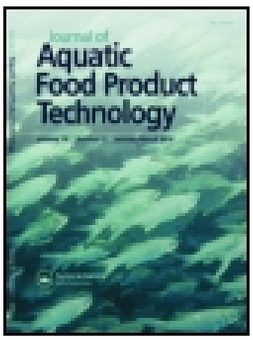

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Current Practice and Innovations in Fish Packaging

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ABSTRACT

Fish and seafood are food products of high commercial value but with short shelf life. The objective of this article is to review the available packaging techniques and their applications on fish products, focusing on research and latest innovations. Modified atmosphere packaging (MAP) has been investigated for the selection of optimum packaging conditions for different fish products. Recent innovations include the combined application of MAP with other preservative factors, such as minimal processing or the addition of antioxidant and/or antimicrobial compounds. Smart packaging, including active packaging and quality control and monitoring systems (gas and moisture control, antimicrobial/antioxidant packaging, smart labels) and edible films and coatings are innovative packaging technologies, which may result in higher quality and extended shelf life of perishable food. The market for active and intelligent packaging methods is anticipated to rise significantly in the near future with their integration into fish packaging.

KEYWORDS

Modified atmospheres; active packaging; intelligent packaging; smart labels; edible coatings

Introduction

The objective of food packaging is to contain the product in a cost-effective way that fulfils industry and customer needs, preserves food quality and safety, and reduces food waste and environmental impact (Restuccia et al., 2010). The complex requirements of society have put even greater demands on the packaging industry (Dainelli et al., 2008). In general, the main functions of food packaging are divided into four categories, i.e. (i) protection: to protect food from deterioration caused by the external environment and to create internal conditions that extend shelf life (e.g. modified atmosphere and active packaging), (ii) communication: to communicate as a marketing tool, as well as providing storage, preparation, and serving guidelines, (iii) convenience: to assist customers with time effective convenience, and (iv) containment: to contain food products of different sizes and shapes (Walsh and Kerry, 2012). In addition to these beneficial properties, food packaging causes rising concern for the environment due to its high production volume, often short usage time, and problems related to waste management and littering. Reduction, reuse, and recycling, as well as redesign support the aims of the circular economy (Geueke et al., 2018).

The most important step in the design and development of a food packaging system that will eliminate undesirable quality modifications and enhance the development and maintenance of desirable quality attributes is the systematic study and understanding of the deteriorative mechanisms of the target food product (Walsh and Kerry, 2012). However, packaging of the new generation affects the food product and thus controls its quality. Several terms have been reported to describe new technologies of packing: active, smart, interactive, and intelligent (Wyrwa and Barska, 2017).

Fish and seafood products have high nutritional value. At the same time, fish consumption has increased from 9.9 kg to approximately 20 kg between 1960 and 2015 (FAO, 2016). High

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susceptibility to microbial growth at elevated temperatures and short shelf life of fresh and chilled fish are major issues for their quality status at any stage of the cold chain. Spoilage of refrigerated and lightly preserved fish is attributed mostly to microbial growth (Gram and Huss, 1996). Often, the fish landing stations are a long distance from the processing plants or market locations, and therefore, long distance and time consuming transportation is necessary. Fish and fish products must be refrigerated or frozen immediately after harvesting to inhibit microbial growth and quality deterioration. At the same time, dehydration during transportation and storage might significantly affect the quality status of the fish products and shorten remaining shelf life. Under this concept, the type and quality of packaging materials and the method of packaging are of great importance for preserving fish quality. According to regulations 1935/2004/EC and 450/2009/EC, active materials can be used to maintain or improve the quality status of packed food and prolong shelf life. Packaging of fish products provides protection against chemical, biological, and physical modifications during storage.

Modified atmosphere packaging

Modified atmosphere packaging (MAP) is a food packaging method that was originally developed for the preservation of fresh produce. In the case of plant origin food products, MAP aims to reduce the rate of respiration and ethylene production, which are often associated with the benefits of retardation of physiological and deteriorative processes occurring in the product (Dermesonluoglu et al., 2016). On the other hand, the aim of MAP of fish and meat products is to modify the headspace in the food package to delay bacterial activity and chemical reactions. MAP is a technology that dates back to the 1930s and has been a critical area of research in terms of minimizing waste through spoilage in fish and fish products (Farber, 1991). Advances in the application of MAP to preserve quality and extend shelf life are occurring at a fast pace. This is evident by the large amount of published studies not only addressing the potential applications in fishery products but also in muscle foods in general (DeWitt and Oliveira, 2016). Stammen et al. (1990) defined MAP as a system where the air within a package is instantly replaced by a mixture of different gases at the time of sealing.

MAP has been reported to significantly inhibit spoilage and prolong shelf life of fresh fish products (Torrieri et al., 2006). Oxygen, CO_2, and N_2 are the most widely used gases in MAP applications, and their concentrations depend on the food product and the spoilage mechanism that limits shelf life (Kirtil et al., 2016). In the USA, carbon monoxide is used in the MAP of meat and fish products (Zhang et al., 2015). The existence of CO can inhibit metamyoglobin formation and promote metamyoglobin reduction in meat that reduce lipid oxidation and color degradation and consequently results in better quality and extended shelf life, as observed in CO-pretreated salmon (Bjørlykke et al., 2011). CO_2 inhibits microbial growth in MA-packaged fish and is the most widely used gas for MAP of fish products. In addition, other gases, such as CO and Ar, have been investigated for their effectiveness as components of MAP for different food products (Walsh and Kerry, 2012). CO_2 concentration plays an important role in the inhibition of microbial growth. CO_2 can delay the growth of respiratory organisms such as *Pseudomonas* spp. and *Shewanella putrefaciens* (Sivertsvik et al., 2002). Under this context, the shelf life of refrigerated fish products can be effectively prolonged by MAP.

The effect of MAP on fish has been investigated in several studies, indicating significant extension of shelf life, depending on species and storage conditions (Dalgaard et al., 1997; Lyhs et al., 2007; Özogul et al., 2004; Pantazi et al., 2008; Stamatis and Arkoudelos, 2007; Torrieri et al., 2006). The diversification of the dominant microbiota in MA-packaged fish depends on the geographical origination, water temperature, and storage conditions. It has been reported that Gram-positive microorganisms, such as lactic acid bacteria (LAB), which exhibit significant resistance to CO_2, play a significant role in the spoilage process of MA-packaged finfish species from warm waters, such as the east Mediterranean basin (DeWitt and Oliveira, 2016; Sivertsvik et al., 2002; Stenström, 1985). The ability of LAB to inhibit growth

of other microorganisms can be attributed to lactic acid and bacteriocin production, which may contribute to their selective growth in fish products at anaerobic conditions (Araújo et al., 2015; Lim, 2016; Stamatis and Arkoudelos, 2007). LAB have been reported as dominant bacteria in the final population in MA-packaged gilthead seabream fillets (Tsironi et al., 2008a and 2008b and 2011; Tsironi and Taoukis, 2010), with significant reduction in the growth rate with increase of CO_2 concentration (from 20 to 80%) (Tsironi et al., 2008). Parlapani et al. (2014) reported co-dominance of LAB and *Brochothrix thermosphacta* in MA-packaged (60% CO_2, 10% O_2, 30% N_2) gilthead seabream fillets under refrigerated storage (0–15°C). In a previous study by Drosinos et al. (1997), co-dominance of *Brochothrix thermosphacta* and LAB in MA-packaged (40% CO_2) gilthead seabream has also been reported. H_2S-producing bacteria were dominant in MAP (10% O_2, 20–60% CO_2, 30–70% N_2) Mediterranean mullet stored at 4°C, followed by *Brochothrix thermosphacta* and LAB (Pournis et al., 2005). According to Kostaki et al. (2009), the dominant microflora in MA-packaged sea bass fillets (40–60% CO_2, 50–30% N_2, 10% O_2) were pseudomonads and H_2S-producing bacteria, while LAB were also part of the dominant microflora. However, recent studies based on molecular analysis methods, such as 16S rRNA gene sequence, have proven that storage temperature and packaging atmosphere significantly affect the synthesis of spoilage microbiota of fish. For example, new dominant species, such as *Carnobacterium maltaromaticum, Carnobacterium divergens*, and *Vagococcus fluvialis*, have been reported for gilthead seabream fillets stored under MAP (60% CO_2, 10% O_2, 30% N_2) at 5°C by Parlapani et al. (2015), while *Pseudomonas veronii* dominated in MA-packaged fillets stored at 0°C. In general, a large diversification in the spoilage microflora of MA-packaged fish other than Mediterranean fish has been reported, especially using DNA-based microbiological analyses. Alfaro et al. (2013) reported that the SSOs in MA-packaged horse mackerel fillets, genotypically characterized by 16S RNA sequencing at the time of sensory rejection, were a combination of *Carnobacterium, Serratia, Shewanella* and *Yersinia* species. Macé et al. (2013) reported that the dominant spoilage bacteria in MA-packaged Atlantic salmon (*Salmo salar*) fillets were *Carnobacterium maltaromaticum, Hafnia alvei*, and Photobacterium phosphoreum, whereas *Shewanella* spp. and *Carnobacterium* spp. dominated the bacterial communities in MA-packaged Atlantic salmon that was farm-raised in southeastern Australia (Powell and Tamplin, 2012). However, after 1 month of storage of MA-packaged (96% CO_2) Atlantic salmon from the Tamar River (Tasmania), the spoilage microflora was dominated by *Pseudomonas* spp., identified by the sequencing of a 16S rRNA gene clone library (Milne and Powell, 2014). *Photobacterium phosphoreum* has been identified as the SSO in MA-packaged fish from cold and temperate water, such as cod (Dalgaard et al., 1997, 1993), and this has been verified by DNA-based methodology. Based on the sequencing of the 16S rDNA gene, Hansen et al. (2016) and Kuuliala et al. (2018) observed also that *Photobacterium* spp. was the dominant spoilage species in both vacuum- and MA-packaged cod fillet portions and loins. Additionally, *Carnobacterium maltaromaticum*, together with members of *Shewanella* and *Psychrobacter*, have been identified as the main spoilage bacterial groups in cooked whole tropical shrimp (*Penaeus vannamei*) and peeled brown shrimp (*Crangon crangon*) packed under MA (Calliauw et al., 2016; Macé et al., 2014, 2012). Several studies investigate the shelf life extension of fish by MAP and are summarized in Table 1. The kinetic study and mathematical modelling of CO_2 and temperature dependence of the studied food product is essential for effective packaging design and optimization of shelf life (Zhang et al., 2015). A limited number of mathematical models that describe the synergistic effect of storage temperature and gas content in the MAP environment have been developed for spoilage bacteria (Alfaro et al., 2013; Dalgaard, 1995; Koutsoumanis et al., 2000). A modified Arrhenius model was proposed by Tsironi et al. (2008) and validated for its applicability for predicting LAB growth and consequent quality and shelf life of MA-packaged seabream fillets at different storage conditions (0–15°C and 20–80% CO_2) (Tsironi et al., 2011).

However, an excessive amount of the product in the package may result in limited preservative effect of MAP on the food product (e.g. due to insufficient amount of CO_2, which guarantees microbiological stability of stored raw material). Due to the interactions between preservative gases and the food product, it is essential to experimentally define the appropriate ratio, so that the protective atmosphere will be maintained. In general, it has been suggested that the volume ratio gas:product for food animal

Table 1. Shelf life extension of fish by MAP as reported in the literature.

Fish	MAP composition	Storage conditions, pre-treatment[(1)]	Shelf life extension	References
Albacore tuna (*Thunnus alalungua*)	40%O_2, 30%O_2	2°C	7 days	López-Gálvez et al., 1995
Atlantic herring (*Clupea harengus*)	30%CO_2, 70%N_2	2%NaCl, 4–10°C	2–3 days	Lyhs et al., 2007
Atlantic herring (*Clupea harengus*)	20%CO_2, 80%N_2 or 40% CO_2, 60%N_2	2°C	2 days	Randell et al., 1995
Atlantic herring (*Clupea harengus*)	60%CO_2, 40%N_2	0 and 5°C	2–4 days	Dhananjaya and Stroud, 1994
Atlantic mackerel (*Scomber scombrus*)	60%N_2, 40%CO_2 or 30% N_2, 40%CO_2, 30%O_2 or 100%CO_2	2–4°C	2 days	Fagan et al., 2004
Atlantic mackerel (*Scomber scombrus*)	100%CO_2	−2°C	> 21 days	Hong et al., 1996
Albacore tuna (*Thunnus alalungua*)	40%O_2, 30%O_2	2°C	7 days	López-Gálvez et al., 1995
Atlantic salmon (*Salmo salar*)	50%CO_2/50%N_2	HP (150MPa/10 min/ 5°C), 5°C	4 days	Amanatidou et al., 2000
Atlantic salmon (*Salmo salar*)	60%CO_2/40%N_2	−2°C	14 days	Sivertsvik, 2003
Atlantic salmon (*Salmo salar*)	60%N_2, 40%CO_2 or 30% N_2, 40%CO_2, 30%O_2 or 100%CO_2	2–4°C	2 days	Fagan et al., 2004
Atlantic salmon (*Salmo salar*)	60%CO_2, 15%N_2, 25% O_2	4.4°C	6 days	Stier et al., 1981
Atlantic salmon (*Salmo salar*)	40%CO_2, 60%N_2, 60% CO_2, 40%N_2	2°C	5 days	Randell et al., 1999
Atlantic salmon (*Salmo salar*)	25–90%CO_2 and N_2	−1.5°C	>14 days	Fernández et al., 2010
Atlantic salmon (*Salmo salar*)	25–90%CO_2 and N_2	Rosemary extract, Sea-i®, −1.5°C	11 days	Fernández et al., 2009
Bluefin tuna (*Thunnus thynnus*)	40%CO_2, 60%O_2; 100% N_2	APF, 3°C	>18 days	Torrieri et al., 2011
Carp (*Cyprinus carpio*)	40%CO_2, 60%N_2; 100% CO_2	3°C	>5 days	Babic et al., 2015
Catfish (*Pseudoplatystoma* spp.)	75%CO_2, 25%N_2	4–16°C	25 days	Reddy et al., 1997a
Chub mackerel (*Scomber colias*)	50%CO_2, 50%N_2	3 and 6°C	3–4 days	Stamatis and Arkoudelos, 2007
Cod (*Gadus morhua*)	60%CO_2, 40%N_2	1°C	>2 days	Woyewoda et al., 1984
Cod (*Gadus morhua*)	25%CO_2, 75%N_2	0°C	2 fold	Villemure et al., 1986
Cod (*Gadus morhua*)	0–100%CO_2	2°C	15–30 days	Stenström, 1985
Cod (*Gadus morhua*)	2–97%CO_2, 3–98%N_2	0°C	2–7 days	Dalgaard et al., 1993
Cod (*Gadus morhua*)	0–100%CO_2, 0–100% N_2, 0–4%O_2	4–26°C	17 days	Post et al., 1985
Cod (*Gadus morhua*)	40%CO_2, 60%N_2 and 40%CO_2, 40%N_2, 20% O_2	FR-TH, 2°C	8–9 days	Guldager et al., 1998
Cod (*Gadus morhua*)	60%CO_2, 40% air	IR (1kGy), 0°C	14 days	Licciardello et al., 1984
Cod (*Gadus morhua*)	60%CO_2, 40%N_2	FR-TH, 2°C	>10 days	Bøknæs et al., 2000
Cod (*Gadus morhua*)	60%CO_2, 10–40%O_2, 0–30%N_2	6°C	>3 days	Debevere and Boskou, 1996
Cod (*Gadus morhua*)	60%CO_2, 40%N_2	CO_2 emitter pad or liquid absorbent pad, 2°C	6 days	Hansen et al., 2016
Cod (*Gadus morhua*)	60%CO_2, 40%O_2; 60% CO_2, 5%O_2, 35%N_2	4 and 8°C	<5 days	Kuuliala et al., 2018
Cod (*Parapercis colias*)	100%CO_2	SM, 3°C and −1.5°C	<3 months	Penney et al., 1994
Dolphinfish (*Coryphaena hippurus*)	45%CO_2, 50%N_2, 5%O_2	*Halocnemum strobilaceum* extract, −1°C	>3 days	Messina et al., 2015
Eel (*Anguilla anguilla*)	40%CO_2, 30%N_2, 30% O_2	0°C	7 days	Arkoudelos et al., 2007
European hake (*Merluccius merluccius*)	20%CO_2, 0% air, 40% CO_2, 0% air	2°C	4–11 days	Ordónez et al., 2000
European hake (*Merluccius merluccius*)	50%CO_2, 45%N_2, 5%O_2	NaCl, 2°C	2–8 days	Pastoriza et al., 1998

(*Continued*)

Table 1. (Continued).

Fish	MAP composition	Storage conditions, pre-treatment[(1)]	Shelf life extension	References
European hake (*Merluccius merluccius*)	0–100%CO_2, 0–100% N_2, 0–4%O_2	4–26°C	13 days	Post et al., 1985
European hake (*Merluccius merluccius*)	50%CO_2, 50%O_2	2°C	2 days	Alvarez et al., 1996
European pilchard (*Sardina pilchardus*)	60%CO_2, 40%N_2	4°C	9 days	Özogul et al., 2004
European pilchard (*Sardina pilchardus*)	80%CO_2, 20%N_2 or 20% CO_2, 80%N_2	5°C	2 fold	Fujii et al., 1989
Fish salad marinated (squid, surimi, mussels, shrimp and octopus)	50–70%CO_2 and N_2	2°C	>3 months	Gunsen et al., 2010
Gilthead seabream (*Sparus aurata*)	30%CO_2, 40%O_2, 30% N_2	OD (100 g/L NaCl, 8°C, 1 h, 1:1), EO oregano (0,4 or 0,8%), 4°C	7–13 days	Goulas and Kontominas, 2007
Gilthead seabream (*Sparus aurata*)	50%CO_2 and air	OD (50% HDM, 5% NaCl, nisin), 0–15°C	<38 days	Tsironi and Taoukis, 2010
Gilthead seabream (*Sparus aurata*)	20–80%CO_2 and air	0–15°C	>5 days	Tsironi et al., 2011
Gilthead seabream (*Sparus aurata*)	40%CO_2, 30%O_2, 30% N_2	D-glucose (0,1 or 0,2%), 1°C	>10 days	Drosinos et al., 1997
Gilthead seabream (*Sparus aurata*)	60%CO_2, 10%O_2, 30% N_2	0–15°C	4 days	Parlapani et al., 2014
Gilthead seabream (*Sparus aurata*)	60%CO_2, 10%O_2, 30% N_2	0 and 5°C	6 and 3 days	Parlapani et al., 2015
Rainbow trout (*Salmo gairdneri*)	20%CO_2, 80%N_2 or 60% CO_2, 40%N_2,	1.7°C	3 days	Randell et al., 1995
Rainbow trout (*Salmo gairdneri*)	80%CO_2, 20%N_2	PS (2,3%), 1.7°C	18 days	Barnett et al., 1987
Rainbow trout (*Salmo gairdneri*)	50%CO_2, 10–30%O_2, 20–40%N_2 or 50%CO_2, 10–30%O_2, 20–40%Ar	1°C	>16 days	Giménez et al., 2002
Rainbow trout (*Salmo gairdneri*)	100%CO_2	4°C	6 days	Banks et al., 1980
Rainbow trout (*Oncorhynchus mykiss*)	45%CO_2/5%O_2/50%N_2	EO (0.2% (v/w) oregano), 4°C	7–8 days	Pyrgotou et al., 2010
Rainbow trout (*Oncorhynchus mykiss*)	75%CO_2, 25%N_2	4–16°C	3–7 days	Reddy et al., 1997b
Rainbow trout (*Oncorhynchus mykiss*)	80%CO_2, 20%N_2	UV-C (106.32mJ/cm^2), 4°C	>2 fold	Rodrigues et al., 2016
Red drum (*Sciaenops ocellatus*)	50%CO_2, 50%N_2	4°C	14 days	
Red hake (*Urophycis chuss*)	60%CO_2, 20%O_2, 20% N_2	PS (0.1, 1 and 2%), 1°C	20 days	Fey and Regenstein, 1982
Red mullet (*Mullus surmuletus*)	10%O_2, 20–60%CO_2, 30–70%N_2	4°C	2–4 days	Pournis et al., 2005
Red mullet (*Mullus surmuletus*)	50%CO_2, 50%N_2	OZ, 1°C	>6 days	Bono and Badalucco, 2012
Rockfish (*Sebastes* spp.)	80%CO_2, 20%N_2 and 100%CO_2	1,7°C	7 days	Parkin et al., 1981
Sea bass (*Lates calcalifer*)	80%O_2, 10%CO_2, 10% N_2	2g/100mL STPP or PP or TSP, 4°C, 10min, 1:3, 4°C	11 days	Masniyom et al., 2002
Sea bass (*Dicentrarchus labrax*)	0–40%O_2, 0–70 CO_2	3°C	>2 days	Torrieri et al., 2006
Sea bass (*Dicentrarchus labrax*)	40%CO_2, 50%N_2, 10% O_2 or 60%CO_2, 30%N_2, 10%O_2	EO (0.2% (v/w) thyme), 4°C	11 days	Kostaki et al., 2009
Sea bass (*Dicentrarchus labrax*)	40%CO_2, 60%N_2	2°C	3 days	Poli et al., 2006
Sea bass (*Dicentrarchus labrax*)	40–60%CO_2 and N_2	4°C	11–14 days	Provincial et al., 2010)
Sea bass (*Dicentrarchus labrax*)	80–100%CO_2	4°C	>20 days	Masniyom et al., 2002
Sea bass (*Morone sawafilis, Morone chrysops*)	60%CO_2, 6%O_2, 34%N_2	2°C	6 days	Handumrongkul and Silva, 1994
Seer fish (*Scomberomorus commerson*)	70%CO_2, 30%O_2	SA, 0–2°C	14–20 days	Yesudhason et al., 2014
Speckled trout (*Cjmoscion nebulosus*)	100%CO_2	4°C	2 days	Banks et al., 1980
Swordfish (*Xiphias gladius*)	40%CO_2, 30%N_2, 30% O_2	4°C	4–5 days	Pantazi et al., 2008
Swordfish (*Xiphias gladius*)	40–100%CO_2, 0–60% N_2, 0–60%O_2	2°C	12 days	Oberlender et al., 1983

(*Continued*)

Table 1. (Continued).

Fish	MAP composition	Storage conditions, pre-treatment[(1)]	Shelf life extension	References
Swordfish (*Xiphias gladius*)	5%O_2, 50%CO_2, 45%N_2	EO (0.1% (v/w) thyme), 4°C	7 days	Kykkidou et al., 2009
Tilapia (*Tilapia* spp.)	75%CO_2, 25%N_2	4°C	12–16 days	Reddy et al., 1995
Tilapia (*Tilapia* spp.)	50–75%CO_2	4°C	4–21 days	Reddy et al., 1994
Tilapia (*Tilapia* spp.)	75%CO_2/25%N_2	4°C	>12 days	Reddy et al., 1995
Wolffish (*Anarhichas minor*)	60%CO_2/40%N_2	4°C	5–7 days	Rosnes et al., 2006
Whiting (*Merlangius merlangus*)	60%N_2, 40%CO_2 or 30% N_2, 40%CO_2, 30%O_2 or 100%CO_2	2–4°C	2 days	Fagan et al., 2004
Whiting (*Merlangius merlangus*)	50%CO_2/50%N_2; 20% CO_2/80%N_2	4°C	2 days	Hassoun and Karoui, 2016
Yellowfin tuna (*Thunnus albacares*)	0–60%CO_2, 0–40%N_2, 0–60%O_2	1 and 3°C	10 days	Emborg et al., 2005
Yellowfin tuna (*Thunnus albacares*)	70%CO_2, 30%O_2	4 and 8°C	0 days	Silbande et al., 2016
Yellowtail flounder (*Limanda ferrugina*)	100%CO_2 or 100%N_2	8–26°C	7 days	Post et al., 1985

[(1)]AP: active packaging films, EO: addition of essential oil, FR-TH: freezing-thawing, HP: high pressure, IR: irradiation, OD: osmotic dehydration, OZ: ozone treatment, PP: polyphosphoric sodium, PS: potassium sorbate, SA: sodium acetate, SM: smoking, STPP: tripolyphosphoric sodium, TSP: Trisodium phosphate, UV-C: UV-C radiation.

origin foods should be less 3:1 to both inhibit the adverse reactions connected with the presence of O_2 inside and to avoid package deformation (20172017).

Although shelf life is prolonged by the inhibition of aerobic spoilage bacteria, MAP cannot inhibit the growth of *Clostridium botulinum*. This microorganism has the potential to produce a powerful neurotoxin in foods, especially under anaerobic conditions. The lethal dose of botulinum toxin in adults is approximately 1 ng/kg. Fish inoculated with levels of *C. botulinum* spores and stored under MAP or vacuum have become toxic within 6–8 days of storage at 10°C (Arritt et al., 2007). This is a significant concern, since in distribution and food product displays, product temperatures have been reported to fluctuate between 4 and 10°C (Arritt et al., 2007). For this reason, the U.S. Food and Drug Administration (FDA) issued specific guidelines about MA-packaged fish and seafood product handling, storage and transportation, so as to eliminate the risk for *Clostridium botulinum* growth and toxin formation (FDA, 2011).

Concerns have also been expressed about the ability of the other psychrotrophic pathogens (e.g. *Aeromonas, Listeria*, and *Yersinia* spp.) to grow in MAP products. In general, the majority of the results reported in the literature indicate that the risks from foodborne pathogens in MAP are no greater and are frequently less than those from aerobically stored foods. More specifically, it has been reported that in no instance was the growth/survival of any of the pathogens examined (i.e. *Listeria monocytogenes, Aeromonas* spp., *Yersinia enterocolitica*, and *Salmonella typhimurium*) greater in MAP than in the aerobically stored cod (*Gadhus morhua*) and rainbow trout (*Oncorhynus mykiss*) (Church, 1994). In most cases, growth of pathogens in fish products is reported to be reduced under MAP conditions (Provincial et al., 2013; Yesudhason et al., 2014).

Minimal processing methods have shown the potential to further prolong the shelf life of MA-packaged foods by the combined application of preservative hurdles such as low storage temperature, addition of antimicrobials and/or antioxidants, water activity, pH, and high pressure processing (Bouletis et al., 2017; Sivertsvik et al., 2002).

Active and intelligent packaging

Apart from the required function to protect and ensure the integrity and safety of food products, recent packaging applications aim to provide supplementary functionalities. Smart packaging may contribute to prolonging the shelf life and can provide essential information regarding food safety and quality, enabling effective cold chain management, food waste reduction, and increased

consumer protection (Figure 1). Under this context, the "smartness" of packaging refers to the ability to communicate essential information regarding product quality; for example, package integrity and time and temperature history of the packed food. Smart packaging may also directly inform the users about the quality status of the food, as for example the freshness indicators that give information on quality (Janjarasskul and Suppakul, 2017; Smolander, 2003; Taoukis and Tsironi, 2016).

Active packaging

A packaging method may be regarded as active if it performs an alternative role to providing an inert protection from the external environment (Biji et al., 2015; Rooney, 1995). According to the EU Guidance to the Commission Regulation (EC) No 450/2009, packaging is termed active when it provides functions beyond the traditional protection and inert barrier to the external environment (EU, 2009). The main difference between intelligent and active packaging is that active packaging senses modifications of the internal or external environment and responds accordingly so as to alter its properties. On the other hand, the function of intelligent packaging switches on and off according to the modifications of the external or internal environmental conditions and communicates information to the user regarding the quality status of the product (Fellows., 2016). Based on EC/450/2009, the intelligent materials are defined as tools that monitor the status of the packed food or its surrounding environment.

Gas control

Several applications of active packaging solutions are directly connected with MAP. The atmosphere inside packaging can be actively controlled by substances that absorb (scavengers) or release (emitters) gases (Wyrwa and Barska, 2017). In dark-fleshed fish and red meat, deoxymyoglobin is responsible for a purple color, which upon exposure to O_2 is rapidly oxidized to cherry red

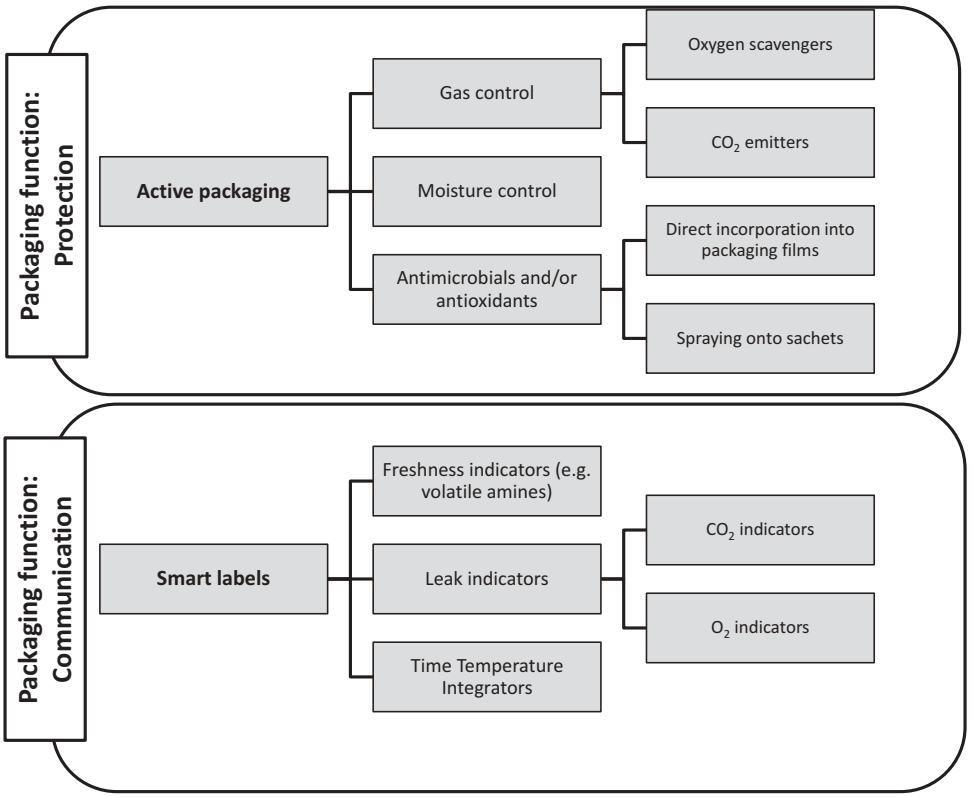

Figure 1. Active and intelligent packaging of fish.

oxymyoglobin. Oxygenation of the oxymyoglobin derivative results in the formation of metamyoglobin, thereby providing a brown color associated with loss of freshness. In general, the reduction of O_2 concentration to levels lower than 0.05% has been reported to minimize the extent of quality deterioration in muscle products (Faustman and Cassens, 1990). The first active packaging approach is O_2 scavengers, which up to now are the most extensively used active packaging systems for foods (Remya et al., 2017). O_2 scavengers are commercially available by numerous companies (e.g. Ageless-Mitsubishi Gas Chemical Co Ltd., Japan; Bioka-Bioka Ltd., Finland; Dri-Loc®-Sealed Air Corporation, USA; Freshmax-Multisorb, USA; Oxyguard-Tokyo Seikan Kaisha Ltd., Japan) in several formats, such as sachets, films, and alternative active compounds, such as metals, enzymes, and dyes (Ahmed et al., 2017). The different mechanisms of O_2 scavenging technologies include oxidation of iron, unsaturated fatty acids and ascorbic acid, and photosensitive dye oxidation. These compounds are able to reduce the levels of oxygen to below 0.01%, which is lower than the level typically found (0.3–3%) in the conventional systems of modified atmosphere, vacuum, or substitution of internal atmosphere for inert gas (Cruz et al., 2007). Currently, O_2 scavengers based on the oxidation of iron and ferrous salts are the most effective and commonly used scavengers available commercially (Miltz and Perry, 2005; Otero-Pazos et al., 2018). In general, O_2 scavengers can prevent oxidation of fats and lipids or other O_2 sensitive components and the subsequent development of off-flavors and loss of O_2 sensitive nutrients, such as vitamins A, C, and E and unsaturated fatty acids and prevent proliferation of aerobic microorganisms without the addition of chemical additives (Bolumar et al., 2016; Dombre et al., 2015; Hutter et al., 2016; Johnson et al., 2018).

A significant disadvantage of MAP is the demand of high gas volume to product volume ratio and the resulting demand on space. Increased concentration of CO_2 in the headspace and high gas volume to product ratio lead to increased dissolution of CO_2 in the fish flesh; however at low ratios, the inhibitive effect of CO_2 on microbial growth is limited. The higher solubility of CO_2 at increasing gas to product volume ratio is attributed to higher partial pressure of CO_2 (Hansen et al., 2007). Carbon dioxide emitters have been additionally developed by some companies, which utilize the O_2 from the package atmosphere to form CO_2 and to develop a CO_2/N_2 headspace into the package without implicating any gas insertion. Alternative techniques to generate CO_2 into the food package after sealing include the utilization of dry ice or carbonate in some cases in combination with weak acids (EFSA, 2016; Hansen et al., 2016). Currently, CO_2 generators are used in the active packaging system for the purpose of increasing the lag phase and inhibiting growth of bacteria in certain food products. The effect of CO_2 varies upon microorganisms. For example, moderate to high CO_2 concentrations (10–20%) can slow down growth of aerobic bacteria, while growth of LAB is stimulated by CO_2 (Ahmed et al., 2017). The commercially available CO_2 emitters in most cases include ferrous carbonate and a metal halide catalyst to absorb O_2 and produce equal volumes of CO_2 (Biji et al., 2015; Sivertsvik, 2003). UltraZap® XtendaPak is an absorbent pad that can be applied to meat or fish packaging and has a dual effect due to the simultaneous inclusion of antimicrobial agents and CO_2 emitter (Ahmed et al., 2017). McAirlaid's FishPad (Steinfurt, Germany) is a CO_2 pad that produces CO_2 gas in contact with water that is obtained from liquid leaking from the fish flesh. Thus, this CO_2 emitter may also simultaneously act as a liquid absorber. A CO_2 emitter prepared by $NaHCO_3$ and citric acid has been reported to sufficiently reduce the transport volume of MA-packaged farmed cod (Hansen et al., 2007) and Atlantic salmon (Hansen et al., 2009). The CO_2 emitter releases gas during storage and thereby compensates for the reduced gas volume to product volume ratio.

Moisture control

Food spoilage is often attributed to excess moisture. For this reason, moisture absorbers are used for the protection of dehydrated products and thus show limited applicability on fish products. The decrease of water activity at the surface of food has been reported as an effective approach to extend shelf life of fresh fish (Vermeiren et al., 1999). Moisture absorbent sheets, blankets, and pads are usually employed for controlling fluid exudates from food products (Biji et al., 2015). However,

moisture absorbing pads are not often considered to be active packaging. According to the EU Guidance to the Commission Regulation (EC) No 450/2009, "*Materials and articles functioning on the basis of the natural constituents only, such as pads composed of 100% cellulose, do not fall under the definition of active materials because they are not designed to deliberately incorporate components that would release or absorb substance*." On the other hand, moisture absorbing pads containing components that "*are intentionally designed to absorb moisture from the food*" can be considered as active packaging (Yildirim et al., 2018).

Additionally, moisture can be removed from meat products by using desiccants in the form of sachets, such as calcium oxide, calcium chloride, molecular sieves, natural clays, and silica gel (Sängerlaub et al., 2013). Silica gel is the most extensively used desiccant among these due to its non-toxic and non-corrosive nature. Typical extra absorbent polymers such as starch copolymers carboxymethyl cellulose (CMC), chitosan, and polyacrylate salts have strong affinities for moisture (Gaona-Forero et al., 2018; Rajamani and Maliyekkal, 2018). These absorbing pads can be placed under the packaged product to absorb possible fluid exudates from the tissues.

Numerous companies have launched moisture regulators in the form of sheets, trays, and blankets for regulating high water activity food. A wide range of polypropylene (PP) or polyethylene terephthalate (PET) absorbing trays containing an in-built patented high capacity absorbent core is available for packaging meat and fish products (Ahmed et al., 2017). Showa Denko Co (Tokyo, Japan) designed a plastic film that consists of a layer of humectant propylene glycol between layers of polyvinyl alcohol, which can result in 2–4 days shelf life prolongation in fresh fish (Labuza, 1993; Sivertsvik, 2003). Nor® Absorbit (Nordenia International AG), has been introduced as a flexible film, with the ability to absorb drip losses from packaged foods during microwave cooking (Unipack, 2011).

Antimicrobial and/or antioxidant packaging

Active packaging systems link the preservative role of antimicrobials and other components to the standard role of packaging (Ahmed et al., 2017; Mauriello et al., 2004; Scannell et al., 2000). The packaging material releases compounds into the food or the headspace surrounding the product, or it absorbs food-derived substances from the food or the packaging environment. The internal environment of the package can be modified by the incorporation of active compounds into the package via pad, tablet, or sachet and enabling mechanisms, such as evaporation and absorption, to hinder the microbial proliferation and other degradation processes (Ahmed et al., 2017; Lee, 2010). The controlled release of the bioactive compounds provides protection over food quality and may prolong shelf life, especially for solid foods such as fish, where quality deterioration is evident at the surface of food and the compounds are released at the places that are appropriate. In general, the direct incorporation of antimicrobial agents into the packaging films is more useful in achieving antimicrobial activities. Examples of antimicrobials applied under this context include bacteriocins, organic acids, or their salts (Fellows., 2016). Silver substituted zeolite is widely used in Japan as antimicrobial agent in the form of a thin layer onto the food contact surface of the laminate. Other antimicrobial packaging solutions aim to release volatile antimicrobials, e.g. chlorine dioxide, carbon dioxide, and ethanol. For this type of antimicrobial packaging, where volatile compounds show antimicrobial activity in the environment of the package and on the surface of the food, polymers are not necessarily in direct contact with the food. Spraying ethanol onto food or sachets that generate ethanol can also be used (Biji et al., 2015). Essential oils (EOs) are considered as important ingredients for active packaging, especially as natural compounds with antimicrobial activity. However, these additives may significantly affect the sensory parameters of the food product (mainly color, odor, and taste), and this is a major drawback for their commercial application on active food packaging systems. Extracts obtained from spices, herbs, or food processing by-products, such as barley husks, pomegranate peel, and olive leaves, have been reported to exhibit antioxidant activity as well, enabling their utilization as food additives (Ganiari et al., 2017). Recent applications of natural extracts incorporated into packaging polymers for fish fillets have been reported

in the literature, e.g. tea polyphenols into gelatin systems (Feng et al., 2017) and rosemary, laurel, thyme, and sage into nanoemulsions (Ozogul et al., 2017).

Smart labels

Freshness indicators

Freshness indicators are devices that are placed inside the sealed food package and are designed to inform the end user about the quality status of the packed product, which is affected by microbial and physicochemical modifications. Food quality in terms of microbial status can be visualized through the interactions between microbial metabolites and indicators integrated in the food package (Vanderroost et al., 2014). Most of the proposed systems are based on the color change of an indicator as a result of the production of microbial metabolites during microbial spoilage, indicating that the food is no longer appropriate for consumption (Rhim and Kim, 2014). Additionally, freshness indicators can be applied for the estimation of the remaining shelf life of food products at any point of the supply chain (Kuswandi et al., 2013).

The prerequisite for the design and application of an adequate freshness indicator for a specific product is understanding of the metabolites that determine quality of the target food. Of course, an appropriate indicator should be able to react with these specific agents in a reproducible and sensitive manner. The ideal indicator must also comply with the current legislation, as this type of label should be in direct contact with the food or within the package headspace (Smolander, 2008). The total amount of volatile basic compounds (i.e. ammonia and amines, such as trimethylamine, dimethylamine etc.) are referred as total volatile basic nitrogen (TVBN), which has been used as spoilage indicator for fish products (Commission Regulation No. 2074/2005). Several indicators have been developed to monitor freshness of fish products correlated to volatile amines (Smolander, 2008). FreshTag® (COX Technologies, Belmont, NC, USA) is a color indicator that can detect volatile amines that are correlated with the "fishy odor" in fish (Williams and Myers, 2005; Williams et al., 2006). The volatile compounds interact with a nontoxic food dye (indicator) that results in a gradual color change, indicating that the product is no longer appropriate for consumption (end of shelf life). A freshness indicator consisting of a polymer-based matrix solution that contains a pH-sensitive dye (bromocresol green) has been investigated by Chun et al. (2014) for monitoring mackerel fillet volatile amines as a result of *Pseudomonas fragi* growth.

Leak indicators

A leak indicator is a device used to determine if a leak has occurred in the packaging and thus ensures package integrity throughout the production and distribution chain. Preservation of packaged fish products in terms of quality and safety is a complicated issue, due to significant modifications of the headspace composition that can occur by leakage or the gases resulting from microbial activity (Lee and Rahman, 2014; Taoukis and Tsironi, 2016). Additionally, the main drawback of MAP is the fact that the shelf life of the packed food is strongly dependent on the package integrity (Dalgaard and Huss, 1995). Lack of package integrity (i.e. leak) will quickly eliminate the protecting atmosphere by increasing O_2 and decreasing CO_2 concentration. Under this context, a smart label capable of monitoring CO_2 level could ensure the maintenance of CO_2 concentration in the package headspace. Giannoglou et al. (2012) proposed a CO_2 indicator (a bicarbonate buffer in a CO_2-permeable pouch) as a monitoring tool of quality and shelf life of MA-packaged seabream fillets during refrigerated storage. Visual color response of the indicator is attributed to the color change of a pH indicator. O_2 indicators can monitor the concentration of O_2 inside the MA package and thus indicate a possible leakage. The combined indication of O_2 concentration and time-temperature history of the packaged food would provide additional information on the quality status and remaining shelf life of packed food at any stage of the supply chain (Ahvenainen et al., 1995). Optical O_2 sensors have been recently applied on several food products (Wang et al., 2010). The Tell-

Tab is a tablet type O_2 indicator designed by IMPAK Corporation (Los Angeles, CA, USA) (Lee and Rahman, 2014). Saarinen et al. (2015) demonstrated the fabrication of an UV light activated colorimetric O_2 indicator on paper and plastic substrates. The authors reported that this system, which is based on a methylene blue/TiO_2 mixture, is appropriate for application on MAP fish products.

Time Temperature Integrators

Shelf life of perishable food, such as fish, is significantly shortened if these products are not transported and/or stored under the recommended temperature conditions in the entire supply chain, from the point of production up to consumption. Temperature monitoring is therefore necessary for appropriate shelf life monitoring and cold chain management (Taoukis and Tsironi, 2016). A TTI is defined as an inexpensive, smart label that can show time and temperature dependent changes, which reflect the time-temperature history of the food to which it is attached (Taoukis and Labuza, 1989). A TTI-based cold chain management system, which aims to improve the quality and safety of the products at any stage of the food supply chain, may be designed by the application of the cutting edge technology in TTIs in conjunction with validated predictive models for microbial growth and risk evaluation. The development of reliable shelf life models for fish products could provide the appropriate information to enable the design of reliable practical systems, such as TTIs, for monitoring, recording, and translating the effect of temperature, from harvest to the consumer (Taoukis et al., 1999; Taoukis and Tsironi, 2013). TTI systems are integral parts of interactive intelligent packaging systems and can be considered as part of an active signal of quality status and shelf life in conjunction with the conventional "use-by date" (Taoukis and Tsironi, 2016).

The principle of TTI operation is a mechanical, chemical, electrochemical, enzymatic, or microbiological irreversible change that is in most cases expressed as a visual response (i.e. mechanical deformation, color change, or movement). Between 1985 and 2017, several TTI systems were proposed, but a limited number reached the industrial prototype and even fewer found commercial application (Taoukis and Tsironi, 2016). The chronology of the development of TTI development is summarized by Taoukis (2010). The CheckPoint® TTI (VITSAB A.B., Malmö, Sweden) is an enzymatic TTI, which is based on a color change by pH decrease due to the controlled enzymatic hydrolysis of a lipid substrate by a microbial lipase. The functionality of the Fresh-Check® TTI (Temptime Corp., NJ, USA) is attributed to a solid state polymerization. The OnVu™ TTI (Bizerba, Germany) is based on the inherent reproducibility of reactions in crystal phase. The TOPCRYO (former eO®) TTI (CRYOLOG, Gentilly, France) is based on a time-temperature dependent pH change, due to controlled microbial growth, and color change of an appropriate pH indicator. The TT Sensor™ TTI (CCL Design, Strongville, OH, USA) is based on the concept of a diffusion reaction. The 3M Monitor Mark® (3M Co., St. Paul, MN, USA) is another diffusion polymer based indicator. The CoolVu (Freshpoint, Nesher Haifa, Israel) consists of a metal base label and a secondary transparent label containing an etchant. The Keep-it® indicator (Keep-it Technologies® AS, Oslo, Norway) is based on a time-temperature dependent migration of a pH modifying agent into a mutarotational reducing system. A novel TTI has been recently developed by FreshStrips (FreshStrips B.V., Eindhoven, Netherlands) and is based on shape memory of a mechanically embossed chiral nematic polymer network of liquid crystals.

In order to select an appropriate TTI smart label to monitor the quality of fish fillets, Tsironi et al. (2011) studied an UV activatable photochromic TTI. A composite mathematical model was developed that predicts the response of the TTI at different levels of activation, which enables the estimation of the appropriate charging time for quality monitoring of MA-packaged gilthead seabream fillets at any predetermined packaging and storage conditions. A systematic approach for shelf life modeling of fish products and methodology for appropriate TTI selection for the design of an effective quality monitoring scheme for the fish supply chain has been previously developed for products, such as chilled boque (Taoukis et al., 1999), seabream (Giannakourou et al., 2005), tuna

(Tsironi et al., Tsironi et al., 2008a), turbot (Nuin et al., 2008), grouper (Hsiao and Chang, 2016), and cod (Mai et al., 2011).

Two different types of TTI smart labels (i.e. an enzymatic and a photochromic) have been developed and studied for monitoring quality and shelf life of frozen seafoods within the IQ-Freshlabel project (FP7-SME-2008–2-243423, http://www.iq-freshlabel.eu). Appropriate methodology has been proposed for the design and selection of optimum TTIs for specific frozen seafood products, and their applicability has been validated under simulating trials of the cold chain and in pilot studies (Tsironi et al., 2015a). Giannoglou et al. (2014) and Tsironi et al. (2016) selected and validated the effectiveness of selected photochromic and enzymatic TTIs for shelf life monitoring of frozen blueshark (*Prionace glauca*) slices and arrow squid (*Nototodarus sloanii*) in the cold chain.

Shelf Life Decision System (SLDS) (Giannakourou et al., 2005) and Safety Monitoring and Assurance System (SMAS) (Giannakourou et al., 2005) are integrated cold chain management systems that lead to an optimized handling of products in terms of quality and safety risk. According to Tsironi et al. (2008), the spoilage profile of vacuum packed yellowfin tuna slices handled with SMAS was significantly improved compared to the conventional First-In-First-Out (FIFO) approach.

The current TTI technology and the scientific approach regarding the quantitative study of safety risk in food products may enable the next important step, which is the application of TTIs to manage food safety risks (Koutsoumanis and Gougouli, 2015). TTIs of high accuracy and suitable design for fish and seafood safety monitoring have been developed and proposed. Tsironi et al. (2017a) proposed specific enzymatic TTIs, suitable to indicate the growth potential of *Vibrio parahaemolyticus* or *Vibrio vulnificus* in oysters from the point of harvest up to storage for further distribution and retail display. Tsironi et al. (2017b) selected appropriate enzymatic TTI labels that signal predetermined potential histamine levels (i.e. 50, 100 or 200 mg/kg) in mullet. The FDA has issued guidelines for handling of seafood products, including the application of appropriate TTI, to eliminate the risk for growth of *Clostridium botulinum* and toxin formation (FDA, 2011). Vitsab A.B. (Malmö, Sweden) has designed an enzymatic TTI (L5-8 Seafood TTI) adapted to the Skinner and Larkin boundary (Skinner and Larkin, 1998), which predicts the time and temperature conditions required by *Clostridium botulinum* strains to produce the potent toxin (Ronnow et al., 2015). A similar application has been also proposed for the Timestrip® Seafood label produced by Timestrip UK Ltd (Cambridge, UK).

It is therefore concluded that continuous temperature monitoring by appropriate TTIs could result in reliable estimation of the safety and quality status of food, enabling effective shelf life management and optimization of the fish and seafood supply chain. However, the adoption of TTI technology in the consumer market has yet to materialize despite the many benefits that TTIs bring to food manufacturers, retailers, and consumers. According to Penannen et al. (2015), an important issue is the relevant lack of knowledge regarding consumers' perceptions of TTIs. For this reason, a systematic consumer study was carried out within the IQ-Freshlabel project, including 16 focus group discussions and a quantitative survey in 4 EU countries (i.e. Finland, Greece, France and Germany) during May-October 2012. TTIs were found useful and easy to understand, an effective tool for monitoring both external and consumers (domestic) cold chain, and showed the potential to increase trust in the food chain in each country. More specifically, the quantitative study showed that consumers in all countries considered TTIs at least moderately relevant for fresh and frozen fish, meat, and poultry products, and qualitative study findings revealed that French, Greek, and German participants considered TTIs to increase food safety and security (Pennanen et al., 2015).

On the other hand, the food producers' reluctance to accept the benefits of the TTIs technology has related to cost, reliability, and applicability. The cost is volume dependent, ranging from $0.02 to 0.20 per unit. If the other issues were resolved, the cost-benefit analysis would certainly favor the adoption of the TTI (Taoukis, 2010). Such TTI smart labels would be used to make a conservative estimate of shelf life for cold chain management. Thus, the time to the end of shelf life, based mainly on safety criteria, would be solved by labelling with the expiration date along with the TTI reading. Under this context, TTI labels used in conjunction with open dates can help to assure high product

quality once products leave the manufacturer. Products could be labeled as "use by xx unless indicator shows…", with the latter depending on the TTI design (Newsome et al., 2014).

Edible films and coatings

Edible coating or film is defined as a thin layer of material used for coating or wrapping different food systems to extend shelf life (Dehghani et al., 2018). Edible coatings and films provide a replacement and/or fortification of the natural layers at the product surfaces to prevent moisture loss, gas aroma, and solute movement out of the food, while selectively allowing for controlled exchange of important gases, such as O_2, CO_2, and ethylene, involved in food product respiration (Embuscado and Huber, 2009). Edible films are prepared separately and subsequently applied to the food, while coatings are formed directly onto the surface of the food (Cordeiro de Azeredo, 2012), as illustrated in Figure 2. Both methods are reported to enhance the organoleptic characteristics of packed food products when properly formulated. Additionally, by the incorporation of antibacterial and antioxidant agents, they can function to retard oxidation and/or delay microbial spoilage (Dehghani et al., 2018; Ganiari et al., 2017). Several materials can be used to develop edible films and coatings for fish products. These materials must be capable of forming a film and be dissolved in an appropriate and safe solvent, also compatible with the

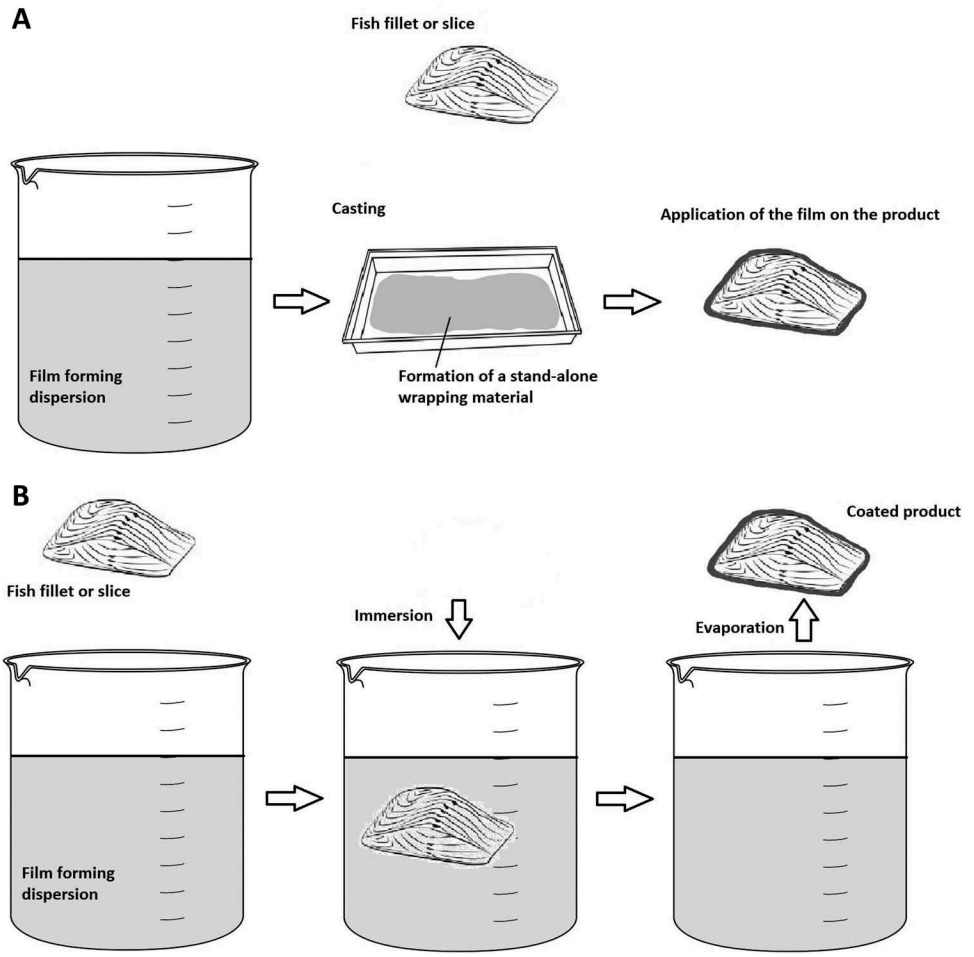

Figure 2. Schematic representation of the application of (a) edible films and (b) edible coatings on fish fillets.

specific plasticizers, antioxidant and/or antimicrobial compounds, etc. The potential materials can be classified as lipids (e.g. acyglycerol, fatty acids), hydrocolloids (e.g. polysaccharides, alginates), and composites (Donhowe and Fennema, 1993).

Polysaccharide-based films and coatings can be made using cellulose, starch, pectin derivatives, seaweed extracts (e.g. alginates, carrageenan and agar), exudate gums, and chitosan (Dehghani et al., 2018). The most commonly used polysaccharides are gums and chitosan. Hydrogen bonds between the solvent and the polymer allow gums to dissolve in water. In solution, the polymer molecules may rearrange into another structure (micelle), which is stabilized or strengthened by intermolecular hydrogen bonds. Micelles are stable during drying and enable film formation. Chitosan is the second most abundant polysaccharide, consisting of (1,4)-linked 2-amino-deoxy-β-δ-glucan and is the deacetylated derivative of chitin. Chitosan is a non-toxic, biodegradable, biofunctional, biocompatible polysaccharide with strong antimicrobial and antifungal properties (Li et al., 2013). Chitosans with high molecular weight form films with higher viscosity and higher particle size compared to films consisting of chitosans with lower molecular weight (Fernández-Pan et al., 2015). Chitosan-based coatings have been extensively applied for the preservation of fish, since they are non-toxic, biodegradable, biocompatible, and they exhibit antimicrobial and antifungal activities and film-forming properties (Ojagh et al., 2010). The coating effect of a lactoperoxidase system incorporated into chitosan has been reported to result in significant shelf life prolongation of rainbow trout during chilled storage at 4°C (Jasour et al., 2014). Jeon et al. (2002) presented the applicability of chitosan for the formation of a preservative coating system for herring and cod that may result in reduction or elimination of moisture loss, oxidation of lipids, and microbial activity. Another widely used cellulose derivative for the formation of edible films is carboxy-methyl-cellulose (CMC). CMC has been proposed as an effective compound for the formation of edible coatings, due to its specific desirable properties, such as water-solubility, high viscosity, biocompatibility, biodegradability, hydrophilicity, moderate moisture, and O_2 permeability, as well as appropriate film-forming ability. Additionally, it is odorless, tasteless, non-toxic, non-allergenic, flexible, and colorless (Tharanathan, 2003). According to Choulitoudi et al. (2016), EO and extracts of the plant *Satureja thymbra* incorporated in CMC edible coating resulted in shelf life prolongation of gilthead seabream fillets. Extension of 25 and 35% in the shelf life at 0°C was estimated for the addition of the extract and the combination of extract and EO, respectively, which showed significant antimicrobial effect when incorporated in a 1.5% CMC edible coating. A CMC based edible coating with the addition of rosemary (*Rosmarinus officinalis*) EO and extracts inhibited microbial spoilage and oxidation of lipids in smoked eel fillets during refrigerated storage at 4°C (Choulitoudi et al., 2017).

Film-forming proteins are derived from animals (casein, whey protein concentrate and isolate, collagen, gelatin, egg albumin, etc.) or plants (corn, soybean, wheat, cottonseed, peanut, rice etc.). The main protein film formation mechanism refers to protein denaturation resulting from heat, presence of specific solvents, or pH modifications, followed by association of peptide chains through new intermolecular interactions (Cordeiro de Azeredo, 2012; Dehghani et al., 2018). Gelatin extracted from fish processing by-products, such as skin and bones, has been reported as able to form edible coatings that act as barriers to O_2, moisture, and light (Yang and Wang, 2009). Cat fish gelatin has been reported as an effective coating with antimicrobial activity that may prolong shelf life of fresh white shrimp (*Penaeus vannamei*) (Jiang et al., 2010). Fish gelatin hydrolysate based coatings significantly inhibited lipid oxidation in boiled-dried anchovy (Kim et al., 2016). The combination of gelatin and chitosan for the formation of edible coatings and films has also been investigated. Gómez-Estaca et al. (2010) proposed a gelatin/chitosan film incorporated with EOs (i.e. clove, fennel, cypress, lavender, thyme, pine, verbena, rosemary) for inhibiting growth of spoilage bacteria and pathogens and extending shelf life of chilled fish products. Edible coatings consisting of chitosan and gelatin inhibited quality deterioration of golden pomfret fillets stored at 4°C (Feng et al., 2016).

Edible film and coatings based on hydrophobic materials such as lipids have been used particularly for limiting moisture transmission from foods. Hydrophobic substances are efficient barriers

against moisture migration (Embuscado and Huber, 2009). Unlike polysaccharides and proteins, lipids are not bio-polymers and do not have the ability to form cohesive, independent films. Therefore, they can be either applied as coatings or incorporated into other biopolymers to make composite films. Lipid compounds that can be used as protective coatings may be acetylated monoglycerides, natural waxes, and surfactants. The most effective lipid compounds are paraffin wax and beeswax (Bourtoom, 2008). Lipids incorporated into edible coatings and films may improve the cohesiveness, hydrophobicity and flexibility of the materials. This methodology has been reported to improve the freshness, aroma, color, and microbiological stability of fish products (Dehghani et al., 2018). According to Cecchini et al. (2017), the addition of lipids (i.e. beeswax or sunflower oil) enhanced the water barrier properties of composite films with whey protein concentrate and brea gum. Limited research has dealt with the effectiveness of lipids as protective coatings and films for fish products (Dehghani et al., 2018).

Future trends

Recent research has been initiated to address three major trends in the food packaging sector, namely (i) the health trend, (ii) the green movement, and (iii) the food safety trend. The three main trends are set to incorporate new and improved levels of convenience to alleviate the pressures of increasingly hectic lifestyles and to fit with the needs of an ageing global population (Walsh and Kerry, 2012). Emerging concepts of active and smart packaging technologies provide all these functionalities and numerous other innovative solutions for prolonging the shelf life and improving the quality and safety of food products (Realini and Marcos, 2014). The most recent packaging technique used for fish and meat storage is skin packaging from traditional vacuum packaging. In this case, the food product is placed on a plastic tray, covered by a plastic film that is thermoformed acquiring exactly the shape of the product. The exclusive shrinking of the upper skin by heating in vacuum skin packaging avoids the formation of air, reducing the eventual visible formation of exudate and prolonging the microbiological shelf life (Stella et al., 2018). It has been reported that skin packaging in combination with superchilling storage could significantly extend the shelf life of sea bream fillets (Duran-Montgé et al., 2015). DuPont Teijin Films (Chester, PA, USA) has combined the high temperature properties of polyester film with the 'skin-like' behavior and recently developed a revolutionary skin film that can be safely oven or microwave cooked directly from the freezer of refrigerator.

Further applications of antimicrobial and antioxidant packaging systems may result in shelf life extension of perishable food products and considerable waste reduction. Continued research into edible films and their applications as edible coatings is also expected. Utilization of materials from renewable resources in active packaging components could be exceptional in overcoming the challenges of predicted climatic changes in the future. Recently, biodegradable polymers obtained from renewable resources, such as agro-industrial and marine wastes and byproducts, have been considered as sustainable alternatives to petroleum-derived polymers. The application of biopolymers and natural additives for food protection and shelf life extension may be advantageous in terms of environmental sustainability and consumer acceptability. Biodegradable and edible materials derived from plants and animals, such as proteins, polysaccharides, and lipids, have shown a potential ability to be used as edible films in contact with food (Etxabide et al., 2017). For example, poly(lactic acid) (PLA) is a relatively new and promising bio-based thermoplastic polyester that can be derived from renewable, bio-derived monomers obtained from a range of plants containing polysaccharides. According to Tawakkal et al. (2018), PLA composites containing kenaf show the potential to be developed as rigid, compostable food packaging items, such as trays, from biodegradable and renewable resources.

Nanotechnology has been introduced as a very promising approach for the development and design of novel food packaging systems, which could involve nano-sized innovative materials (nanocomposites) that may serve as barriers for microbial growth and/or physicochemical reactions (Kour et al., 2015). Nanobiocomposites technology is still in early stages and aims to the

improvement of physical properties of biopolymers (i.e. mechanical strength, thermal stability, antimicrobial activity, and gas barrier properties). In the case of food packaging in general, a major emphasis is on the development of high barrier properties against the migration of water vapor, oxygen, carbon dioxide, and flavor compounds (Ghanbarzadeh et al., 2015).

Further research is required to fully understand the synergistic action of MAP, temperature, and additives to selectively target and influence beneficial product microbiota, such as lactobacilli, at the expense of more noxious spoilage bacteria such as *Pseudomonas* with the aim not only to ensure product quality but also to more effectively control dangerous pathogens. Another important and currently unexploited area that deserves further attention is the optimization of MAP parameters for bulk packaging and transportation of fish and seafood products to distant markets (DeWitt and Oliveira, 2016). The patented SAF-D® system for shipping ocean freight by BluWrap (San Francisco, CA, USA) (https://www.bluwrap.me) uses fuel technology to create and maintain a high CO_2 and minimal O_2 atmosphere that extends the shelf life of fish products, resulting in lower carbon emissions, replacing polystyrene with recyclable materials, and eliminating the need for ice in the seafood supply chain. On the other hand, the FDA Seafood HACCP guidelines (Chapter 13) suggest a minimum oxygen transmission rate in the final package of fish of at least 10,000 cc/m^2/24 h at 24°C to provide sufficient oxygen that allows growth of aerobic spoilage organisms before *B. botulinum* toxin formation under moderate abuse temperatures, thus limiting innovation and application of new packaging methods in the fish industry sector (FDA, 2011). Under this context, particular care should be taken in determining the safety of packed fish products, when processing extends significantly the shelf life of fish products, as for example high pressure (Tsironi et al., 2015). Future research should be focused on initiating hurdle technologies for optimum active and smart packaging systems by incorporating multiple active components or active and smart functionalities in one system (Ahmed et al., 2017).

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