.org/10.1016/j.wasman.2022.12.022

Peng, W., Wang, Z., Shu, Y., Lü, F., Zhang, H., Shao, L., & He, P. (2022). Fate of a biobased polymer via high-solid anaerobic co-digestion with food waste and following aerobic treatment: Insights on changes of polymer physicochemical properties and the role of microbial and fungal communities. *Bioresource Technology, 343*. https://doi.org/10.1016/j.biortech.2021.126079

Pettersen, M. K., Bardet, S., Nilsen, J., & Fredriksen, S. B. (2011). Evaluation and suitability of biomaterials for modified atmosphere packaging of fresh salmon fillets. *Packaging Technology and Science, 24*(4), 237–248. https://doi.org/10.1002/pts.931

Phothisarattana, D., Wongphan, P., Promhuad, K., Promsorn, J., & Harnkarnsujarit, N. (2022). Blown film extrusion of PBAT/TPS/ZnO nanocomposites for shelf-life extension of meat packaging. *Colloids and Surfaces B: Biointerfaces, 214*. https://doi.org/10.1016/j.colsurfb.2022.112472

Plackett, D., & Siró, I. (2011). Polyhydroxyalkanoates (PHAs) for food packaging. In *Multifunctional and nanoreinforced polymers for food packaging* (pp. 498–526). Woodhead Publishing.

Rabnawaz, M., Wyman, I., Auras, R., & Cheng, S. (2017). A roadmap towards green packaging: The current status and future outlook for polyesters in the packaging industry. *Green Chemistry, 19*(20), 4737–4753.

Rahman, M. H., & Bhoi, P. R. (2021). An overview of non-biodegradable bioplastics. *Journal of Cleaner Production, 294*, Article 126218. https://doi.org/10.1016/j.jclepro.2021.126218

Reshmy, R., Philip, E., Vaisakh, P. H., Sindhu, R., Binod, P., Madhavan, A., … Tarafdar, A. (2021). In B. Biomass (Ed.), *Biodegradable polymer composites* (pp. 393–412). Biochemicals: Elsevier.

Riboni, N., Bianchi, F., Cavazza, A., Piergiovanni, M., Mattarozzi, M., & Careri, M. (2023). Mass spectrometry-based techniques for the detection of non-intentionally added substances in bioplastics. *Separations, 10*(4), 222. https://doi.org/10.3390/separations10040222

Robertson, G. L. (2013). *Food packaging: Principles and practice* (3rd ed.). Taylor & Francis Group.

Rosenboom, J. G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials, 7*(2), 117–137. https://doi.org/10.1038/s41578-021-00407-8

Rowe, L. J., Maddock, K. R., Lonergan, S. M., & Huff-Lonergan, E. (2004). Influence of early postmortem protein oxidation on beef quality. *Journal of Animal Science, 82*(3). https://doi.org/10.2527/2004.823785x

Rudnik, E. (2013). Compostable polymer properties and packaging applications. In *Plastic films in food packaging* (pp. 217–248). William Andrew Publishing.

Sadeleer, I. E. A. F. (2018). *Environmental benefits of household plastic and bioplastic packaging management in the municipality of Trondheim (Master's thesis, NTNU)*.

Samantaray, P. K., Little, A., Haddleton, D. M., McNally, T., Tan, B., Sun, Z., Huang, W., Ji, Y., & Wan, C. (2020). Poly (glycolic acid)(PGA): A versatile building block expanding high performance and sustainable bioplastic applications. *Green Chemistry, 22*(13), 4055–4081.

Scarfato, P., Avallone, E., Galdi, M. R., Di Maio, L., & Incarnato, L. (2017). Preparation, characterization, and oxygen scavenging capacity of biodegradable α-tocopherol/PLA microparticles for active food packaging applications. *Polymer Composites, 38*(5). https://doi.org/10.1002/pc.23661

Schumann, B., & Schmid, M. (2018). Packaging concepts for fresh and processed meat–Recent progresses. *Innovative Food Science & Emerging Technologies, 47*, 88–100. https://doi.org/10.1016/j.ifset.2018.02.005

Seray, M., Hadj-Hamou, A. S., Uzunlu, S., & Benhacine, F. (2022). Development of active packaging films based on poly (butylene adipate-co-terephthalate) and silver–montmorillonite for shelf life extension of sea bream. *Polymer Bulletin, 79*(6), 3573–3594. https://doi.org/10.1007/s00289-021-03671-4

Sid, S., Mor, R. S., Kishore, A., & Sharanagat, V. S. (2021). Bio-sourced polymers as alternatives to conventional food packaging materials: A review. *Trends in Food Science & Technology, 115*, 87–104. https://doi.org/10.1016/j.tifs.2021.06.026

Siddiqui, S. A., Yang, X., Deshmukh, R. K., Gaikwad, K. K., Bahmid, N. A., & Castro-Muñoz, R. (2024). Recent advances in reinforced bioplastics for food packaging–A critical review. *International Journal of Biological Macromolecules, 130399*. https://doi.org/10.1016/j.ijbiomac.2024.130399

Siracusa, V., & Blanco, I. (2020). Bio-polyethylene (Bio-PE), bio-polypropylene (Bio-PP) and bio-poly(ethylene terephthalate) (Bio-PET): Recent developments in bio-based polymers analogous to petroleum-derived ones for packaging and engineering applications. *Polymers, 12*(8), 1641. https://doi.org/10.3390/polym12081641

Siracusa, V., Lotti, N., Munari, A., & Dalla Rosa, M. (2015). Poly (butylene succinate) and poly (butylene succinate-co-adipate) for food packaging applications: Gas barrier properties after stressed treatments. *Polymer Degradation and Stability, 119*, 35–45. https://doi.org/10.1016/j.polymdegradstab.2015.04.026

Soares, A. G., Silva, F., Bento de Carvalho, T., Dourado, F., Gama, M., Teixeira, P., & Poças, F. (2023). Performance of bacterial nanocellulose packaging film functionalised in situ with zinc oxide: Migration onto chicken skin and antimicrobial activity. *Food Packaging and Shelf Life, 39*. https://doi.org/10.1016/j.fpsl.2023.101140

Soroudi, A., & Jakubowicz, I. (2013). Recycling of bioplastics, their blends and biocomposites: A review. *European Polymer Journal, 49*(10), 2839–2858. https://doi.org/10.1016/j.eurpolymj.2013.07.025

Stoleru, E., Vasile, C., Irimia, A., & Brebu, M. (2021). Towards a bioactive food packaging: Poly(lactic acid) surface functionalized by chitosan coating embedding clove and argan oils. *Molecules, 26*(15). https://doi.org/10.3390/molecules26154500

Tavassoli, M., Khezerlou, A., Firoozy, S., Ehsani, A., & Punia Bangar, S. (2023). Chitosan-based film incorporated with anthocyanins of red poppy (Papaver rhoeas L.) as a colorimetric sensor for the detection of shrimp freshness. *International Journal of Food Science and Technology, 58*(6). https://doi.org/10.1111/ijfs.16432

Taweechat, C., Wongsooka, T., & Rawdkuen, S. (2021). Properties of banana (Cavendish spp.) starch film incorporated with banana peel extract and its application. *Molecules, 26*(5). https://doi.org/10.3390/molecules26051406

Tyagi, V., Wang, Y., Badgujar, P., & Bhattacharya, B. (2023). Diffusion-controlled release of sorghum bran polyphenols from potato starch–zein film extends shelf-life of chicken meat. *Journal of Polymers and the Environment, 31*(2), 621–636. https://doi.org/10.1007/s10924-022-02642-8

Umaraw, P., Munekata, P. E., Verma, A. K., Barba, F. J., Singh, V. P., Kumar, P., & Lorenzo, J. M. (2020). Edible films/coating with tailored properties for active packaging of meat, fish and derived products. *Trends in Food Science & Technology, 98*, 10–24. https://doi.org/10.1016/j.tifs.2020.01.032

Umare, S. S., Chandure, A. S., & Pandey, R. A. (2007). Synthesis, characterization and biodegradable studies of 1,3-propanediol based polyesters. *Polymer Degradation and Stability, 92*(3), 464–479. https://doi.org/10.1016/j.polymdegradstab.2006.10.007

Upadhyay, A., Kumar, P., Kardam, S. K., & Gaikwad, K. K. (2022). Ethylene scavenging film based on corn starch-gum acacia impregnated with sepiolite clay and its effect on quality of fresh broccoli florets. *Food Bioscience, 46*. https://doi.org/10.1016/j.fbio.2022.101556

Van den Oever, M., Molenveld, K., van der Zee, M., & Bos, H. (2017). Bio-based and biodegradable plastics: facts and figures: focus on food packaging in the Netherlands (No. 1722). *Wageningen Food & Biobased Research*.

Vicente, D., Proença, D. N., & Morais, P. V. (2023). The role of bacterial polyhydroalkanoate (PHA) in a sustainable future: A review on the biological diversity. *International Journal of Environmental Research and Public Health, 20*(4), 2959.

Vo, T. V., Dang, T. H., & Chen, B. H. (2019). Synthesis of intelligent pH indicative films from chitosan/poly(vinyl alcohol)/anthocyanin extracted from red cabbage. *Polymers, 11*(7). https://doi.org/10.3390/polym11071088

Vytejčková, S., Vápenka, L., Hradecký, J., Dobiáš, J., Hajšlová, J., Loriot, C., Vannini, L., & Poustka, J. (2017). Testing of polybutylene succinate based films for poultry meat packaging. *Polymer Testing, 60*, 357–364. https://doi.org/10.1016/j.polymertesting.2017.04.018

Wang, C., Cao, J., Liu, T., Jin, L., Hang, C., Zhang, C., Qian, X., Jiang, D., & Jiang, C. (2023). Preparation and characterization of antioxidant and pH-sensitive films based on arrowhead (Sagittaria sagittifolia) starch, κ-carrageenan and black chokeberry (Aronia melanocarpa) extract for monitoring spoilage of chicken wings. *International Journal of Biological Macromolecules, 224*. https://doi.org/10.1016/j.ijbiomac.2022.10.143

Wang, H. Y., & Huang, M. F. (2007). Preparation, characterization and performances of biodegradable thermoplastic starch. *Polymers for Advanced Technologies, 18*(11), 910–915. https://doi.org/10.1002/pat.930

Wang, G. Y., Li, M., Ma, F., Wang, H. H., Xu, X. L., & Zhou, G. H. (2017). Physicochemical properties of Pseudomonas fragi isolates response to modified atmosphere packaging. *FEMS Microbiology Letters, 364*(11), fnx106. https://doi.org/10.1093/femsle/fnx106

Weng, Y. X., Wang, X. L., & Wang, Y. Z. (2011). Biodegradation behavior of PHAs with different chemical structures under controlled composting conditions. *Polymer Testing, 30*(4), 372–380.

Wensing, J., Caputo, V., Carraresi, L., & Bröring, S. (2020). The effects of green nudges on consumer valuation of bio-based plastic packaging. *Ecological Economics, 178*. https://doi.org/10.1016/j.ecolecon.2020.106783

Wickramasinghe, N. N., Ravensdale, J., Coorey, R., Chandry, S. P., & Dykes, G. A. (2019). The predominance of psychrotrophic pseudomonads on aerobically stored chilled red meat. *Comprehensive Reviews in Food Science and Food Safety, 18*(5), 1622–1635. https://doi.org/10.1111/1541-4337.12483

Wojnowska-Baryła, I., Kulikowska, D., & Bernat, K. (2020). Effect of bio-based products on waste management. *Sustainability, 12*(5), 1–12. https://doi.org/10.3390/su12052088

Woraprayote, W., Kingcha, Y., Amonphanpokin, P., Kruenate, J., Zendo, T., Sonomoto, K., Benjakul, S., & Visessanguan, W. (2013). Anti-listeria activity of poly (lactic acid)/sawdust particle biocomposite film impregnated with pediocin PA-1/AcH and its use in raw sliced pork. *International Journal of Food Microbiology, 167*(2). https://doi.org/10.1016/j.ijfoodmicro.2013.09.009

Woraprayote, W., Pumpuang, L., Tosukhowong, A., Zendo, T., Sonomoto, K., Benjakul, S., & Visessanguan, W. (2018). Antimicrobial biodegradable food packaging impregnated with Bacteriocin 7293 for control of pathogenic bacteria in pangasius fish fillets. *Lebensmittel-Wissenschaft & Technologie, 89*, 427–433. https://doi.org/10.1016/j.lwt.2017.10.026

Wu, F., Misra, M., & Mohanty, A. K. (2021). Challenges and new opportunities on barrier performance of biodegradable polymers for sustainable packaging. *Progress in Polymer Science, 117*, Article 101395.

Xiong, Z., Sun, D. W., Zeng, X. A., & Xie, A. (2014). Recent developments of hyperspectral imaging systems and their applications in detecting quality attributes of red meats: A review. *Journal of Food Engineering, 132*, 1–13. https://doi.org/10.1016/j.jfoodeng.2014.02.004

Yildirim, S., Röcker, B., Pettersen, M. K., Nilsen-Nygaard, J., Ayhan, Z., Rutkaite, R., … Coma, V. (2018). Active packaging applications for food. *Comprehensive Reviews in Food Science and Food Safety, 17*(1), 165–199. https://doi.org/10.1111/1541-4337.12322

Yildiz, E., Sumnu, G., & Kahyaoglu, L. N. (2021). Monitoring freshness of chicken breast by using natural halochromic curcumin loaded chitosan/PEO nanofibers as an intelligent package. *International Journal of Biological Macromolecules, 170*. https://doi.org/10.1016/j.ijbiomac.2020.12.160

Zakowska-Biemans, S., Sajdakowska, M., & Issanchou, S. (2016). Impact of innovation on consumers liking and willingness to pay for traditional sausages. *Polish Journal of Food and Nutrition Sciences, 66*(2), 119–127. https://doi.org/10.1515/pjfns-2016-0004

Zaukuu, J. L. Z., Bazar, G., Gillay, Z., & Kovacs, Z. (2019). Emerging trends of advanced sensor based instruments for meat, poultry and fish quality– a review. In *Critical reviews in food science and nutrition*. https://doi.org/10.1080/10408398.2019.1691972

Zeid, A., Karabagias, I. K., Nassif, M., & Kontominas, M. G. (2019). Preparation and evaluation of antioxidant packaging films made of polylactic acid containing thyme, rosemary, and oregano essential oils. *Journal of Food Processing and Preservation, 43* (10), Article e14102. https://doi.org/10.1111/jfpp.14102

Zhang, P., Luo, S., & Gao, D. (2021). Effects of poly(butylene adipate-co-terephthalate)/TiO2 nanocomposite antimicrobial films on chilled pork quality. *Packaging Technology and Science, 34*(11–12), 709–715. https://doi.org/10.1002/pts.2605

Zhang, M., Tao, N., Li, L., Xu, C., Deng, S., & Wang, Y. (2022). Non-migrating active antibacterial packaging and its application in grass carp fillets. *Food Packaging and Shelf Life, 31*, Article 100786. https://doi.org/10.1016/j.fpsl.2021.100786

Zhang, W., Xiao, S., & Ahn, D. U. (2013). Protein oxidation: Basic principles and implications for meat quality. *Critical Reviews in Food Science and Nutrition, 53*(11), 1191–1201. https://doi.org/10.1080/10408398.2011.577540

Zhang, J., Zou, X., Zhai, X., Huang, X. W., Jiang, C., & Holmes, M. (2019). Preparation of an intelligent pH film based on biodegradable polymers and roselle anthocyanins for monitoring pork freshness. *Food Chemistry, 272*, 306–312. https://doi.org/10.1016/j.foodchem.2018.08.041

Zheng, H., Tang, H., Yang, C., Chen, J., Wang, L., Dong, Q., Shi, W., Li, L., & Liu, Y. (2022). Evaluation of the slow-release polylactic acid/polyhydroxyalkanoates active film containing oregano essential oil on the quality and flavor of chilled pufferfish (Takifugu obscurus) fillets. *Food Chemistry, 385*, Article 132693. https://doi.org/10.1016/j.foodchem.2022.132693

Zwicker, M. V., Brick, C., Gruter, G. J. M., & van Harreveld, F. (2023). Consumer attitudes and willingness to pay for novel bio-based products using hypothetical bottle choice. *Sustainable Production and Consumption, 35*, 173–183. https://doi.org/10.1016/j.spc.2022.10.021