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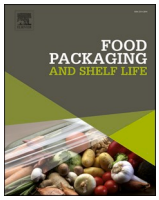

Active packaging containing natural antimicrobials as a potential and innovative technology to extend shelf-life of fish products – A review

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ABSTRACT

The spoilage of fish and seafood is a major problem in all categories in the food sector, with 50 % of the 8.2 million tonnes of marketable fish caught within the EU each year being wasted. Apart from the material linked to quota restriction issues, this waste is largely due to inefficiencies in processing and packaging. Optimal packaging materials and systems, combined with cold storage, are critical to preserving seafood quality. While conventional packaging has proven its worth over the past decades, it now faces modern challenges such as requirements for longer shelf-life, consumer demand for ready-to-eat products, logistical issues pertaining to extended distribution cold-chains and environmental issues with plastic waste. To collectively address these challenges, there is growing interest in active packaging systems that contain natural antimicrobials (NAM) such as chitosan, organic acids, essential oils, etc. NAM are food-safe, clean label, sustainable and have a broad spectrum of antimicrobial activity against both Gram-positive and Gram-negative microbes. As part of hurdle technology, synergistic NAM combinations can potentially be used in antimicrobial-active packaging materials (AAPM) to extend the shelf-life of fish products, reduce waste and improve sustainability. This review highlights the importance of innovative packaging solutions to combat fish spoilage, focusing on the potential usage of NAM in active packaging materials and packaging systems.

1. Introduction

Fish is one of the most traded foods on the globe, accounting for almost 50 % of all animal protein consumed, and is therefore an important source of protein for global food security (Mei et al., 2019; Tsironi, 2023). Fishery products play a significant role in the European diet due to their high nutritional properties (e.g., high digestible protein content, long chain and omega polyunsaturated fatty acids, vitamins, and minerals) (Dehghani et al., 2018). In terms of consumption, the EU is the third largest market for fishery and seafood products in the world, and to maintain this high consumption, the EU relies on imports (Altmayer, 2024; Scholaert, 2020). Compared to other muscle foods, fish products are highly perishable due to inherent properties, such as: poikilothermic status, high microbiological loading in the external body muscillage, high water activity, presence of autolytic endogenous enzymes, presence of large amounts of unstable long-chain fatty acids and almost neutral pH (Abedi-Firoozjah et al., 2023; Dehghani et al., 2018; Hao et al., 2021). This property causes them to deteriorate rapidly and develop undesirable odours and flavours. Microbial growth is reported to be responsible for up to 95 % of fish spoilage (Blakeney, 2019) resulting in a loss of freshness and quality (Amaral et al., 2021). According to recent reports, 59 million tonnes (Mt) of all food in the EU (Eurostats, 2022), and about 1.3 billion tonnes of all food produced for human consumption worldwide (Blakeney, 2019), are lost or wasted each year throughout the supply chain. Consequently, the global estimate of fresh fish waste along the supply chain (post-catch handling, transportation, packaging, and storage) to consumption is 30 % (Anagnostopoulos et al., 2023; Blakeney, 2019). In the EU, 50 % of the 8.2 Mt of fish on the market is wasted annually (Caldeira et al., 2019; Greggio et al., 2021). Therefore, the development and application of novel technologies to extend the shelf-life of fish products, and thus reduce product spoilage and waste, is of commercial importance. With the global population expected to reach 9.8 billion people by 2050 (Blakeney, 2019; Halonen et al., 2020), reducing fish waste is imperative if we are to feed the world's growing population sustainably and ensure global food security (Blakeney, 2019).

Conventional preservation technologies (chilling, freezing, drying, smoking, salting and chemical additives) have been used to extend the

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shelf-life of fish products (Huang et al., 2021; Sung et al., 2013). However, consumer health concerns, behaviours and lifestyles have led to an increased demand for fresh, convenient, healthier, more natural and safer fish products (Halonen et al., 2020; Oliveira et al., 2021; Rao et al., 2019). A recent study found that 50–75 % of consumers associated freshness, safety and higher quality with products that contained natural or fewer additives or possessed other attributes such as being environmentally friendly, nutritionally enhanced, sustainably or ethically sourced (Singh et al., 2021). Therefore, the seafood industry and markets face the challenge of meeting consumer demands by increasingly adopting sustainable fish production methods. To address this, research to develop novel technologies to extend the shelf-life of fish products, while providing consumers with high-quality, safe and nutritious products, will become increasingly important over time (Mei et al., 2019). Consequently, hurdle technology (defined as a smart combination of two or more mild preservation techniques) has been used to improve the shelf-life of fish (Amaral et al., 2021; Giannakourou et al., 2023; Leistner & Gorris, 1995; Tsironi, 2023). When mild preservation technologies are used in combination with AAPM, they have the potential to deliver safe, sustainable food products (Cruz-Romero et al., 2013). AAPM containing NAM interacts with packaged foods and/or the packaging headspace to reduce, delay or even inhibit the growth of spoilage and pathogenic microorganisms (Ahmed, Dora, et al., 2017; Nie et al., 2022; Otoni et al., 2016; Singh et al., 2021). The fundamental aspects of packaging materials and systems are containment, protection, preservation, information and economically providing convenience while considering the limitations imposed on their use from both a legal and environmental perspective (Sullivan et al., 2018). All these basic principles equally apply to AAPM and the developed packaging systems around them. According to the EU Guidance to the Commission Regulation (EUGCR) No 450/2009, packaging material is considered active if, besides its primary use, it also performs an additional function by absorbing or releasing substances from the food or the environment surrounding the food, such as antimicrobials and antioxidants (European Commission, 2009; Fang et al., 2017). Active packaging further interacts positively with package components and food to extend shelf life, enhance safety, and improve sensory properties, while maintaining product quality (Yildirim, 2011). As part of the hurdle concept, AAPM have been used in combination with various mild preservation technologies such as modified atmosphere packaging (MAP) (Toro et al., 2019), vacuum packaging (Lambrianidi et al., 2019; Xiong et al., 2021), high hydrostatic pressure (HPP) (Kung et al., 2020) in conjunction with cold storage to extend the shelf-life of fresh fish products.

In the development of AAPM, current research focuses on the use of clean label and naturally derived preservatives from plant or animal origin (Ben Amor et al., 2021; Mirsharifi et al., 2023; Rivera de la Cruz et al., 2023; Tariq et al., 2019; Van de Vel et al., 2019). The most used commercially available NAM includes organic acids, polysaccharides (e.g. chitosan), plant-derived essential oils (EOs) and microbially-derived antimicrobial agents (e.g. nisin, bacteriocin, pediocin, reuterin) (Aşik & Candoğan, 2014; Doğan & İzci, 2017; Pandey et al., 2021; Sullivan et al., 2018). Their use in AAPM ensures a controlled release from the packaging material in contact with the food product in a more efficient way, maintaining the quality and organoleptic properties, as well as the microbial safety, of the product over time (Hassoun & Emir Çoban, 2017; Tongnuanchan & Benjakul, 2014; Sullivan et al., 2018).

AAPM have been used to extend the shelf- life of muscle foods such as beef (Azarifar et al., 2020), pork (Xiong et al., 2020), chicken (Konuk Takma & Korel, 2019) and fish products (Dong et al., 2019; Ma et al., 2017; Yang et al., 2016). For the development of AAPM, NAM can be applied/added to polymeric packaging films like polyethylene terephthalate (PET), polyethylene (PE), low-density polyethylene (LDPE) or polypropylene (PP), commonly used in the food industry. Although these synthetic polymeric packaging materials offer many advantages, they are hydrophobic and have a low surface energy, thereby limiting the adhesion of NAM (Perera et al., 2022). Therefore, to achieve adhesion, the polymer material requires chemical or physical surface modification employing techniques such as plasma discharge, corona discharge, UV/ozone treatment, etc., prior to adhesion (Lee & Coote, 2016; Morris et al., 2017). Plasma treatment is becoming increasingly popular due to its sustainability benefits and minimal processing waste (Dong et al., 2018; Hoque et al., 2022; Perera et al., 2022).

Environmental considerations in packaging selection and usage have always been fundamentally important. However, they can sometimes be overlooked during implementation, particularly at the end of the packaging's lifecycle. Sustainability is now the standard requirement for the packaging industry as consumers demand packaging that is derived from sustainable sources, is circular in application and still provides all the technical and commercial functions required for the packaging of any given specific food or beverage product. Therefore, using sustainable packaging materials to develop AAPM not only has the potential to reduce fish waste throughout the supply chain, but also to minimise environmental packaging impact (Oliveira et al., 2021). The sustainability of AAPM can be assessed by the reduction of food waste and its environmental impact using standardized methodologies like Life Cycle Assessment (LCA) (Boone et al., 2023; Tsouti et al., 2023).

This review presents recent advances in the development of AAPM through the incorporation of NAM and the application of these materials to extend the shelf-life of fish products to reduce fish waste and its impact on the environment. The review is organized into sections covering NAM with proven broad-spectrum antimicrobial activity commonly used for fish preservation, the development and application of AAPM as part of the hurdle approach to extending the shelf-life of fish products, the factors influencing the antimicrobial activity of AAPM, the environmental impact of using AAPM to reduce food waste, regulatory, safety and economic considerations to be taken into account when using AAPM to extend the shelf-life of fish products.

2. Natural antimicrobials to extend the shelf-life of fish products

Natural antimicrobial agents, originating from plants, animals and beneficial microbes (El-Saber Batiha et al., 2021), are increasingly recognized by consumers as healthier alternatives to conventional food preservatives, which are now widely accepted by consumers as being healthier food preservatives (Dehghani et al., 2018). For NAM to be suitable substitutes for existing synthetic chemical preservatives, they should have similar or better properties than synthetic preservatives (e.g., high efficacy, low toxicity, biodegradability and stability) (Hemmati et al., 2021). A range of NAM, including organic acids, plant essential oils, naturally occurring polymers such as chitosan and their combinations, have been used to extend the shelf-life of fish products (Alkan Tas et al., 2019). However, the effectiveness of NAM in ensuring fish safety can be influenced by the fish's intrinsic properties, such as pH, water activity, fat and protein content, as well as the antimicrobial spectrum and the fish's microflora present (Mei et al., 2019; Sullivan et al., 2018). Additionally, the organoleptic characteristics of fish can also play a significant role in the choice and efficacy of NAM (Biswas et al., 2023). In this section, the most common NAM forms, their mechanisms of action and applications for the control of microbial spoilage in fish products are presented. The AAPM development and delivery of these NAM, as part of the hurdle approach, will also be highlighted.

2.1. Plant essential oils

Essential oils (EOs) are hydrophobic, aromatic, volatile liquids extracted from various parts of plant materials including leaves, buds, seeds, barks, peels, roots, flowers and fruits (Rehman et al., 2020; Tongnuanchan & Benjakul, 2014). In general, EOs have broad-spectrum antimicrobial activity against many foodborne pathogens such as *Staphylococcus aureus*, *Bacillus cereus* and *Escherichia coli* (Maurya et al., 2021), as well as a variety of food spoilage microorganisms (Mei et al., 2019; Rao et al., 2019; Sugumar et al., 2016; Swamy et al., 2016). EOs

(e.g., rosemary, clove, cinnamon, thyme, oregano, garlic, bay leaf, lavender, sage, basil, etc.) have been used as antimicrobial agents and have shown great potential in extending the shelf-life of raw fish products (Altiok et al., 2010; Feng et al., 2016; Hosseini et al., 2016; Patel, 2015; Selmi & Sadok, 2008).

The antimicrobial efficacy of EOs is dependent upon the bioactive compounds present in these substances (e.g., terpenes, phenylpropanoids and terpenoids) (Tongnuanchan & Benjakul, 2014) and closely related to primary constituents (e.g. thymol, carvacrol, linalool, citronellal, menthol, geraniol, eugenol and cinnamaldehyde) (Ebrahimzadeh et al., 2023; Hassoun & Emir Çoban, 2017; Hyldgaard et al., 2012; Jayasena & Jo, 2013). The antimicrobial activity of EOs is influenced by several factors such as target bacteria (Gram-positive or Gram-negative), growth conditions, age, harvest time, variety or plant part used, extraction method, interaction with food matrices, etc. (Angane et al., 2022). EOs are notably more effective against Gram-positive bacteria due to the unique composition of their cell membranes. These cell membranes, characterized by the presence of lipophilic ends and lipoteichoic acids, facilitate the penetration and interaction of EOs with their bioactive compounds, thereby enhancing their antimicrobial activity (da Silva et al., 2021). This process initiates interactions with the bacterial cell wall's polysaccharides, fatty acids and phospholipids, causing the loss of protons, ions and intracellular contents, ultimately leading to cell death (Zubair et al., 2022). Conversely, Gram-negative bacteria have an extrinsic membrane or cell wall lipopolysaccharides that limit the diffusion rate of hydrophobic EOs Sullivan et al., 2018. However, different mechanisms of EOs' action have been reported and attributed to the presence of a wide range of compounds acting at multiple sites of cellular components (Maurya et al., 2021).

2.2. Chitosan

Chitosan is a natural polymer consisting of a linear binary heteropolysaccharide synthesized by diacylation of chitin from marine shells or fungal cell walls (Flórez et al., 2022; Hosseini et al., 2009). It owes its popularity in the food packaging industry to its antimicrobial activity against bacteria and fungi, antioxidant effect, excellent film-forming properties, biodegradability, non-toxicity, biocompatibility, low gas permeability (Flórez et al., 2022; Huang et al., 2021; Xiong et al., 2021; Zhao et al., 2022) and GRAS status (USFDA, 2013).

The antimicrobial properties of chitosan are influenced by factors such as its origin, degree of acetylation, concentration, molecular weight, interaction with the fish matrix and the target microorganisms of interest (Flórez et al., 2022; Gnanasekaran, 2019; Inanli et al., 2020; Yuan et al., 2016). Generally, chitosan has shown a broad spectrum of activity against both Gram-positive and Gram-negative bacteria (Flórez et al., 2022). The antimicrobial effect of chitosan on Gram-negative bacteria is due to the higher affinity of chitosan amino groups for anionic radicals in the bacterial cell wall (Ardean et al., 2021; Hassan et al., 2018; Helander et al., 2001). Similarly, Gram-positive bacteria are sensitive to the antimicrobial activity of chitosan because they lack the outer membrane barrier that is present in Gram-negative bacteria (Ardean et al., 2021). Chitosan is active when dissolved in an acidic medium with a pH of ≤ 6, which leads to the protonation of its primary amino groups (Jeon et al., 2014; Yan et al., 2021). The most plausible mode of antimicrobial action involves the electrostatic binding of positively charged chitosan to the negatively charged bacterial surface, resulting in cell membrane disruption, leakage of intracellular components and eventual cell death (Jeon et al., 2014). Other mechanisms include; (a) the formation of films by high-molecular-weight chitosan on the cell surface (porins) that hinder nutrient exchange, thereby killing cells; (b) the penetration of low-molecular-weight chitosan into the cytoplasm, altering DNA/RNA and protein synthesis and; (c) the disruption of the cell membrane as amino groups of chitosan can chelate metal ions present on the bacteria's surface (Yan et al., 2021).

2.3. Organic acids

Organic acids are naturally occurring organic compounds, including short-chain weak acids, (mono) carboxylic acids consisting of the R-COOH general structure of carboxylic acid, fatty acids and amino acids, and are present in many fruits or plants (Cruz-Romero et al., 2013; Gómez-García et al., 2019; Rathod et al., 2021a). The interest shown to this class of chemicals in terms of their preservation properties, especially for seafood applications, stems from their strong antimicrobial activity against relevant spoilage microorganisms, such as *Pseudomonas* spp., *Enterobacteriaceae*, LAB and H_2S-producing bacteria, as well as pathogens, such as *Listeria monocytogenes*, *E. coli* and *Vibrio* spp. (Ibrahim Sallam, 2007; Rossi et al., 2021). The antimicrobial mode of action associated with organic acids derives from the lipophilic state of their undissociated acid form, thereby enabling easy penetration across the peptidoglycan layer (Gram-positive) or phospholipid (Gram-negative) membrane of bacteria (Scicutella et al., 2021). Once inside the cell, the organic acid dissociates, decreasing the cytoplasmic pH and subsequently, changing proton-anion concentrations and disrupting the nutrient transport system in the cytoplasm, thereby inducing cell collapse (Dibner & Buttin, 2002; Gómez-García et al., 2019). The antimicrobial effect of organic acids against microorganisms is, however, affected by their carbon chain length, degree of unsaturation, pKa of the acid and pH of the food matrix. Application methods such as dipping and spraying are commonly used for fish preservation; however, long dipping times and concentrations of organic acids may result in destruction of fish muscle, loss of water-holding capacity and undesirable colour owing to protein denaturation (Amaral et al., 2021). Therefore, the use of polymers such as chitosan and starch (Akhter et al., 2019), polyvinyl alcohol films (Liang et al., 2019) and polyamide (Becerril et al., 2020) containing organic acids presents an appropriate strategy to preserve fish products and maintain quality without imparting textural and sensorial properties (Mei et al., 2019). Food-grade organic acids, including; lactic, malic, tartaric, citric, acetic, formic, propionic, butyric, sorbic and fumaric acids and their salts (such as sodium acetate, potassium sorbate, sodium lactate and sodium citrate) have been reported in the literature as effective in extending the shelf-life of raw fish through the inhibition of bacterial growth (Ahmed, Dora, et al., 2017; Lee et al., 2019; Mohan et al., 2019; Monirul et al., 2019; Nie et al., 2020; Jacobsen et al., 2022; Logrén et al., 2022; Remya et al., 2022; Yehia et al., 2022; Anagnostopoulos et al., 2023). Phenolic acids, a type of organic acid, have a phenolic ring structure and a carboxylic acid group, and have been shown to have antimicrobial properties. Common examples include gallic acid, caffeic acid, cinnamic, vanillic and ferulic acid. These acids are utilized as natural preservatives to inhibit microbial growth, reduce lipid oxidation, and maintain sensory characteristics, thereby extending the shelf-life of fish (Olatunde & Benjakul, 2018; Wu et al., 2016) (Table 1).

2.4. Application of NAM as part of the hurdle approach in fish processing

Hurdle technology refers to an intelligent combination of two or more mild preservation technologies to establish a series of preservative factors (hurdles) that microorganisms are unable to overcome (Amaral et al., 2021; Leistner & Gorris, 1995). In the case of perishable products such as fish, chill storage and packaging have long been used as preservation hurdles. However, maintaining a cold chain can be costly, and if fish is exposed to high temperatures during distribution and storage, this hurdle approach breaks down, resulting in quality deterioration and increased safety risks (Lin et al., 2022; Tsironi et al., 2020). Additionally, the high initial microbial growth of fish products, possibly owing to unhygienic post-catch handling conditions, may completely overcome the packaging and low-temperature hurdles. These challenges have led to the use of more innovative processes, among them AAPM, MAP, vacuum packing, HPP and irradiation treatments, together with chill storage to deliver microbial stability, safety and sensory quality of fish

Table 1
The antimicrobial effects of NAM on raw fish products when applied as a hurdle for shelf-life extension.

Fish product	NAM (Concentration)	Additional hurdles	Application method/ Support Matrix	Antimicrobial activity effect	References
Rainbow Trout fillets	Coriander EO (0.5 %) + Garlic extract (0.5 %)	Storage at 4 °C	Chitosan coating and air-packed in PE bags	NAM combination significantly reduced bacterial count to 7 log CFU/g and extended shelf-life by 6–9 days compared to the control	Foromandi and Khani (2023)
Red Snapper fillets	Basil EO (0–4.5 %)	Storage at 4 °C	Wrapped in chitosan films	Chitosan films treated with basil EO at a concentration of 3 % and 4.5 % extended shelf-life by reducing bacterial count ($<3 \times 10^5$ CFU/g) for 6 days of storage	Setyaningsih R, Pangastuti A (2023)
Megram fillets	Chitosan (2 %)	Storage at 4 °C	Dip coating in chitosan solution	NAM extended shelf-life by 3 days by maintaining a TVC limit of 6 log CFU/g when compared to the uncoated samples	Elnaggar et al. (2023)
European Sea Bass fillets	Acetic acid, Citric acid (3 %)	Vacuum packaging and storage at 4 °C	Marination in NAM	NAM significantly reduced TVC and selected spoilage bacteria (*Pseudomonas* spp., H_2S-producing and lactic acid bacteria), As a result, NAM (acetic acid) extended shelf-life at 30 and 40 days under aerobic and vacuum packaging respectively, while fillets marinated with citric acid were at 25 and 35 days	Anagnostopoulos et al. (2023)
Common Carp fillets	EO (Thyme, Pimento and Oregano) emulsions (0.5–1.5 %)	Storage at 4 ºC	Sodium alginate coating and air-packed in PE bags	NAM decreased TVC and inhibited *Pseudomonas* spp., H_2S-producing bacteria and *Enterobacteriaceae*. This maintained the quality of the fillets and extending their shelf-life by 2–4 days compared to uncoated fillets	Hao et al. (2022)
Large Yellow Croaker fillets	Chitosan (1 %, 2 %)	Storage at 4 °C	Chitosan coating and air-packed in PE bags	NAM maintained a slow growth trend of TVC and psychrophilic bacteria counts therefore extending shelf-life for up to 6 days compared to uncoated fillets	Lan et al. (2022)
Catfish fillets	Chitosan (0.5–2 %)	Storage at 4 °C	Dip coating in chitosan solution	NAM decreased TVC and extended shelf-life for up to 3 days compared to chitosan uncoated fillets	Nurhayati et al. (2022)
Mullet fillets	Potassium sorbate (0.1 %) + Sodium benzoate (0.2 %)	Ice storage	Dip in ice containing NAM	NAM decreased TVC and psychrophilic bacteria compared to samples immersed on ice only. This extended the shelf-life for up to 17–19 days	Yehia et al. (2022)
Salmon fillets	Provian K (blend of potassium acetate and potassium diacetate) and Provian NDV (buffered dry vinegar potassium salt) (0.9 %)	Cold-smoking, vacuum packaging and storage at 4	Dry salting	NAM reduced TVC (<2.8 log CFU/g) and inhibited the growth of *L. monocytogenes,* and as a result extended shelf-life for 29 days of storage	Jacobsen et al. (2022)
Baltic Herring fillets	Acetic, Citric, Lactic, Malic and Tartaric acids (2–5 %)	Vacuum packaging and storage at 3 °C	Pickling	NAM extended shelf-life by significantly reducing TVC (<1.0 log CFU/g) during the 4-month storage period	Logrén et al. (2022)
Silver Pomfret steaks	Fumaric acid (0.5 %)	Storage at 4 °C	Corn starch coating and air-packed in EVOH films	NAM reduced counts of total mesophilic and psychrotrophic bacteria, H2S-producing bacteria and *Pseudomonas* spp. This extended shelf-life to 15 days compared to 6 days of untreated coated samples	Remya et al. (2022)
Grey Mullet steaks	Clove EO (1.5 %)	Storage at 4 °C	Chitosan coating	NAM delayed microbial (aerobic plate count, psychrotrophic bacteria, yeasts and molds and total coliform bacteria) growth, as a result, shelf-life was extended for up to 24 days compared to 12 days of uncoated samples	Aref et al. (2022)
Atlantic Salmon fillets	Gallic acid (0.2 %) + clove EO (0.5 %)	Vacuum packaging and storage at 4 °C	Chitosan-gelatine coating	NAM combination together with chitosan coating significantly inhibited TVC, thereby extending the shelf-life of fillets for at least 5 days	Xiong et al. (2021)
Catfish fillets	Oregano EO (4.5 %)	Vacuum packaging and storage at 4 °C	Rice starch film wrappings	NAM showed less microbiological growth (10^7 CFU/g) compared to the control (10^8 CFU/g), thus showing the capacity to increase the shelf-life of fish fillets	Martins, Bagatini (2021)
Pacific Mackerel fillets	Clove EO (2–3 %) oregano EO (2–2.5 %) and cinnamon EO (1.25 %)	Storage at 4 °C	Films of collagen	NAM significantly reduced TVC and selected spoilage bacteria (*E. coli*, *B. subtilis*, *Shewanella putrefaciens, S. aureus* and *V. parahaemolyticus),* extending shelf-life by ~4 days compared to untreated samples	Hu et al., 2021
Rainbow Trout fillets	Lemon EO (0.5–1 %) and cinnamon EO (0–1 %)	Vacuum packaging and storage at 4 °C	Dip coating	NAM combination highly suppressed bacterial growth of TVC, lactic acid bacteria and coliforms therefore extending shelf-life for more than 7 days compared to untreated samples	Kunová et al. (2021)
Catfish fillets	Aspartic acid	Storage at 4 °C	Dip coating in chitosan solution	NAM lowered total aerobic mesophilic bacteria and total aerobic psychrophilic bacteria while extending the shelf-life of fillets by 4 days compared to uncoated samples	Karsli et al. (2021)
Atlantic Horse Mackerel fillets	Gallic acid (0.1 %)	Storage at 4 °C	Dip coating in chitosan solution	NAM decreased TVC for more than 2 log cycles up to late storage thereby extending the shelf-life of fish by 3 days compared to uncoated fillets	Zarandona et al. (2021)

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Table 1 (*continued*)

Fish product	NAM (Concentration)	Additional hurdles	Application method/ Support Matrix	Antimicrobial activity effect	References
Rainbow Trout fillets	Potassium sorbate (PS) (2 %) and Zataria multiflora EO (ZEO) (0.5–1.5 %)	MAP (30 % N_2, 30 % O_2 and 40 % CO_2) and storage at 4 °C	Spray coating	ZEO 1.5 % reduced the growth of inoculated *L. monocytogenes*, TVC, as well *P. aeruginosa*. As a result, the shelf-life of fillets was extended by at least 3 days as compared to PS-treated or untreated control samples	Motavaf et al. (2021)
Sardine fillets	Cumin EO (1 %) and chitosan (1 %)	Storage at 4 °C	Chitosan coating	NAM extended the microbiological shelf-life of fish to between 10 and 15 days by significantly reducing TVC, total pseudomonads count and lactic acid bacteria compared to uncoated fillets	Homayonpour et al. (2021)
Japanese Sea Bass fillets	Eugenol EO (0.15 %)	Storage at 4 °C.	Coatings of sodium alginate and flaxseed gum	NAM significantly reduced TVC, *Pseudomonas* spp., H_2S-producing and psychrophilic bacteria and as a result, extended the shelf-life for 16 days compared to untreated fillets	Li et al. (2020)
Asian Sea Bass fillets	Cinnamon (488 mg/L)	Storage at 4 °C	Dip coating	NAM inhibited the growth of TVC bacteria by 1–3 log CFU/g thereby extending the shelf-life to at least 2–6 days compared to untreated fillets	Chuesiang et al. (2020)
Rainbow Trout fillets	Citrus (orange, grapefruit mandarin and lemon) EOs (4 %)	Storage at 4 °C	Dip coating	NAM reduced mesophilic aerobic bacteria, *Enterobacteriaceae* and psychrophilic viable counts. This increased the shelf-life by 4 days for orange and lemon EOs and 6 days for mandarin and grapefruit EOs compared to the untreated fillets.	Durmus (2020)
Sea Bream fillets	Oregano EO (0.1 %)	MAP (60:40 CO_2/ N_2) and storage at 4 °C	Treatment with vapourised EO	NAM reduced microbial growth, especially *Enterobacteria* and *Pseudomonas,* and as a result extended shelf-life by 7 days compared to untreated fillets	Navarro-Segura et al. (2020)
Turbot fillets	Chitosan (1 %) and vanillin (2 mg/ mL)	Storage at 4 °C	Dip coating	NAM decreased significantly the growth of *Pseudomonadaceae* and *Lactobacillacea*e and as a result, prolonged shelf-life for 6–7 days compared to untreated fillets	Li et al. (2020)
Fish burger from Common Carp	Sage EO (0.5 %)	Storage at 4 °C	Chitosan film wrapping	NAM significantly suppressed psychrotrophic bacterial count, *Pseudomonas* spp. and *Shewanella* spp, extending the shelf-life by at least 5 days compared with untreated fillets	Ehsani et al. (2020)
Tilapia fillets	Chitosan (1 %) and gallic acid (1 %)	Storage at 4 °C	Coated LDPE films	NAM slowed the growth of TVC and *Vibrio parahaemolyticus* by about 1.82 log CFU/g and 1.76 log CFU/g, respectively. This prolonged shelf-life by 3 days compared to untreated fillets	Loke et al. (2021)
Mori fillets	Chitosan (1 %) and Rosemary EO (1 %)	Vacuum packaging and storage at 4 °C	Dip and spray coating	NAM significantly lowered the TVC (6 log CFU/g) and prolonged the shelf-life for more than 6 days compared to the control	Nawaz et al. (2020)
Rainbow Trout fillets	Mentha piperita, Artemisia dracunculus and Zataria multiflora EOs (0.2 %)	Storage at 4 °C	Chitosan and alginate coating	NAM significantly reduced the growth of foodborne spoilage bacteria (TVC, psychrotrophic bacterial count and lactic acid bacteria). This prolonged shelf-life for more than 12 days when compared to untreated fillets	Raeisi et al. (2020)
Japanese Sea Bass fillets	Gallic acid (GA) (5 %)	Storage at 4 °C	Pectin coating	NAM significantly reduced TVC and psychrophilic bacterial count and this prolonged shelf-life for 20 days compared to 15 days of untreated fillets	Nie et al. (2020)
Black Pomfret steaks	Sodium acetate (2.5 %)	Storage at 4 °C	Dip coating	NAM inhibited the production of TMA-N, which relates to the presence of spoilage microorganisms, and prolonged shelf-life for more than 7 days when compared to untreated fillets	Mevada J et al. (2020)
Silver Carp fillets	Acetic acid (1 %) and Ascorbic acid (2 %)	Storage at 4 °C	Spray coating	NAM significantly reduced TVC and prolonged shelf-life for more than 9 days when compared to untreated fillets	Monirul et al. (2019)
Tilapia fillets	Ascorbic acid (AA) (2.5–5 %) and Chitosan (1–2 %)	Storage at 4 °C	Dip coating	NAM reduced the growth of aerobic plate count, in which the bacteria count only increased by 0.92 log CFU/g in 15 days of refrigeration. This extended the shelf-life to at least 15 days as compared to untreated fillets (less than 6 days)	Lee et al. (2019)
Seer steaks	Sodium acetate (2 %)	Storage at 2 °C	Dip coating	NAM significantly reduced TVC and prolonged shelf-life to 21 days compared to 12 days of untreated fillets	Mohan et al. (2019)
Snakehead fish fillets	Chitosan (2 %) and Chlorogenic acid (0.2–1 %)	vacuum packaging and storage at 2 °C	Dip coating	NAM reduced TVC (< 5.5 log CFU/g), prolonging shelf-life by 2 months	Cao et al. (2020)
Japanese Thread Fin Bream	Propolis extract (0.1 %) and Chitosan (1 %)	Storage at 4 °C	Dip coating	NAM significantly reduced total mesophilic count and total psychrophilic count, leading to an increase (>10 days) in the shelf-life when compared to untreated fillets	Ebadi et al. (2019)
Salmon fillets	Chitosan (1 %)	Storage at 4 °C	Films of chitosan	NAM reduced TVC, *Pseudomonas*, *Enterobacteriaceae* and specific fish spoilers by	Gómez-Estaca et al. (2019)

(*continued on next page*)

Table 1 (*continued*)

Fish product	NAM (Concentration)	Additional hurdles	Application method/ Support Matrix	Antimicrobial activity effect	References
				2–4 log CFU/g and, as a result, prolonged shelf-life for more than 19 days when compared to untreated fillets	
Rainbow Trout fillets	Laurel EO (2 %)	Vacuum packaging and storage at 4 °C	Spray coating	NAM delayed microbial spoilage (TVC, total psychrotrophic bacteria, *Pseudomonas*, lactic acid bacteria, *Enterobacteriaceae* and coliforms), thereby extending the shelf-life by approximately 4 days compared to untreated fillets	Aksoy and Sezer (2019)
European Eel fillets	Chitosan (2 %) and oregano EO (0.3 %)	Vacuum packaging and storage at 4 °C	Dip coating	NAM significantly reduced counts of mesophilic bacteria, *Pseudomonas*, *Shewanella*, yeasts and molds during storage, extending shelf-life by more than 18 days compared to 6 days of untreated fillets	Lambrianidi et al. (2019)
Salmon fillets	Aromatic vinegar (1.5 %)	MAP (13.46 % O_2 and 28.22 % CO_2) and storage at 4 °C	Spray coating	NAM reduced microbial growth during storage, on psychrotrophic loads and *Pseudomonas* spp, and extended shelf-life by 3 days compared to untreated fillets	Toro et al. (2019)
Bream fillets	Clove EO (1 % and 1.5 %)	Vacuum packaging and storage at 4 °C	Pectin dip coating	NAM inhibited bacterial growth, especially Psychrophilic bacteria and *Pseudomonas* spp., thereby extending shelf-life for at least 15 days as compared to the untreated fillets (9 days)	Nisar et al. (2019)
Rainbow Trout fillets	Clove (1 %) and Shirazi thyme (2 %)	Storage at 4 °C	Farsi gum dip coating	NAM improved the microbial quality (TVC, psychrophilic and lactic acid bacteria count), and increased shelf-life to 12 days compared to 5 days of untreated fillets	Dehghani et al. (2018)
Bluefin Tuna fillets	Clove EO (0.5 %)	Storage at 2 °C	Films of soy isolate	NAM-containing films maintained up to 2 log CFU/g lower in TVC, *Pseudomonas* spp. and *Enterobacteriaceae* compared to the control. This subsequently prolonged shelf-life by 2 days.	Echeverría et al. (2018)
Grass Carp fillets	Oregano, thyme and star anise EOs (0.1 %)	Storage at 4 °C	EO emulsions dip coating	NAM effectively inhibited the growth of *Aeromonas* and *Shewanella*, increasing the shelf-life by 2 days compared to untreated fillets	Huang et al. (2018)
Catfish fillets	Chitosan (0.5 %)	Storage at 4 °C	vacuum tumbling Spray coating Dip coating	NAM inhibited the proliferation of aerobic plate counts (<6 log CFU/g), *Aeromonas* and *Shewanella*. This extended the shelf-life of vacuum tumbled fillets by 8 days and dip/spray coated fillets by 4 days compared to untreated fillets	Bonilla et al. (2018)
Large Yellow Croaker fillets	Chitosan (1.5 %) and Lysozyme (0.5–4 %)	Storage at 4 °C	Dip coating	NAM maintained TVC below limit (7 log CFU/g), thereby maintaining the shelf-life throughout the 15-day storage period as compared to untreated fillets	Wu et al. (2018)
European Eel fillets	Chitosan (2 %) and thyme EO (3 %)	Smoking and storage at 4 °C	Dip coating	NAM maintained total plate count below limit (7 log CFU/g). As a result, thyme and thyme-chitosan combination extended shelf-life to 42 and > 49 days, respectively, compared to 35 days of NAM untreated fillets	El-Obeid et al. (2018)
Common Carp fillets	Oregano and thyme EOs (112 ± 13 mg/fillet)	Vacuum packaging, UV- irradiation and storage at 3.5 °C	Spray coating	NAMs prolonged the shelf-life of fish by 5–6 times compared to untreated fillets while effectively suppressing formation of biogenic amines (putrescine, cadaverine, tyramine and phenylethylamine)	Křížek et al. (2018)
Asian Sea Bass fillets	Acetic acid (1 %)	Storage at 4 °C	Dip coating and air-packing in LDPE bags	NAM significantly reduced TVC (>2 log CFU/g), extending the shelf-life by 3 days as compared to the control	Ahmed, Lin, et al. (2017)

NAM: Natural antimicrobials; TMA-N: Trimethylamine Nitrogen; TVC: Total viable counts; EO: Essential oil; UV: Ultraviolet light; CFU: Colony forming unit; H_2S: Hydrogen Sulphide; MAP: Modified atmosphere packaging; PE: Polyethylene; LDPE: Low Density Polyethylene

products (Hassoun & Emir Çoban, 2017; Kontominas et al., 2021; Křížek et al., 2018; Kung et al., 2020; Socaciu et al., 2018; Toro et al., 2019).

Application of NAM (e.g., EOs, chitosan and organic acids) as individual antimicrobial agents or in combination utilizing various application methods (such as dip coatings, films, and spraying) and polymers (e.g., chitosan, starch, cellulose, alginate, pectin and gelatine) as carriers, provides an essential hurdle to extending the shelf-life of fish products (Table 1). Synergistic interactions resulting from NAM combinations enhance antimicrobial activity, thereby offering greater potential in the development of AAPM with enhanced antimicrobial activity for fish product application.

2.5. Intrinsic and extrinsic factors that affect the antimicrobial activity of NAM

The interaction of NAM with the fish matrix can affect its antimicrobial efficacy. This interaction may be due to the inherent composition of fish (intrinsic factors) (e.g., nutrients, pH, water activity, oxidation-reduction potential, microflora, etc.) and environmental conditions (extrinsic factors) (e.g., temperature, relative humidity, packaging atmosphere, fish processing, etc.) (Duarte et al., 2020; Papadochristopoulos et al., 2021; Zheng et al., 2023; Zubair et al., 2022). The degree of interaction that intrinsic and extrinsic factors exert on NAM determines its antimicrobial effectiveness and ultimately, its ability to extend the shelf-life of seafood products. As previously described, fish contain high

levels of protein and fat, with high levels of long-chain omega-3 polyunsaturated fatty acids distributed throughout the musculature of pelagic fish species (Totosaus, 2012). Such nutrients are reported to provide a protective effect for spoilage and pathogenic microorganisms (Danilović et al., 2021; Zheng et al., 2023), thereby reducing the antimicrobial activity and effectiveness of NAM (Jackson-Davis et al., 2023). Tajkarimi et al. (2010) reported that EOs were more effective when applied to lean fish, like cod, than to fatty fish, like salmon. Several authors (Angane et al., 2022; Zheng et al., 2023) reported that EOs can interactively bind with protein amino groups, leading to a loss of their antimicrobial potency. Similarly, chitosan contains an active amino group that can interact covalently or electrostatically with fats and proteins, thus inhibiting the antimicrobial activity of chitosan (Inanli et al., 2020). Although the effect of nutrients like carbohydrates on antimicrobial activity is not well defined in fish products, they serve to repair microorganisms injured or stressed by the action of antimicrobials (da Silva et al., 2021; Malhotra et al., 2015). Seafood, except for seasonal variations observed in shellfish, generally contains minimal carbohydrate levels when compared to other primary compositional elements. Other intrinsic factors, such as water activity and pH, serve to enhance the antimicrobial activity of NAM in fish products. High water activity in products assists in the movement of NAM to active microbial cell sites, thereby enhancing their antimicrobial activity (Rao et al., 2019). Similarly, low pH tends to extend the lag phase of bacterial growth and/or inhibit the growth rate of most food-borne bacteria, except for acidophilic bacteria such as lactic acid bacteria or those bacteria that can grow at low pH levels (pH $\leq$4.5). Additionally, NAM such as EOs that contain phenolic compounds become hydrophobic and undissociated at low pH, thereby increasing their penetrative action through the lipid layer of the target bacteria's membrane, thereby enhancing their antimicrobial activity (Ait-Ouazzou et al., 2011; Zheng et al., 2023). Similarly, at low pH, the adsorption of chitosan on bacterial surfaces increases and consequently, cell permeability is perturbed, which ultimately leads to bacterial death (Ardean et al., 2021; Zhou et al., 2021).

Extrinsic factors such as packaging systems and temperature impact the activity of NAM against fish spoilage. Generally, low-temperature storage, employed for most fish products, serves to slow down the microbial activity of psychrophilic bacteria (such as *Shewanella putrefaciens* and *Pseudomonas spp.*), thereby enhancing the inhibitory effects of NAM (Duarte et al., 2020). Packaging systems play a critical role in the NAM dispersion and, therefore, their performance and consistency. In skin or vacuum packaging systems, there is direct contact between the antimicrobial agent and food, and hence diffusivity, solubility and stability of the NAM in the packaging material are crucial for determining its concentration in food. While in MAP, volatile antimicrobial agents like EOs are released from the packaging material into the headspace where they are absorbed by the food (Pongsetkul et al., 2022; Yildirim, 2011).

3. Development of antimicrobial active packaging materials to preserve fish products

Active packaging refers to the deliberate inclusion of subsidiary components in the packaging material or the package headspace to enhance the performance of the package system (Angane et al., 2022; Coma, 2012; Hassoun & Emir Çoban, 2017; Kapetanakou & Skandamis, 2016; Kerry, 2012; Tongnuanchan et al., 2015). For successful application of AAPM using NAM as active agents, certain considerations are required both before and after the insertion of antimicrobials. This includes, amongst others, employed packaging polymers, AAPM processing technologies (direct or coating), target microorganisms, antimicrobial concentration employed, mode of action, release rate and impact on sensorial properties (Amaral et al., 2021; M.C. Cruz-Romero et al, 2019; Papadochristopoulos et al., 2021; Kerry and Butler, 2008). According to Coma (2012), active packaging films containing antimicrobials can be effective by either contact with food products or by releasing active compounds to the headspace of the food package. With regards to antimicrobial action, antimicrobial films in which active compounds are released are reportedly more effective (Tyuftin & Kerry, 2020; Kerry, 2012); . The polymer matrix is therefore important in the application of antimicrobials in ensuring contact or efficient release of active agents to the product (Cushen et al., 2012). The polymer matrix can be bio-based, such as polysaccharides, proteins, polylactic acid, etc., or synthetic plastics, such as PE, LDPE, PP and PET, etc. Synthetic polymers, however, continue to dominate the packaging industry owing to commercial support for the oil industry, the evolution of polymer development since the 1950s to the present day and the wide degree of properties offered by food and beverage grade synthetic polymers, including their lightweight nature (Feng et al., 2016; Jayakumar et al., 2022; Selmi & Sadok, 2008; Suppakul et al., 2003; Totosaus, 2012).

3.1. Application of the NAM into packaging materials

NAM can be added to packaging materials (e.g., films, pads, sachets, labels and trays) to modulate their release into the food product. Several approaches (Coma, 2012; Totosaus, 2012) are used to manufacture AAPM:

1. Direct incorporation of the NAM into the polymeric packaging matrix. This can be achieved by the conventional heat treatment method, such as co-extrusion of packaging films with the thermally stable antimicrobials, or by non-heating methods, such as solvent compounding, electrospinning and casting, which can be used with thermally sensitive antimicrobials (Fang et al., 2017; Sung et al., 2013). During direct incorporation, NAM are incorporated in the polymers using ion or covalent linkages and are released gradually from the packaging films into the packaging headspace or food surface to inhibit microbial growth (Hemmati et al., 2021; M.C. Cruz-Romero et al., 2019). Direct incorporation of active compounds onto polymer surfaces has been found to have a strong interaction, which ensures a slow release of the active compounds (Vasile & Baican, 2021). However, this depends on the dispersion of active agents into the polymer materials, whereby non-uniform dispersion may affect antimicrobial efficacy by minimizing contact with the product (Kumar et al., 2005; M.C. Cruz-Romero et al., 2019; Quintavalla & Vicini, 2002). These can be ensured by the stabilization and attachment of antimicrobial substances onto the surface of the polymer matrix *via* surface coating as described below.
2. Coating of packaging with a matrix that acts as a carrier for antimicrobial compounds that are subsequently released onto the surface of food through evaporation into the headspace (volatile substances) or migration into the food (non-volatile substances) through diffusion (Ahmed, Dora, et al., 2017; Fang et al., 2017). Both coating and direct application methods require substantially lower amounts, and they allow the long-time-controlled release of antimicrobial agents from the film surface to the food matrix (Alkan Tas et al., 2019; Amaral et al., 2021; Pegoretti et al., 2019; Kerry, 2012). Compared to direct application, surface coating is advantageous as there is more direct contact between the antimicrobial substances and the food product/headspace, therefore increasing efficiency (Coma, 2012).
3. Integrating NAM into a sachet or pad, which is then placed within the packaging, is another innovative method for preserving fresh fish products. This approach enables the controlled release of antimicrobial substances, enhancing food safety by inhibiting microbial growth and extending shelf-life (Otoni et al., 2016). These pads are commonly employed in trays for retail-packaged meats to absorb meat exudates, while the integrated antimicrobials effectively inhibit microbial proliferation (Coma, 2012; Fang et al., 2017).
4. The use of inherent antimicrobial film-forming polymers, such as chitosan and poly-L-lysine (Coma et al., 2015). These polymers contain charged amines that react with the negative charges present on the cell membrane of microorganisms, leading to leakage of

intracellular contents and ultimately causing cell death (Fang et al., 2017).

3.2. Surface activation of polymer surfaces

Surface coating of NAM to plastic packaging materials such as PE, LDPE, PET, etc., is challenging because to achieve NAM attachment, there must be a charged attraction between NAM and, particularly, the polymeric surface. The charge present on the polymeric film surface is termed the surface activation energy. This is typically low on most plastics and must be enhanced or elevated to permit the attachment of NAM. Consequently, plastic surfaces are first modified to increase their surface energy, functional nature and crosslinking, hence maximizing coating or attachment of NAM (Morris et al., 2017). Surface modification of plastics is carried out using chemical- or radiation-based treatments (Dehghanpour et al., 2022; Morris et al., 2017; Ramkumar et al., 2018). Chemical treatments involve oxidation by strong acids such as chromic acid solution, ammonium persulfate, or Piranha solution for a specified time before rinsing with water (Morris et al., 2017). After chemical treatment, the double bonds (-C═C-) on the surface of the polymers are disoriented, subsequently generating polar groups like -OH, -CO and -COOH (Bandopadhay et al., 2004). Although chemical treatments provide a good surface activation potential, there are safety concerns related to toxic reagents used and hazardous waste generated, which limit their sustainable industrial application (Morris et al., 2017). Alternatively, radiation-based treatment methods are non-toxic, simple, solventless, environmentally friendly, sustainable and industrially scalable (Fu & Dudley, 2021; Rout et al., 2022). These techniques result in polymer surfaces with enhanced hydrophilic properties, improved surface energy, wettability and adhesion (Dehghanpour et al., 2022; Karam et al., 2016). Radiation forms, such as plasma discharge, corona discharge, UV/ozone treatment, photoactivation (UV), flame treatment, photoactivation (UV), laser, ion beam, ion beam, electron beam and gamma radiation are surface activation processes that can be used to activate the polymer surfaces (Lee & Coote, 2016; Morris et al., 2017; Ravi-Kumar et al., 2019; Tuominen et al., 2010). These processes produce hydroxyl (-OH) or carboxyl (-COOH) functionalities on the plastic surface, thereby increasing overall surface energy and subsequently, film adhesion properties for effective interaction and binding with NAM (Tyuftin & Kerry, 2020). The number of functional groups produced by these methods differs and is impacted by process parameters, such as time duration, power used and intensity. The application of corona and plasma treatments is more common than other approaches owing to their high intensity plasma and industrial scalability.

Plasma treatment consists of plasma (a highly reactive gas that contains ions and radicals) generated by two metal electrodes at a small distance from each other and normally in a chamber filled with the discharge gas (oxygen, argon, helium, nitrogen, etc.) at low or atmospheric pressure. A biasing power source is applied to films holding electrodes to create a significant ion bombardment component during plasma treatment. This treatment approach has been used extensively to functionalise polymer surfaces by altering their physical, chemical and structural properties (Gholamazad et al., 2022; Moradi et al., 2023). Oxygen plasma, for example, reacts with the surface polymer atoms, leading to the etching of the polymer and generation of a variety of oxygen-rich functional groups or polar groups (C-O, C═O, O-C═O, C-O-O and CO_3) at the polymer surface (Morris et al., 2017). These polar groups increase the overall surface energy and subsequently, adhesion properties of films with added coating active agents, such as NAM (Tyuftin & Kerry, 2020). Moradi et al. (2023) investigated the impact of plasma treatment on LDPE. These authors showed that there was a significant change in LDPE surface hydrophilicity following treatment, which was demonstrated by contact angle measurement where the contact angle reduced from 89° to 42° after 45 sec of treatment (350 W). This was due to the cleaving of initial chemical bonds and the forming of new reactive functional groups on the polymer surface. Plasma has also been used to decontaminate packaging surfaces and food processing instruments and to enhance the safety level of several food products (Hoque et al., 2022; Molina-Besch et al., 2019). Plasma treatment is a promising novel technology for surface modification of plastic surfaces and the coating of NAM onto polymeric materials, as it is a very sustainable and efficient method for doing so (Clarke et al., 2017). Atmospheric plasma treatment was used to modify LDPE surfaces before coating them with alginate and the treatment led to the increased adhesion between both materials, leading to the successful creation of a bi-layer film (Gholamazad et al., 2022). Additionally, plasma treatment promotes the coating of functional components onto the polymer layer, enhancing antimicrobial efficacy by enabling stronger and more effective adhesion of bioactive antimicrobial compounds (Bahrami & Zibaei, 2022). For instance, Wong, Hou, et al. (2020) prepared gallic acid (GA) coated polyethylene (PE) film applying plasma treatment. The PE/GA active film reduced the growth of *E. coli* and *S. aureus* by 0.5–1.1 log reduction at a concentration above 1.0 %. Such antimicrobial activity was also reported for plasma-treated polylactic acid (PLA) film coated with nisin, where the active film showed a log reduction of 3.23 against *Listeria monocytogens*, whereas pristine PLA film did not inhibit its growth at all. It was observed that with the increase in plasma treatment time (0–60 sec), microbial reduction further increased, and this could be ascribed to the content of nisin absorbed onto the surface of the PLA (Hu et al., 2018). Wong, Loke, et al. (2020) prepared active packaging films from plasma-treated LDPE coated with carboxymethyl cellulose (CMC) or collagen (COL) containing cinnamaldehyde (CMAL). The application of plasma enhanced the attachment between LDPE and CMC/CMAL or COL/CMAL and showed strong antibacterial activity against *S. aureus* and *E. coli,* which was attributed to the strong attachment of active agent CMAL. Furthermore, the LDPE/COL films containing 0, 2.0, 4.0, 6.0 and 8.0 % CMAL were used for packaging tilapia fillets and stored for 14 days. The total plate count for the fish decreased with increasing CMAL concentration and the LDPE/COL film containing 6.0 and 8.0 % CMAL extended product shelf-life by a minimum of three days. Similarly, plasma-treated polypropylene (PP) films coated with CMC and loaded with Zataria multiflora essential oil (ZEO) showed antimicrobial activity against Gram-positive (*S. aureus*) and Gram-negative (*E. coli, S. typhimurium*, and *P. aeruginosa*) bacteria. This was attributed to the attachment between PP and CMC/ZEO, facilitated by plasma treatment (Honarvar et al., 2017).

Corona discharge is a form of plasma based on electric discharge under a substantially high potential difference between two asymmetric electrodes, producing plasma that interacts with the plastic or polymer surface, thereby increasing surface polarity (Das et al., 2021). It operates at standard atmospheric pressure and produces a similar plasma discharge to the plasma treatment process and similarly affects the packaging surface to plasma, although the effectiveness can be different (Morris et al., 2017). Corona treatment has been reportedly used to surface modify polyamide polymeric films (Rezaei et al., 2015), LLDPE films (Popelka et al., 2018), PE films (Das et al., 2021), biaxially oriented polypropylene film (Lei et al., 2001), PP, PE and PET films (Lindner et al., 2018).

Overall, the attachment and retention of NAM on surface-treated polymeric materials are crucial in ensuring effective immobilization or precise positioning of mobile bioactive compounds. This enables controlled release either onto fish surface tissues or, if gaseous, into the packaging headspace. As a result, the microbiological quality of fish products is preserved, ultimately extending their shelf-life. Therefore, plasma surface modification and coating techniques present an innovative solution for designing novel AAPM tailored for fish, as well as other food and beverage packaging applications. These methods pave the way for enhanced functionality and adaptability in preserving product quality.

4. Environmental implications of using antimicrobial active packaging

Food wastage has a direct environmental impact on perishable products, such as dairy, meat, fish, horticultural produce, etc., generating high volumes of food waste or biomass (Manfredi et al., 2015; Ruiz-Salmón et al., 2021; Sandison et al., 2021). Globally, food waste is responsible for about 6 % of total greenhouse gas emissions, which is approximately three times the emissions from global aviation (Ritchie & Roser, 2024). Therefore, strategies to decrease food waste, including seafood, are critical in terms of achieving sustainable economic and environmental goals for the seafood sector. This also consolidates with the European Commission's newly launched growth strategy (2019), whose objective is to cut pollution and carbon emissions, boost efficiency in the use of resources and restore biodiversity (Zoli et al., 2023). The creation of advanced AAPM using sustainable NAM aligns perfectly with the goals of extending the shelf-life of fish products. This approach addresses critical challenges such as food waste, consumer demands for natural solutions, and environmental sustainability while ensuring high-quality preservation. While antimicrobial packaging is crucial in reducing food waste, it is critical that its development creates no detrimental environmental impacts and that the technologies created are deemed sustainable. Therefore, AAPM development must be assessed in terms of usage impact and environmental sustainability (Kerry, 2012; Ruiz-Salmón et al., 2021).

Life Cycle Assessment (LCA) is a standardized methodology employed to quantify the environmental impact of an entity or process, like that of a food product and packaging system. LCA examines a product's entire life cycle, encompassing stages like raw material extraction, processing, production, distribution, and end-of-life treatment (Molina-Besch et al., 2019). This methodology involves four iterative evaluation phases: defining the goal and scope, conducting inventory analysis, assessing environmental impacts and interpreting the results. Such assessments provide valuable insights into a product's overall environmental footprint (Loubet et al., 2022; Mi et al., 2022; Saha et al., 2022; ISO, 2006). Briefly, the goal and scope definition phase defines the intention of the specific LCA study while describing the product's system, boundaries, allocation procedure, functional unit and impact categories chosen for that specific LCA evaluation (Del Borghi et al., 2020). The life cycle inventory analysis (LCIA) phase consists of compiling the inventory and data collection from the primary data (collected from the specific study) and secondary data (available in databases) (Abdou et al., 2018). The LCIA phase involves the evaluation of the environmental performance of the system studied by analyzing environmental category indicators for the various impact categories, which together represent the LCIA profile for the product system calculation. From these data, interpretations can be derived from the study objective, thereby forming the basis for the impact assessment (Del Borghi et al., 2020). Important factors in LCIA include selecting the impact category that is coherent with the goal and scope definition, model characterization, results classification and calculation of category indicator results (Saha et al., 2022).

LCA has been increasingly applied to assess the environmental impacts of fish and seafood products with more than 60 case studies published in the scientific literature to date (Fernández-Ríos et al., 2022; Loubet et al., 2022). However, despite the potential of AAPM for food waste reduction, the connection between packaging systems used during storage and food waste is lacking, with only limited LCA studies reported in the literature evaluating environmental impacts on the use of packaging systems for food waste reduction (Almeida et al., 2023; Mei et al., 2019). The environmental impact of food waste reduction has been reported for fresh milk products, whereby antimicrobial coatings present on packaging systems reduced milk waste by up to 50 % while lowering overall environmental impacts in most categories (Manfredi et al., 2015). In another study, Zhang et al. (2015) reported food waste reduction in their LCA study on essential oil-containing active packaging for fresh beef. They reported that 0.6 % beef waste reduction counterbalanced the environmental burden of manufacturing active packaging material. Zhang et al. (2017) and Zhang et al. (2019) conducted LCA studies on three nanocomposite-active food packaging systems to assess their environmental impact and food waste reduction. They reported that the use of nanocomposite packaging not only extended food shelf-life but also had the lowest environmental impacts when scrutinized against global warming potential (GWP). In another study, Villanova-Estors et al. (2023) compared the environmental impact of conventional packaging and active packaging containing EO on fresh mixed salads as well as food waste reduction using LCA. Results showed that using active packaging reduced both food waste by 30 % and environmental impact categories, such as GWP, by more than 50 % compared to conventional packaging. Similar LCA studies have been carried out using fresh tomatoes (Tsouti et al., 2023), fresh-cut vegetables (Vigil et al., 2020), pastry cream (Settier-Ramirez et al., 2022) and fresh beef (Zhang et al., 2015). In summary, studies on Life Cycle Assessment (LCA) reveal that active packaging systems contribute significantly to the sustainability of food systems, especially when shelf-life extension is considered. These systems reduce food waste and promote environmental efficiency by maintaining product quality for longer periods. When evaluating the real-time sustainability of a packaging system, the inclusion of the function "avoiding food waste" in the LCA study would be critical in determining if the reduction in fish waste increased the environmental sustainability of the entire fish-packaging system (Wikström et al., 2014). Although LCA studies on the environmental impacts of fish waste reduction do not appear to have been reported in the scientific literature, comparative analyses of conventional packaging materials used in fish packaging have been reported, highlighting; packaging material used, functional unit, system boundary, major inputs and impact categories (Table 2).

5. Regulatory, safety and economic issues on the application of AAPM

The creation and application of AAPM raises numerous regulatory, safety and economic considerations. This includes fitness for use, fitness of purpose, specific considerations around the migration of chemicals from packaging to food products, risk of toxicity of antimicrobial and other active agents, higher costs linked to production, regulatory and labelling packaging requirements, etc. These issues will be described and discussed in more detail below.

5.1. Regulatory issues

NAM, like EOs, are considered safe for use in food products when employed as food ingredients, but when used as active agents in a packaging system, they cease to have generally regarded as safe (GRAS) status and subsequently, may require additional approval by regulatory authorities, such as the Food and Drug Administration (USA), the European Food Safety Authority (EFSA), European Union and others (Malhotra et al., 2015). Additionally, products packaged using AAPM may need to adhere to specific labelling regulations to inform consumers about the presence of antimicrobial agents and any associated safety precautions associated with their usage. Labelling requirements for antimicrobials in food depend on their specific applications, such as being used as ingredients, flavourings, preservatives, or colouring agents, all of which must be declared on the food label. However, when NAM like EOs are used as antimicrobial agents, they are categorized as indirect additives. Since they result in negligible levels within the food product and cause no functional effects, they are typically exempt from food labelling requirements. (Jackson-Davis et al., 2023).

5.2. Safety issues

Antimicrobial packaging must undergo safety testing to assess its

Table 2
LCA of convectional packaging materials in fish packaging; functional unit, system boundaries, packaging, major inputs, and impact categories.

Reference	Functional unit	System boundary	Packaging	Major inputs		Impact category
Sanchez-Matos et al. (2023)	(I) 5 kg gutted rainbow trout	Cradle to gate	Polyethylene lined Cardboard box	Cardboard box	176 g	GWP, TA, FE, WU, FETP, CED
				Individual wrapper bag	50 g	
				Polyethylene labels	0.7 g	
	(II) 1 kg frozen rainbow trout	Cradle to gate	Polyethylene bag	Polyethylene shrink bag	21.6 g	
				Individual wrapper bag	10 g	
Almeida et al. (2023)	1 kg of mackerel	Cradle to gate	Canning in glass jars	Electricity	0.48 KWh	ODP, FE, WU, FET, GWP, ME
				Water	0.02 m^3	
				Glass jars	0.81 kg	
				Lid	0.04 kg	
				Refrigerants	0.0001 L	
				LDPE	0.01 kg	
Fernández-Ríos et al. (2022)	203 g of fresh tuna	Cradle to grave	Aluminium cans with a cardboard box	Electricity	3.5×10^{-4} kWh	GWP, METP, ADP
				Sunflower oil	0.12 L	
				Aluminium can	15.6 g	
				Cardboard box	9.58 g	
Cortés et al. (2021)	1 ton of raw tuna	Cradle to gate	Aluminium cans with corrugated Board	Electricity	180.8 kWh	GWP, TA, FET, MET, FE, SOD, MRS, ME, FRS
				Natural gas	2.6 MWh	
				Water	120.6 L	
				Aluminium can	73 kg	
				corrugated board	34.5 kg	GWP, LU, MET, WU
Konstantinidis et al. (2021)	1 ton of seabass	Gate to gate	Expanded Polystyrene (EPS)	Energy	93.11 KW	HnCTx, EP, FET
				Ice	0.370 m^3	
				EPS	28.505 kg	
Jonas et al. (2021)	1 kg Atlantic cod fillet	Cradle to consumer	Plastic	Electricity	0.5 kg	GWP, HTP, HnCTx, AP, TETP, METP, POMF, FE
				Plastic packaging	0.01 kg	
				Packaging boxes	0.109 kg	
Kallitsis et al. (2020)	1000 kg Mediterranean sea bass & sea bream	Cradle to gate	Styrofoam	Electricity	320 kWh	AP, ODP, ADP, POMF, TETP, METP, HTP, EP
				Styrofoam	110 kg	
Parker (2018)	1 kg of salmon	Farm to gate	Polyethylene lined Polystyrene boxes	Electricity	0.11 KWh	GWP, CED, EP, AP, POMF, ODP
				Natural gas	5.7 mL	
				Petrol	0.47 mL	
				Polystyrene boxes	17.9 g	
				Polyethylene	3.8 g	
Laso et al. (2018)	1 kg European anchovy	Cradle to grave	Aluminium cans with a cardboard box	Electricity	1.76 MJ	EP, AP, GWP
				Aluminium can	44 g	
				olive oil	303 g	
				Cardboard box	52 g	

ADP: Abiotic depletion potential; GWP: Global warming potential; ODP: Ozone depletion potential; FETP: Fresh water aquatic ecotoxicity; METP: Marine aquatic ecotoxicity; TETP: Terrestrial ecotoxicity; POMF: Photochemical oxidation formation; AP: Acidification potential; EP: Eutrophication potential; SOD: Stratospheric ozone depletion; FE: Freshwater eutrophication; ME: Marine eutrophication; MRS: Mineral resources scarcity; FRS: Fossil resources scarcity; TA: Terrestrial acidification; HTP: Human toxicity; HnCTx: Human non-carcinogenic toxicity; WU: Water use; LU: Land use; CED: Cumulative energy

impact on food and consumer health. Such testing includes the assessment of the potential migration of antimicrobial substances from the packaging into the food and the evaluation of the toxicity risk associated with such agents when they combine with food components (Han et al., 2018; Wyrwa & Barska, 2017). While the objective of employing NAM is to enhance food safety, ensuring that NAM does not lead to the formation of resistant strains of microorganisms is crucial (Malhotra et al., 2015). Consequently, migration of active substances incorporated into packaging should comply with regulation (EC) No.1935/2004, be listed as authorized and should not exceed 0.01 mg/kg if migration occurs (Kontominas et al., 2021; Kampa et al., 2010). A toxicological threshold is provided by the EFSA, while the EU Commission regulation No. 10/2011 lists regulated substances and their specific limits of usage (European Commission., 2011). Therefore, the industry should ensure that the food contact material complies with all required regulations (Mendes & Pedersen, 2021).

EOs are GRAS compounds and have been reported to have little or no toxicity at a dose level of up to 2000 mg/kg; oral toxicity occurs if this level is exceeded (Rai et al., 2017; Ju et al., 2019; Angane et al., 2022). Acute oral testing, which entails measuring the median lethal dose value LD50, is used to evaluate the safety of any EO. (Rout et al., 2022). In the EU, the maximum permissible concentrations of EOs used for fish preservation would be subject to regulations set forth by the EFSA and the European Commission. However, it is important to note that specific concentration limits may vary depending on factors, such as the type of EO used, application method and the specific fish species being preserved. EOs used in fish preservation may fall under the category of novel foods, which are foods or food ingredients that were not consumed

to a significant degree in the EU before May 1997. Novel foods must undergo a safety assessment and receive authorization before they can be placed on the market. Therefore, EOs used in fish preservation would need to comply with the safety requirements outlined in Regulation (EU) 2015/2283 on novel foods (European Commission, 2017). Conversely, as a food additive, organic acids can generate derivatives with toxicity, posing a safety hazard. (Rathod et al., 2021a) and can produce astringent, metallic, or bitter tastes in foods (Inanli et al., 2020). Additionally, the allergenicity of chitosan has been reported in animal-sourced chitosan and therefore, chitosan derived from fungi is permitted and has been listed as a novel food additive via the Commission Implementing Regulation (EU) 2017/247017 (European Commission, 2017).

5.3. Economic issues

Active packaging development involves a delicate balance between functionality, cost and safety. AAPM using NAM offers sustainability benefits and aligns with consumer demands for eco-friendly packaging. Therefore, balancing functionality (e.g., antimicrobial) with cost-effectiveness is crucial (Westlake et al., 2023). AAPM manufacture will be more costly than conventional packaging manufacture owing to costs related to antimicrobial agent usage and their integration into the packaging. Therefore, manufacturers need to weigh production costs against potential benefits like product shelf-life extension. Consequently, the demand for AAPM may influence its economic viability with consumers perceiving benefits like extended shelf-life, greater storage stability, improved food safety, and reduced food wastage more than their associated costs (Fadiji et al., 2023). In addition, active packaging materials may be more expensive to recycle, and this economic obstacle may discourage investment in the infrastructure and technology required to properly recycle these materials at the industrial level.

6. General conclusion

In conclusion, AAPM usage presents a promising solution to enhancing the shelf-life and safety of fish and seafood products. The reviewed studies demonstrate that AAPM can significantly reduce fish waste and environmental impact, making it a sustainable option for the seafood industry. The use of NAM further supports consumer preferences for healthier food preservatives. However, the effectiveness of AAPM is dependent upon several factors, including the intrinsic properties of fish and the specific antimicrobial agents used. Future research should focus on optimizing these factors to maximize the benefits of AAPM. Overall, the industrial adoption of AAPM could play a crucial role in improving food safety, reducing food waste, enhancing food storage stability, supporting food security and promoting environmental sustainability.

CRediT authorship contribution statement

Calderon Paola Alzate: Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Kamau Paul G.:** Writing – original draft, Methodology, Investigation, Conceptualization. **Morris Michael:** Project administration, Formal analysis, Conceptualization. **Cruz-Romero Malco:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Kerry Joe P.:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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