Essential oils for antimicrobial and antioxidant applications in fish and other seafood products

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Abstract

Background: Fish and other seafoods are highly perishable food products due basically to microbiological growth and lipid oxidation, which are known to be the principal causes of quality deterioration of such products. Therefore, offering safe and high quality seafoods combined with consumers' desire for natural products free from chemical preservatives creates real challenging problems. In the recent past, there has been extensive focus on antioxidant and antimicrobial effects of natural preservatives such as essential oils (EOs), as effective alternative to synthetic additives, in order to enhance oxidative and microbial stability of foods and extend their shelf life.

Scope and approach: In this review, the main spoilage mechanisms of fish and seafood products and the most common techniques used to preserve quality and extend shelf life of such products are first discussed. The chemistry and modes of action of some selected EOs are then briefly presented. The antioxidative and antimicrobial activities of some common EOs, either alone or in combination with other preservative systems, in fish and other seafoods are reviewed. Finally the limitations and the future trends are shown.

Key findings and conclusions: Several EOs have shown i) great antimicrobial activities versus many spoilage and pathogenic microorganisms, and ii) remarkable antioxidant powers against lipid oxidation in fish and other seafoods during processing or storage. However, much more works are still required in order to better understand the exact mechanism of action of EOs or their main components, the effective dose, and the best combination strategy.

***Keywords**:* Fish, Preservation, Oxidation, Quality, Shelf life, Microbial spoilage, Natural additives

1. Introduction

In recent years, food quality and safety have become a major concern to consumers, producers, food industries, and regulatory agencies worldwide. Such recent trends may be due to the globalization of the food trade and changes in eating habits and consumer behavior, such as increasing demand for natural, fresh, minimally processed, easily prepared, and ready-to-eat products (Jayasena & Jo, 2013; Lucera, Costa, Conte, & Del Nobile, 2012). Therefore, production of safe and high quality food products in general and fish and other seafoods in particular has gained more and more attention around the world in the recent past. Due to their high nutritional value, fish and other seafoods are considered among the most important commodity for human diet, and hence their consumption has risen substantially over the past few decades (Ghanbari, Jami, Domig, & Kneifel, 2013; Sampels, 2015a). Indeed, according to the Food and Agriculture Organization of the United Nations, fish consumption increased from an average of 9.9 kg in the 1960s to around 20 kg in 2015 (FAO, 2016).

Fish and other seafoods are extremely perishable food products and are especially susceptible to both chemical and microbiological spoilage during processing or storage. For this reason, one or more adequate preservation methods are required in order to maintain the safety and quality and extend the shelf life of such products (Ghanbari et al., 2013; Hassoun & Karoui, 2017; Noseda, Vermeulen, Ragaert, & Devlieghere, 2014). Various traditional processing methods including drying, salting, smoking, marinating, fermentation and so on, have been widely used since ancient times to preserve fish quality or add more value to the product (Sampels, 2015a). Moreover, low temperature storage and chemical preservatives used for controlling water activity, enzymatic, oxidative, and microbial spoilage are extensively used in food industry (Ghaly, Dave, Budge, & Brooks, 2010). However, due to the growing concerns regarding the safety of chemical and synthetic preservatives, alternative mechanisms based on the use of natural compounds have been increasingly tested over the last years (Amorati, Foti, & Valgimigli, 2013; Calo, Crandall, O'Bryan, & Ricke, 2015; Hyldgaard, Mygind, & Meyer, 2012; Lucera et al., 2012). In this context, essential oils (EOs) could represent a promising option since numerous reports have confirmed their antioxidant (Amorati et al., 2013; Jayasena & Jo, 2014) and antimicrobial (Burt, 2004; Jayasena & Jo, 2013; Swamy, Akhtar, & Sinniah, 2016) effects. Thus, these natural preservatives could meet perfectly the increasing consumer demands for clean-label products that are fresh and free of chemical additives.

Although there have been several prior reviews on the use of EOs in food applications (Calo et al., 2015; De Souza, da Cruz Almeida, & de Sousa Guedes, 2016; Jayasena & Jo, 2013, 2014), the antimicrobial and antioxidant properties of EOs for application in fish and other seafoods have not yet been reviewed. Therefore, this review provides up-to-date information about the most recent published data regarding antimicrobial and antioxidant mechanisms of common EOs or their main components as well as their potential applications in fish and other seafood products.

2. Fish spoilage mechanisms

Although fish flesh is generally regarded as sterile when fish is alive, fish spoilage can occur very rapidly after catch or harvest and during the different stages of the production chain, processing, and subsequent storage conditions. Although the importance of the enzymatic autolysis, occurring mainly after capture or harvest, the following section will focus only on microbial and chemical (oxidation) spoilage occurring during processing and storage of fish.

2.1. Microbial spoilage

Fish and other seafoods have high contents of free amino acids, a high *post mortem* pH, high water contents, and many fish species contain trimethylamine oxide (TMAO) (Chaillou et al., 2015; Gram & Dalgaard, 2002). Such characteristics promote growth of bacteria, including both the Gram-positive and Gram-negative types which survive well in a wide range of temperatures. That is why the microbial growth is considered to be the major cause of quality deterioration of fish and other seafood products, causing up to 25-30% loss of such products (Ghaly et al., 2010; Gram & Dalgaard, 2002). There is a general agreement that each food product has its own unique flora, which is determined by the raw materials, the processing parameters and subsequent storage conditions, and the abilities of microorganisms to tolerate the preservation conditions. For example, it was reported that psychrotolerant Gram-negative bacteria such as species within the genera *Pseudomonas* and *Shewanella* are the most commonly spoilage bacteria of aerobically stored chilled fish, while CO_2-tolerant microorganisms, including *Photobacterium phosphoreum* and lactic acid bacteria, may dominate the microflora and become responsible for spoilage of packed fish products (Chaillou et al., 2015; Giuffrida, Valenti, Giarratana, Ziino, & Panebianco, 2013; Gram & Dalgaard, 2002; Gram & Huss, 2000).

Although freshly caught fish is contaminated naturally with various microbiota, only a small fraction of these microorganisms, called specific spoilage organisms (SSOs), are responsible for seafood spoilage (Gram & Dalgaard, 2002). In particular, the seafood SSOs have the ability to convert TMAO to TMA-N, produce ammonia, biogenic amines, organic acids and sulphur compounds from amino acids, hypoxanthine from ATP degradation products, and acetate from lactate. Microorganisms capable of converting TMAO to TMA include *Aeromonas spp., Enterobacteriaceae, Photo-bacterium phosphoreum, Shewanella putrefaciens, and Vibrio spp.* (Gram & Dalgaard, 2002). Research studies demonstrated that *Pseudomonas* was the dominant bacteria for Atlantic salmon (*Salmo salar*) packed in a modified atmosphere (Milne & Powell, 2014) and for bighead carp (*Aristichthys nobilis*) fillets sprinkled with 2% salt, whereas *Aeromonas* was the SSOs of unsalted fillets during storage at 4 °C (Liu, Zhang, Li, & Luo, 2017).

Several microbial growth parameters such as total viable counts (TVC), mesophilic aerobic counts (MAC), and aerobic plate count (APC) have been used to gives a quantitative idea about the presence of microorganisms in the investigated sample (Cheng & Sun, 2015; Rodrigues et al., 2016). For example, when the TVC of bacteria exceeds a microbial load of 10^7 colony-forming units (CFU) per gram or cm^2, it means that the fish muscle becomes dangerous for consumption and can cause very severe health problems due to the possibility of toxic substances produced (Ellis, 2002). Additionally, counts of SSOs obtained on Lyngby Iron Agar plates (Oxoid LTD., Basingstoke, Hampshire, England) after 3 days incubation at 20 °C, have been used as microbial growth parameters for number of Gram-negative and non-fermentative bacteria (Gram., Trolle, & Huss, 1987). Moreover, various other parameters have been widely measured to reveal microbiological quality of fish, such as the nucleotide degradation, the formation of biogenic amines, the production of total volatile basic nitrogen (TVB-N), trimethylamine nitrogen (TMA-N), among others (Rodrigues et al., 2016; Zhu, Ma, Yang, Xiao, & Xiong, 2016).

2.2. Oxidative spoilage

Spoilage caused by oxidation is another prevalent problem, especially for fish species containing high amounts of polyunsaturated fatty acids, resulting in several problems such as off-flavor formation, changes in colour and texture, and altered nutrient value (Maqsood, Benjakul, Abushelaibi, & Alam, 2014; Secci & Parisi, 2016). Although lipid oxidation could undergo several types of oxidation, such as photo-oxidation, thermal oxidation, enzymatic oxidation, and auto-oxidation; this latter, defined as the spontaneous reaction of atmospheric oxygen with lipids, is the most common process causing oxidative deterioration (Shahidi &

Zhong, 2005). This process occurs via a free radical chain reaction, and proceeds through three phases: initiation, propagation, and termination. Initiation phase starts with the abstraction of a hydrogen atom adjacent to a double bond in a fatty acid, and this may be catalyzed by light, heat, or metal ions to form a free radical. The resultant free radicals react with oxygen to form peroxyl radicals, which in turn react with other lipid molecules to form hydroperoxides and a new free radical during the propagation phase. Termination phase occurs when a build up of these free radicals interact to form non-radical products. Lipid hydroperoxides have been identified as primary products of autoxidation; being unstable, decomposition of hydroperoxides results in a complex mixture of products including aldehydes, ketones, alcohols, hydrocarbons, volatile organic acids, and epoxy compounds, which are known as secondary oxidation products (Ghaly et al., 2010; Shahidi & Wanasundara, 2002; Xu, Riccioli, & Sun, 2015).

3. Fish preservation methods

Several traditional preservation techniques can be applied in order to retard deterioration of seafood products and extend their shelf life as much as possible. Preservation techniques are usually based on the control of temperature, available oxygen, water activity, microbial loads, or several of these parameters at the same time.

3.1. Temperature-based techniques

It is well-known that temperature has a marked effect on the microbial growth and oxidation process occurring during *post mortem* storage or processing and handling of fish and other seafood products. Indeed, on one hand, temperatures have a direct physical impact on microbial growth and may lead to retardation of the growth and spoilage activity of microorganisms. On the other hand, according to the Arrhenius relation, the rates of undesirable biochemical and chemical reactions decrease as temperature is lowered (Hall, 2010; Jessen, Nielsen, & Larsen, 2014).

The cooling (or chilling) of fish with normal ice flakes, chilled seawater, or ice slurries has been considered as simple and efficient preservation method, keeping the fish in a cool condition with a temperature ranging between 0 and 4 °C. However, it is important to ice the fish as quickly as possible after catch or harvest in order to minimize biochemical and microbiological reactions (Ghaly et al., 2010; Sampels, 2015b). Although the importance of the chilling in keeping fish freshness, it must be emphasized that this technique cannot prevent enzyme activities or microbial spoilage (Sampels, 2015b). So, chilling process should be completed with other preservation method. Another low temperature-based technique is superchilling. This term has been used to describe the decrease in temperature of a food product to 1–2 °C below the freezing point, so that only a minor part of the product's water content is frozen (Kaale, Eikevik, Rustad, & Kolsaker, 2011; Stonehouse & Evans, 2015). In fish sector, the superchilling has been applied successfully and shown to extend shelf life of many seafood products as a result of inhibition of most autolytic and microbial reactions in fish compared with normal cooling (Duun & Rustad, 2008; Kaale et al., 2011; Sampels, 2015b).

Freezing has been considered the most popular method of conservation and successfully employed to retain the quality of food products, especially fish and other seafoods, over long storage periods (Hall, 2010; Jessen et al., 2014). Although freezing (-18 to -30 °C) inhibits the rate of chemical reactions and microbial growth, enzymatic and non enzymatic reactions persist but at lower rate. An important consideration to be in mind when using freezing technique is the formation of ice crystals during the process, being a critical point, since the formation of large ice crystals may increase the risk of texture damage, loss of water holding capacity, and oxidation (Alizadeh, Chapleau, de Lamballerie, & Le-Bail, 2007; Ghaly et al., 2010; Karoui, Hassoun, & Ethuin, 2017). That is why a fast freezing should be conducted in order to provide small and regular ice crystal formation.

3.2. Modified atmosphere packaging

Modified atmosphere packaging (MAP) has received increasing attention, becoming a popular preservation technique in a wide range of application in food products to meet consumer demands for fresh and natural foods with an extended shelf life (Mastromatteo, Conte, & Del Nobile, 2010a; Santos et al., 2013). This technique is based on the modification of percentage of the three principal gases (i.e., % CO_2, %O_2, and %N_2) inside the package containing food product to provide an optimal condition for effective retardation of microbiological and chemical processes. Generally speaking, the modification of the atmosphere within the package can be achieved by reducing the oxygen content while increasing the levels of carbon dioxide and/or nitrogen (Mastromatteo et al., 2010a; Noseda et al., 2014). The effect of MAP on the shelf life of foods in general and fish in particular has been reviewed by several authors (Bouletis, Arvanitoyannis, & Hadjichristodoulou, 2017; Sivertsvik, Jeksrud, & Rosnes, 2002). By using different CO_2 and N_2 levels, Provincial and co-workers obtained the best results in term of shelf life of sea bass (*Dicentrarchus labrax*) for MAP samples stored with high CO_2 levels (Provincial et al., 2010). These results were then confirmed by other research study which was conducted on turbot (*Psetta maxima*) fillets, indicating the protective effect of the different MAP studied, especially those with a higher percentage of CO_2 (Santos et al., 2013). Recently, our result obtained on whiting (*Merlangius merlangus*) fillets allowed recommending the use of MAP with 50% CO_2 and 50% N_2 to maintain quality and extend the shelf life of fish samples (Hassoun & Karoui, 2016).

3.3. High pressure processing

High pressure processing (HPP) has attracted widespread attention in recent years due to its potential of inactivating microorganisms and autolytic enzymes at low temperature, thus extending the shelf life of fish products (Rastogi, Raghavarao, Balasubramaniam, Niranjan, & Knorr, 2007; Truong, Buckow, Stathopoulos, & Nguyen, 2014). As it is performed at room temperature, this technique holds the characteristics of low energy consumption, making it an environmentally friendly processing technology compared with traditional thermal processing methods (Huang, Wu, Lu, Shyu, & Wang, 2017; Rastogi et al., 2007; Truong et al., 2014).

The HPP has shown to be effective in inhibiting microbial growth and maintaining the quality in raw octopus (*Octopus vulgaris*) (Hsu, Huang, & Wang, 2014), reducing microbial loads in shrimp (*Penaeus monodon*) (Kaur, Srinivasa Rao, & Nema, 2016), and extending the shelf life of fresh salmon (*Salmo salar*), cod (*Gadus morhua*), and mackerel (*Scomber scombrus*) fillets (Rode & Hovda, 2016). However, this technique may cause some undesirable effects on flesh color and texture, on lipid and protein oxidation, as well as on protein denaturation in the fish (Guyon, Meynier, & de Lamballerie, 2016; Truong et al., 2014)

3.4. Chemical preservatives and natural alternative solutions

Several chemical preservatives have been used to control microbial, oxidative, and autolytic enzymatic spoilage of fish and fish products (Ghaly et al., 2010). For example, the effects of salts of organic acids, such as sodium acetate, sodium lactate, and sodium citrate, on the quality and shelf life of sliced salmon (*Onchorhynchus nerka*) were investigated during refrigerated storage (Sallam, 2007). The author reported that the use of these preservatives extended the shelf life of the fish by 5 - 8 days compared with control samples. Additionally, synthetic phenolic compounds such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and dodecyl gallate (DG) have been widely used as antioxidants and antimicrobial agents for fish and other seafoods (Brewer, 2011).

However, the increasing consumers' concern regarding the safety of such compounds has encouraged food industry to develop new natural alternative food preservation strategies (Amorati et al., 2013; Brewer, 2011; Lucera et al., 2012). Among alternative preservation methods, the use of lactic acid bacteria and their metabolites as biopreservation techniques to extend the shelf life and enhance the hygienic quality of fish and other seafood, has received much attention by the scientific community in the last two decades (Ghanbari et al., 2013). Moreover, the use of natural compounds, such as tea polyphenols, rosemary, and sage extracts has become very popular for food preservation (Emir Çoban & Özpolat, 2013; Kenar, Özogul, & Kuley, 2010; Li et al., 2012; Pezeshk, Ojagh, & Alishahi, 2015). Additionally, application of chitosan has widespread in the last years in several applications in the seafood industry, due to its useful biological activities, including among other the antibacterial and antioxidant characteristics (Alishahi & Aïder, 2012; Yuan, Chen, & Li, 2016).

3.5. Hurdle technology

The combination of two or more preservation methods, referred as "hurdle technology" may lead to synergistic or additive interactions, offering a greater inhibitory effect against the targeted microorganisms than any single treatment (De Souza et al., 2016; Khan, Tango, Miskeen, Lee, & Oh, 2017). Examples for the application of combined preservation methods are given by Duun and Rustad (2008) for Atlantic salmon (*Salmo salar*) and Fernández et al. (2009) for the same fish species, as well as Zhu et al. (2016) for catfish (*Clarias gariepinus*). In details, the use of vacuum packaging combined with superchilling storage at two temperature levels (−1.4 or -3.6 °C) was evaluated in salmon fillets by using several quality parameters (Duun & Rustad, 2008). The findings revealed that the storage time of vacuum packed samples can be doubled by superchilled storage, maintaining good quality of fish up to 17–21 days compared to ice chilled storage. In another study, superchilling storage (−1.5 °C) was combined with MAP at different gas concentrations, and the combined effects of these technologies on salmon fillets were monitored by sensory, chemical, and microbiological analysis (Fernández, Aspe, & Roeckel, 2009). The authors noticed an important increase of shelf life from 11 days for control sample to 22 days in superchilled fish stored in the presence of MAP at high CO_2 (90% CO_2: 10% N_2). These findings were confirmed in a recent study (Zhu et al., 2016) conducted on catfish fillets stored at superchilling temperature (−0.7 °C) combined with MAP at high levels of CO_2 (60% CO_2: 40% N_2). Compared to the other storage conditions, the authors reported that this combination maintained effectively the quality of fish fillets and prolonged significantly their shelf life. Other combination method was proposed by Rodrigues and others using MAP (80% CO_2: 20% N_2) and short-wave ultraviolet radiation in order to extend shelf life of rainbow trout (*Oncorhynchus mykiss*) fillets. The findings demonstrated that this combination was effective in reducing the total microbial count and delaying the chemical changes and, consequently, enhancing the shelf life of the fish fillets at least twice (Rodrigues et al., 2016). Recently, a research study was conducted to determine the impact of combination of two treatments using chitosan and pomegranate peel extract on the quality of Pacific white shrimp (*Litopenaeus vannamei*) during 10 days of iced storage (Yuan, Lv, Tang, Zhang, & Sun, 2016). The authors observed a synergistic effect between these treatments since the efficacy of chitosan coating to inhibit the microbial growth, melanosis, changes in color and texture, and other sensory parameters was increased when it was applied in combination with pomegranate peel extract.

4. Essential oils

Essential oils (EOs) are produced by different part of plants as defence mechanisms against microorganisms. These naturally occurring antimicrobial and antioxidant agents are highly complex mixtures of often hundreds of individual aromatic volatile oily compounds, which are extracted from different plant materials, such as leaves, barks, stems, roots, flowers, and fruits (Calo et al., 2015; Jayasena & Jo, 2013). In total, more than 3000 types of EOs are known, of which only 300 are of commercial interest for applications in the food or other industries (Bakkali, Averbeck, Averbeck, & Idaomar, 2008; Burt, 2004)

4.1. Main chemical components and principal sources

It has been well documented that the biological properties of EOs are primarily due to the presence of major compounds, accounting up to 85% of the oil, while minor compounds, present only in trace quantities, may have synergistic impact with other compounds (Bakkali et al., 2008; Burt, 2004). Chemically, the EOs consist of a diverse family of organic compounds with low molecular weight, which could be divided into several groups according to their chemical structure: terpenes, terpenoids, aromatic (phenylpropanoids) and other compounds (Bakkali et al., 2008; Hyldgaard et al., 2012). Terpenes are hydrocarbons consisting of several isoprene units, which could be classified by the number of isoprene units in the molecule (mono-, sesqui- and diterpenes). Terpenoids are terpenes containing oxygen, and could be classified into alcohols, esters, aldehydes, ketones, ethers, and phenols. Examples of well-known terpenoids found in EOs are thymol, carvacrol, linalool, linalyl acetate, citronellal, piperitone, menthol, and geraniol, while eugenol and cinnamaldehyde are the best known phenylpropanoids (Hyldgaard et al., 2012; Jayasena & Jo, 2013). It should be stressed that phenolic compounds such as thymol, carvacrol, and eugenol are the main group responsible for the preservative effects of EOs (Burt, 2004; Jayasena & Jo, 2014).

According to our literature review, EOs from oregano, rosemary, thyme, laurel, sage, cinnamon, clove, and basil have been the most used antimicrobial and antioxidant agents in fish and seafood products.

Oregano (*Origanum vulgare*) leaves are a characteristic spice of the Mediterranean cuisine and have been widely used in raw or cooked food due to their distinct pleasant aroma and taste. Besides, the oregano EO has been studied for its antimicrobial and antioxidant activity in various commercial or model foods (Goulas & Kontominas, 2007; Vatavali, Karakosta, Nathanailides, Georgantelis, & Kontominas, 2013). The carvacrol and thymol are reported to be the main compounds responsible for the antimicrobial and antioxidant activity of oregano EO (Rodriguez-Garcia et al., 2016). EO extracted from thyme (*Thymus vulgaris*) has received much attention from researchers and food processors as a potential natural antimicrobial and antioxidant agent as a result of its high content of phenolic compounds (Hyldgaard et al., 2012; Kostaki, Giatrakou, Savvaidis, & Kontominas, 2009).

Due to its antimicrobial activity against a wide range of microorganisms, basil (*Ocimum basilicum*) EO has been used extensively for many years in flavouring food (Suppakul, Miltz, Sonneveld, Bigger, & Qd, 2003). This activity has been attributed to the major active volatile components, including linalool, methylchavicol, eugenol, methyl eugenol, methyl cinnamate, 1,8-cineole, and caryophyllene (Kuorwel, Cran, Sonneveld, Miltz, & Bigger, 2011; Perricone, Arace, Corbo, Sinigaglia, & Bevilacqua, 2015). Rosemary (*Rosmarinus officinalis*) EO has been reported to exhibit an effective antioxidant and antimicrobial activity, which is mainly related to phenolic diterpenes compounds such as carnosol and carnosic acid (Bozin, Mimica-Dukic, Samojlik, & Jovin, 2007; Kenar et al., 2010; Makri, 2013).

Many recent studies have investigated the preservative effects of EOs obtained from other sources such as clove (*Eugenia caryophyllata*) (Emir Çoban & Patir, 2013), sage (*Salvia officinalis L.*) (Emir Çoban, Patir, Özpolat, & Kuzgun, 2016), *Zataria multiflora* Boiss (Emir Çoban & Kelestemur, 2016), turmeric and lemongrass (Masniyom, Benjama, & Maneesri, 2012), and lemon (Alfonzo et al., 2017). The results of these studies demonstrated that the use of these EOs applied to the fish or other seafoods alone or in combination with other preservation methods, was effective in improving the quality and extending the shelf life of the treated products.

4.2. Methods of application

EOs can be applied using various methods in the fish industry: the direct treatment of fish and seafood products with EOs during manufacturing and processing is the most commonly employed approach, followed by the use of EOs as edible films and coatings and the addition of EOs to animal feed.

Although the direct addition of EOs (Emir Çoban & Patir, 2013; Karoui & Hassoun, 2017) or their compounds (Giarratana et al., 2016; Mahmoud et al., 2004) to fish and other seafoods has been the most common method of application, this technique has some disadvantages and criticisms that limit its application to such products. Indeed, it has been generally observed that a greater concentration of EOs is needed to achieve the same effect in food compared to *in vitro* assays. Moreover, even at low doses some EOs could have a negative impact on the sensory attributes (Lv, Liang, Yuan, & Li, 2011; Sánchez-González, Vargas, González-Martínez, Chiralt, & Cháfer, 2011). Thus, some authors suggested the use of edible coating films enriched with EOs as alternative and interesting option in order to reduce the required doses (Doğan & İzci, 2017; Ojagh, Rezaei, Razavi, & Hosseini, 2010; Sánchez-González et al., 2011; Yuan, Chen, et al., 2016). Additionally, some authors reported that fish sedated with EOs during transport before slaughter could delay the loss of fish freshness and increase the shelf life. In this regard, Daniel and co-workers demonstrated that silver catfish (*Rhamdia quelen*) exposed to 40 µL/L of *Aloysia triphylla* (L'Her.) Britton EO during *in vivo* transport delayed the nucleotide degradation and loss of quality compared to the control (Daniel et al., 2014).

Recently, another technique has been presented in the literature to minimize the organoleptic effects of EOs using the preparation of micro- and nanoemulsions, which improves not only the antimicrobial and antioxidant stability, but also the functional properties and organoleptic quality of the product (Acevedo-Fani, Soliva-Fortuny, & Martín-Belloso, 2016; Alfonzo et al., 2017; Calo et al., 2015; Ozogul et al., 2017; Perricone et al., 2015). Indeed, the encapsulation of EOs into such emulsions may increase the stability of volatile components, protecting them from interacting with the food matrix, thereby increasing the antimicrobial activity due to increased passive cellular uptake (Sugumar, Ghosh, Mukherjee, & Chandrasekaran, 2016). More recently, numerous reviews have just been published reporting an emerging application of EOs in yet more sophisticated approach as active food packaging, which could extend food shelf life and maintain nutritional and sensory quality (Atarés & Chiralt, 2016; Kapetanakou & Skandamis, 2016; Maisanaba et al., 2017; Ribeiro-Santos, Andrade, Melo, & Sanches- Silva, 2017). Active food packaging includes the incorporation of EOs, among other natural compounds, into the food package in such a way that allows these compounds to be released in a controlled way to maintain or enhance the organoleptic properties and microbiological integrity of food (Atarés & Chiralt, 2016; Ribeiro-Santos et al., 2017).

The use of EOs as fish dietary additives is considered to be an effective method to incorporate natural antioxidant and antioxidant agents into flesh of fish products. For example, one study examined the capacity of rosemary, thymol, carvacrol, and BHT incorporated in the diet of gilthead seabream (*Sparus aurata*) in order to delay lipid oxidation and microbial growth (Alvarez, Garcia Garcia, Jordan, Martinez-Conesa, & Hernandez, 2012). Compared to the control group, the results revealed that fillets from fish fed diet with carvacrol (500 mg/kg) during 18 weeks had the lowest thiobarbituric acid (TBA) content (0.2 mg MDA/kg fillet), while BHT and thymol groups achieved the lowest bacteria counts. These results were confirmed later in another study, where the addition of thyme EO as a feed supplement at different concentrations (500, 1000, 1500 and 2000 mg kg^{-1}) revealed inhibitory effects on microbial growth and lipid oxidation in gilthead seabream fillets during storage at 4 °C for 21 days. Interestingly, the authors reported that high doses of thyme EO resulted in both lower microbiological counts of *Enterobacteriaceae* and coliforms, and higher oxidative stabilities measures as TBA (Hernández, García García, Jordán, & Hernández, 2015).

4.3. Mechanisms of action

4.3.1. Antimicrobial activities

The antimicrobial properties of EOs have been known since antiquity. Most studies investigating the use of EOs as an antimicrobial agent have been performed on bacteria, while less is known about their action on yeast and molds (Hyldgaard et al., 2012). EOs can be applied either to inhibit the bacterial growth (bacteriostatic), which means that the microbial cells will recover their reproductive capacity after neutralization of the agent, or to kill bacterial cells (bactericide), if EOs are used at high concentrations (Swamy et al., 2016). It was reported that lipoteichoic acids in cell membrane of gram positive bacteria may facilitate the penetration of hydrophobic compounds of EOs, while the presence of an extrinsic membrane, surrounding the cell wall of gram negative bacteria limits the diffusion rate of hydrophobic compounds through the lipopolysaccharide layer. That is why gram positive bacteria are slightly more susceptible to EOs than gram negative ones (Rodriguez-Garcia et al., 2016; Tongnuanchan & Benjakul, 2014).

Even though that the possible modes of action for EOs as antimicrobial agents have been widely reviewed, their exact mechanism of action is not yet clear (Calo et al., 2015; Maqsood, Benjakul, & Shahidi, 2013; Tajkarimi, Ibrahim, & Cliver, 2010). Several studies have reported that the antimicrobial activity of EOs can be attributed to their major constituents mainly the phenolic constituents, as well as their interaction with minor constituents present in oils (Burt, 2004; Hyldgaard et al., 2012; Jayasena & Jo, 2013; Perricone et al., 2015). Due to the complexity of the chemical composition of EOs, it was reported that the antimicrobial activity of EOs may not be attributable to a unique mechanism (Burt, 2004). Nonetheless, there is almost a universal agreement on the fact that the hydrophobicity of compounds present in EOs enables them to pass through the cell wall and cytoplasmic membrane, disrupt the structure of their different layers of polysaccharides, fatty acids and phospholipids and permeabilize them. Additionally, EOs can inhibit several enzyme systems including the enzymes responsible for regulation of energy and synthesis of structural components (Bakkali et al., 2008; Burt, 2004; Jayasena & Jo, 2013).

4.3.2. Antioxidant activities

Recently, synthetic antioxidants, such as BHA and BHT have been suspected of causing potentially harmful consequences on human health. On the other side, the use of EOs has been considered as a good alternative since the majority of EOs are classified as generally recognized as safe (GRAS) (Kapetanakou & Skandamis, 2016; Maqsood et al., 2013; Ribeiro-Santos et al., 2017). The application of EOs as natural antioxidants is a field of growing interest due to the inherent ability of some of their components to stop or delay the oxidation of lipids and extend the shelf life of the food products (Amorati et al., 2013; Patel, 2015). Numerous studies reported that the EOs, as antioxidants, have several modes of direct or indirect actions including, among other mechanisms, prevention of chain initiation and free-radical scavenging activity (Maqsood et al., 2013; Rodriguez-Garcia et al., 2016). Again, it has been reported that phenolic compounds such as carvacrol, eugenol, and thymol are the main group responsible for the antioxidant activity of EOs (Amorati et al., 2013; Jayasena & Jo, 2014). The role of phenolic compounds in the retardation of lipid oxidation in fish muscle is mainly due to their redox properties, allowing them to act as hydrogen donors, reducing agents, singlet oxygen quenchers as well as metal chelators (Maqsood et al., 2014; Tongnuanchan & Benjakul, 2014).

Several methods have been used to assess the antioxidant performance of EOs. Although the peroxide value (PV) and TBA are the most commonly used methods for measuring respectively the primary and secondary products of oxidation, other methods, such as the DPPH (2,2-diphenyl-1-picrylhidrazil) radical scavenging method, the absorption capacity of oxygen radicals, and the total phenolic compounds could be used (Amorati et al., 2013; Bozin et al., 2007; Maqsood et al., 2013).

5. Application of EOs to fish preservation

In recent years, the effectiveness of a wide range of EOs against lipid oxidation and microbial growth has been extensively demonstrated by many authors. It has been reported that oregano EO is the most frequently used for applications as fish preservatives, followed by rosemary and thyme EOs (Patel, 2015). Different effects have been observed depending on the EO used, its concentration, as well as the characteristics of the raw material. An overview of the literature reporting studies on the antioxidant and antimicrobial activity of some EOs in fish and fish products are presented in **Table 1**.

A typical example of lipid oxidation inhibition induced by addition of EOs is presented in **Figure 1**, where the effect of *Zataria multiflora* Boiss EO on quality of catfish (*Silurus glanis* Linnaeus, 1758) burgers stored at 4 °C was studied (Emir Çoban & Kelestemur 2016). Among other results, the authors showed that, at both the concentrations tested (0.2% and 0.4%), the PV (**Figure 1A)** and the TBA (**Figure 1B)** were significantly ($P < 0.05$) reduced by the addition of this EO compared with untreated samples, which was attributed to the presence of phenolic compounds such as carnosol, carnosic acid, and rosmarinic acid. However, treatment of the catfish burgers at the concentration of 0.4% *Zataria multiflora* Boiss EO exhibited a greater inhibitory impact on lipid oxidation and microbial growth compared with that obtained for the samples treated with 0.2%. This dose-dependent inhibitory activities of EOs confirmed our previous results, where the higher concentration of clove EO was found to be more effective to inhibit microbial growth and lipid oxidation occurring in sliced smoked *Oncorhynchus mykiss* (Emir Çoban & Patir, 2013).

However, it should be considered that EOs used as natural food additive at high concentrations may lead to undesirable sensory properties on treated fish and may even cause allergic reactions. Indeed, some EOs are characterized by a strong odor and flavor which could leave a bad aftertaste, thus minimizing the acceptance or liking degree for fish and seafood product (Atarés & Chiralt, 2016; Ribeiro-Santos et al., 2017). That is why the antimicrobial effectiveness of EOs is often described using the concept of "minimum inhibitory concentration" which is the lowest concentration capable of inhibiting the growth of challenging organisms (Burt, 2004; Hyldgaard et al., 2012; Mann & Markham, 1998).

One method that has been proposed in the literature in order to reduce organoleptic effects of EOs added to fish and other seafoods is to use coatings enriched with EOs (Lucera et al., 2012; Sánchez-González et al., 2011). For instance, a gelatin coating enriched with cinnamon (*Cinnamomum zeylanicum*) EO at different concentrations (1%, 1.5%, and 2%) was tested as antioxidant and antimicrobial agent on refrigerated rainbow trout (Andevari & Rezaei, 2011). The findings showed that this treatment decreased the lipid oxidation rate, measured by means of TBA and free fatty acids (FFA), and the microbial growth, determined by TVC, APC, and psychrotrophic count. From the obtained results the authors concluded that the gelatin coating enriched with cinnamon EO was suitable for the preservation of quality attributes of rainbow trout fillets to an acceptable level during storage.

In more recent years, micro- and nanoemulsions have been suggested, instead of direct addition of EOs to fish products, as interesting area of research in order to transport active compounds of EOs to food and even enhance functional properties of treated products

(Acevedo-Fani et al., 2016). For instance, one recent study has investigated the effects of a microemulsion containing 0.3% or 1% lemon EO on the quality of salted sardines during 150 days of ripening. The finding revealed a reduction in the concentrations of all examined microbial groups, including *Enterobacteriaceae*, *Staphylococci* and rod *Lactic acid bacteria*. Besides, the addition of this EO, in particular at concentration of 1%, showed a lower accumulation of histamine in the treated sardines compared to those of the control. The authors ascribed the preservative effect of lemon EO to several volatile organic compounds belonging to monoterpene hydrocarbons, oxygenated monoterpenes, and sesquiterpene hydrocarbons (Alfonzo et al., 2017).

The scientific literature seems to indicate that the impact of EOs or their compounds as antimicrobial and antioxidant agents depend on the source of these natural food additives. In more details, Karoui and Hassoun reported that basil and rosemary EOs used at the same concentration (1%) resulted in different preservative activities since the former was found to be more effective at retarding fish spoilage than the latter (Karoui & Hassoun, 2017), while in another study, the rosemary EO was found to be more efficient in preventing lipid oxidation than oregano EO (Makri, 2013). In another investigation, three EOs, including clove, cumin, and spearmint, have been evaluated in vapour phase for their efficacy in preventing quality degradation and prolonging shelf life of red drum (*Sciaenops ocellatus*) fillets during 20 days of refrigerated storage at 4 °C (Cai et al., 2015). Among other results, the authors demonstrated that the addition of these EOs at 4 µl/L reduced biogenic amine contents and microflora counts of various microorganisms, thereby prolonging the shelf life of the fish by 10 days as compared to the control sample; however, more effective activity was obtained for spearmint EO compared to the two other ones. The difference effectiveness of the various EOs could be attributed to the difference in their chemical composition, especially with regard to the major components, which in turn are related to different conditions such as climatic, genetic, etc.

6. Synergy between EOs and other preservation methods

Due to synergistic effects, some authors demonstrated that combined treatments of EOs and other preservative method could have better antimicrobial and/or antioxidant activities than either treatment alone (**Table 2**). According to the literature, it appears that EOs could be applied in combination with various preservation methods, such as vacuum packaging, modified atmosphere packaging, chitosan, nisin, and other factors.

EOs have been demonstrated to be synergistic with vacuum packaging and modified atmosphere packaging, as verified by the following findings. The combined effect of oregano EO at two concentrations; 0.2%, 0.4% and vacuum packaging was evaluated on Mediterranean octopus (*Octopus vulgaris*) stored under refrigeration for a period of 23 days. The results revealed significant antimicrobial and antioxidant stabilities of the vacuum packed samples treated with 0.4% oregano EO as compared to the control. From the obtained results, the authors concluded that the use of this EO in combination with vacuum packaging achieved a shelf life extension of Mediterranean octopus of approximately 17 days compared to untreated samples (Atrea, Papavergou, Amvrosiadis, & Savvaidis, 2009). These results were in agreement with other studies conducted on refrigerated trout (*Oncorhynchus mykiss*) fillets using the same EO at the similar concentration (Frangos, Pyrgotou, Giatrakou, Ntzimani, & Savvaidis, 2010) as well as on common carp (*Cyprinus carpio*) fillets using 0.1% cinnamon EO (Zhang et al., 2016).

In another investigation, the research group of one of us obtained similar results by combining sage EO (2%, 4%) and vacuum packaging during refrigerated storage of rainbow trout (*Oncorhynchus mykiss*) fillets stored at 4 °C (Emir Çoban et al. 2016). Based on some microbiological (total aerobic mesophilic and psychrophilic bacteria) analyses, this combined treatment showed a significant microbiological shelf life extension as shown in **Figure 2**. For example, the total aerobic mesophilic bacteria (**Figure 2A)** exceeded the value of 7 log cfu/g, which is considered as the upper acceptability limit for fish, on day 5 for air packed samples (control) and on day 14 for vacuum packed ones, while the vacuum packaged samples with added sage EO at the both concentrations did not reach this value throughout the whole storage period. It can be concluded that although the use of vacuum packaging exhibited a shelf life extension compared to air packed samples, and its combination with sage EO, in particular at the higher concentration (i.e., 4%), achieved the optimal results, extending the shelf life of fish up to 29 days as compared to only 3 days for the control samples (Emir Çoban et al. 2016).

In another combined strategy, a research team from Greece provided evidence for synergistic effects of thyme EO and MAP on the quality of sea bass (*Dicentrarchus labrax*) (Kostaki et al., 2009) and swordfish (*Xiphias gladius*) fillets (Kykkidou, Giatrakou, Papavergou, Kontominas, & Savvaidis, 2009). The same researchers also found that combination of oregano EO with MAP in different gas mixtures was efficient in extending the shelf life of fresh Swordfish (Giatrakou, Kykkidou, Papavergou, Kontominas, & Savvaidis, 2008) and rainbow trout fillets (Pyrgotou, Giatrakou, Ntzimani, & Savvaidis, 2010).

Various research studies have proposed the use of EOs in combination with chitosan in order to improve quality and extend the shelf life of fish and other seafoods (Alishahi & Aïder, 2012; Yuan, Chen, et al., 2016). For example, the use of a coating chitosan enriched with cinnamon EO delayed lipid oxidation in refrigerated rainbow trout and markedly reduced the TBA and PV values compared with the control samples (Ojagh et al., 2010). In addition, the authors reported that this combination strategy effectively decreased the TVC and psychrotrophic bacteria in the fish during 16 days of cold storage. Similar results were also found in other recent studies, in which chitosan films were enriched by EOs from rosemary and thyme (Doğan & İzci, 2017), oregano (Vatavali et al., 2013), and garlic (Aşik & Candoğan, 2014).

7. Limitations and future trends

Despite the promising antimicrobial and antioxidant activities observed for many EOs, some limitations have been underlined in their application in fish and other seafood products. For example, our review study showed that the efficiency of EOs as natural preservatives was variable, changing from one study to another, possibly due to the differences in either the composition of EOs or the nature and the type of seafood products treated with these EOs. Indeed, one the one hand, many authors reported that the composition of EOs is dependent on many factors, such as the harvesting season, the variety of herb spice, or plant, the part of vegetables used for extraction of EOs, geographical origin, and the method used in the extraction (Burt, 2004; Hyldgaard et al., 2012; Rodriguez-Garcia et al., 2016). On the other hand, some authors (Tajkarimi et al., 2010) reported that the efficiency of EOs may be affected by fat level of fish, since some EOs were found to be more effective on lean fish (e.g., cod) than on fatty fish (e.g., salmon). Moreover, the presence of fats, carbohydrates, proteins, and salts as well as the interaction between these compounds and EOs added to seafood products could reduce the preservative activity of these oils when compared to *in vitro* application. That is why higher concentrations of EOs are usually necessary to achieve satisfactory antimicrobial and antioxidant activity in such products, which in turn may cause negative organoleptic effects and even health problems (Burt, 2004; Calo et al., 2015; Hyldgaard et al., 2012; Solórzano-Santos & Miranda-Novales, 2012).

Recently, some solutions based on the encapsulation of EOs in polymers of edible and biodegradable coatings, or into micro- and nanoemulsions, or the use of EOs in active food packaging, have been proposed to overcome drawbacks related to the possible negative sensory effects of high concentrations of EOs (Acevedo-Fani et al., 2016; Atarés & Chiralt, 2016; Ribeiro-Santos et al., 2017). However, further work is still required in this research area in order to optimize the effectiveness of EO for applications in preservation of fish and other seafoods. This may include a better understanding of the exact mechanisms of action of EOs as antimicrobial and antioxidant agents and the determination of the optimum dose needed to get the desired impacts of this treatment without compromising the sensory property or the safety of seafoods. Additionally, future research should also focus on synergism between EOs and other compounds or preservative techniques, in order to provide the maximum beneficial impact, thereby extending as much as possible the shelf life of fish and other seafood products.

8. Concluding remarks

The information compiled in this review demonstrates that different EOs incorporated directly into fish and other seafoods, or applied indirectly by other methods, can effectively inhibit or reduce lipid oxidation and growth of various microorganisms. Many EOs could be used alone or in combination with other preservative treatments to further prevent or retard oxidation and microbial spoilage in food systems, especially in fish and fish products, thereby extending the shelf life of these products. Indeed, while the importance of the use of EOs in enhancing antioxidant and antimicrobial stability of seafoods is being widely recognised, their combination with other preservation method is resulting in further superior results. Being the principal constituents of EOs, many authors reported that phenolic compounds are mainly responsible for their antimicrobial and antioxidant properties.

Our literature review revealed that EOs from plant materials, such as oregano, rosemary, thyme, sage, clove, laurel, cumin, and basil could be used at different concentrations, and often, the preservative effect was greater as the EO concentration was higher. Therefore, natural additives such as EOs have the potential to replace or partly replace the synthetic additives. However, it must be kept in mind that the application of EOs at high dose could impart some undesirable organoleptic changes and may even induce serious health problems. Hence, some considerations must be taken into account when using EOs in food preservation in order to find a balance between the effective compound dose and the potential risk of toxicity. Future research should thus focus on the safety and possible side effects of EOs before a regularly approval for their use as natural additives of fish and other seafood products.

References

Acevedo-Fani, A., Soliva-Fortuny, R., & Martín-Belloso, O. (2016). Nanostructured emulsions and nanolaminates for delivery of active ingredients: Improving food safety and functionality. *Trends in Food Science & Technology*, *60*, 12–22.

Alfonzo, A., Martorana, A., Guarrasi, V., Barbera, M., Gaglio, R., Santulli, A., … Francesca, N. (2017). Effect of the lemon essential oils on the safety and sensory quality of salted sardines (*Sardina pilchardus Walbaum 1792*). *Food Control*, *73*, 1265–1274.

Alishahi, A., & Aïder, M. (2012). Applications of chitosan in the seafood industry and aquaculture: A review. *Food and Bioprocess Technology*, *5*, 817–830.

Alizadeh, E., Chapleau, N., de Lamballerie, M., & Le-Bail, A. (2007). Effect of different freezing processes on the microstructure of Atlantic salmon (*Salmo salar*) fillets. *Innovative Food Science and Emerging Technologies*, *8*, 493–499.

Alparslan, Y., Yapici, H. H., Metin, C., Baygar, T., Günlü, A., & Baygar, T. (2016). Quality assessment of shrimps preserved with orange leaf essential oil incorporated gelatin. *LWT - Food Science and Technology*, *72*, 457-466.

Alvarez, A., Garcia Garcia, B., Jordan, M. J., Martinez-Conesa, C., & Hernandez, M. D. (2012). The effect of diets supplemented with thyme essential oils and rosemary extract on the deterioration of farmed gilthead seabream (*Sparus aurata*) during storage on ice. *Food Chemistry*, *132*, 1395–1405.

Amorati, R., Foti, M. C., & Valgimigli, L. (2013). Antioxidant activity of essential oils. *Journal of Agricultural and Food Chemistry*, *61,* 10835–10847.

Andevari, G. T., & Rezaei, M. (2011). Effect of gelatin coating incorporated with cinnamon oil on the quality of fresh rainbow trout in cold storage. *International Journal of Food Science & Technology*, 46, 2305–2311.

Aşik, E., & Candoğan, K. (2014). Effects of chitosan coatings incorporated with garlic oil on quality characteristics of shrimp. *Journal of Food Quality*, *37*, 237–246.

Atarés, L., & Chiralt, A. (2016). Essential oils as additives in biodegradable films and coatings for active food packaging. *Trends in Food Science and Technology*, *48,* 51–62.

Atrea, I., Papavergou, A., Amvrosiadis, I., & Savvaidis, I. N. (2009). Combined effect of vacuum-packaging and oregano essential oil on the shelf-life of Mediterranean octopus (*Octopus vulgaris*) from the Aegean Sea stored at 4 °C. *Food Microbiology*, *26*, 166–172.

Attouchi, M., & Sadok, S. (2012). The effects of essential oils addition on the quality of wild and farmed sea bream (*Sparus aurata*) stored in ice. *Food and Bioprocess Technology*, *5*, 1803–1816.

Bakkali, F., Averbeck, S., Averbeck, D., & Idaomar, M. (2008). Biological effects of essential oils - A review. *Food and Chemical Toxicology*, *46*, 446–475.

Bouletis, A. D., Arvanitoyannis, I. S., & Hadjichristodoulou, C. (2017). Application of modified atmosphere packaging on aquacultured fish and fish products: A review. *Critical Reviews in Food Science and Nutrition*, *57*, 2263–2285.

Bozin, B., Mimica-Dukic, N., Samojlik, I., & Jovin, E. (2007). Antimicrobial and antioxidant properties of rosemary and sage (*Rosmarinus officinalis L. and Salvia officinalis L., Lamiaceae*) essential oils. *Journal of Agricultural and Food Chemistry*, *55*, 7879–7885.

Brewer, M. S. (2011). Natural antioxidants: sources, compounds, mechanisms of action, and potential applications. *Comprehensive Reviews in Food Science and Food Safety*, *10*, 221–247.

Burt, S. (2004). Essential oils: Their antibacterial properties and potential applications in foods—A review. *Internation Journal of Food Microbiology*, *94*, 223–253.

Cai, L., Cao, A., Li, Y., Song, Z., Leng, L., & Li, J. (2015). The effects of essential oil treatment on the biogenic amines inhibition and quality preservation of red drum (*Sciaenops ocellatus*) fillets. *Food Control*, *56*, 1–8.

Calo, J. R., Crandall, P. G., O'Bryan, C. A., & Ricke, S. C. (2015). Essential oils as antimicrobials in food systems - A review. *Food Control*, *54*, 111–119.

Chaillou, S., Chaulot-Talmon, A., Caekebeke, H., Cardinal, M., Christieans, S., Denis, C., … Champomier-Vergès, M.-C. (2015). Origin and ecological selection of core and food-specific bacterial communities associated with meat and seafood spoilage. *The ISME Journal*, 9, 1105–18.

Cheng, J. H., & Sun, D. W. (2015). Rapid and non-invasive detection of fish microbial spoilage by visible and near infrared hyperspectral imaging and multivariate analysis. *LWT - Food Science and Technology*, *62*, 1060–1068.

Daniel, A. P., Veeck, A. P. L., Klein, B., Ferreira, L. F., da Cunha, M. A., Parodi, T. V., … Emanuelli, T. (2014). Using the Essential Oil of *Aloysia triphylla* (L'Her.) Britton to Sedate Silver Catfish (*Rhamdia quelen*) during Transport Improved the Chemical and Sensory Qualities of the Fish during Storage in Ice. *Journal of Food Science*, *79*, 1205–1211.

De Souza, E. L., da Cruz Almeida, E. T., & de Sousa Guedes, J. P. (2016). The potential of the incorporation of essential oils and their individual constituents to improve microbial safety in juices: A review. *Comprehensive Reviews in Food Science and Food Safety*, *15,* 753–772.

Doğan, G., & İzci, L. (2017). Effects on quality properties of smoked rainbow trout (*Oncorhynchus mykiss*) fillets of chitosan films enriched with essential oils. *Journal of Food Processing and Preservation*, *41*, e12757.

Duun, A. S., & Rustad, T. (2008). Quality of superchilled vacuum packed Atlantic salmon (*Salmo salar*) fillets stored at -1.4 and -3.6 °C. *Food Chemistry*, *106*, 122–131.

Ellis, D. I. (2002). Rapid and quantitative detection of the microbial spoilage of muscle foods : Current status and future trends. *Trends in Food Science & Technology*, *12*, 414–424.

Emir Çoban, Ö., Patir, B., & Yilmaz, Ö. (2012). Protective effect of essential oils on the shelf life of smoked and vacuum packed rainbow trout (*Oncorhynchus mykiss W.1792*) fillets. *Journal of Food Science and Technology*, *51*, 2741–2747.

Emir Çoban, Ö. (2013). Effect of ginger oil on the sensory and chemical changes of fish finger (*sarda sarda, heckel 1843*) during refrigerated storage. *International Food Research Journal*, 20, 1575–1578.

Emir Çoban, Ö., & Patir, B. (2013). Antimicrobial and antioxidant effects of clove oil on sliced smoked *Oncorhynchus mykiss*. *Journal of Consumer Protection and Food Safety, 8*, 195–199.

Emir Çoban, Ö., & Özpolat, E. (2013). The effects of different concentrations of rosemary (*rosmarinus officinalis*) extract on the shelf life of hot-smoked and vacuum-packed luciobarbus esocinus fillets. *Journal of Food Processing and Preservation*, *37*, 269–274.

Emir Çoban, Ö., Patir, B., Özpolat, E., & Kuzgun, N. K. (2016). Improving the quality of fresh rainbow trout by sage essential oil and packaging treatments. *Journal of Food Safety*, *36*, 299–307.

Emir Çoban, Ö., & Tuna Kelestemur, G. (2016). Qualitative improvement of catfish burger using Zataria multiflora Boiss. essential oil. *Journal of Food Measurement and Characterization*, 1–8.

Erkan, N., Tosun, Ş.¸ Y., Ulusoy, Ş.¸, & Üretener, G. (2011). The use of thyme and laurel essential oil treatments to extend the shelf life of bluefish (*Pomatomus saltatrix*) during storage in ice. *Journal of Consumer Protection and Food Safety*, *6*, 39–48.

FAO. (2016). The state of world fisheries and aquaculture. Contributing to food security and nutrition for all. *Food and Agriculture Organization*. Rome, Italy, 1-23.

Fernández, K., Aspe, E., & Roeckel, M. (2009). Shelf-life extension on fillets of Atlantic Salmon (*Salmo salar*) using natural additives, superchilling and modified atmosphere packaging. *Food Control*, *20*, 1036–1042.

Frangos, L., Pyrgotou, N., Giatrakou, V., Ntzimani, A., & Savvaidis, I. N. (2010). Combined effects of salting, oregano oil and vacuum-packaging on the shelf-life of refrigerated trout fillets. *Food Microbiology*, *27*, 115–121.

Ghaly, A. E., Dave, D., Budge, S., & Brooks, M. S. (2010). Fish spoilage mechanisms and preservation techniques : Review. *American Journal of Applied Sciences*, *7*, 859–877.

Ghanbari, M., Jami, M., Domig, K. J., & Kneifel, W. (2013). Seafood biopreservation by lactic acid bacteria - A review. *LWT - Food Science and Technology*, *54*, 315–324.

Giarratana, F., Muscolino, D., Beninati, C., Ziino, G., Giuffrida, A., & Panebianco, A. (2016). Activity of R(+) limonene on the maximum growth rate of fish spoilage organisms and related effects on shelf-life prolongation of fresh gilthead sea bream fillets. *International Journal of Food Microbiology*, *237*, 109–113.

Giuffrida, A., Valenti, D., Giarratana, F., Ziino, G., & Panebianco, A. (2013). A new approach to modelling the shelf life of Gilthead seabream (*Sparus aurata*). *International Journal of Food Science & Technology*, *48*, 1235–1242.

Goulas, A. E., & Kontominas, M. G. (2007). Combined effect of light salting, modified atmosphere packaging and oregano essential oil on the shelf-life of sea bream (*Sparus aurata*): Biochemical and sensory attributes. Food Chemistry, 100, 287–296.

Gram L., Trolle G., Huss H. H. (1987). Detection of specific spoilage bacteria from fish stored at low (0°C) and high (20°C) temperatures. *International Journal of Food Microbiology*, 4, 65‑72.

Gram, L., & Dalgaard, P. (2002). Fish spoilage bacteria - Problems and solutions. *Current Opinion in Biotechnology*, *13*, 262–266.

Gram, L., & Huss, H. H. (2000). The microbiological safety and quality of foods. In Lund. M, Baired-Parker. AC, & Gould. GW. (Eds.), *The microbiological safety and quality of foods*. Chapman and Hall, London, 472–506.

Guyon, C., Meynier, A., & de Lamballerie, M. (2016). Protein and lipid oxidation in meat: A review with emphasis on high-pressure treatments. *Trends in Food Science and Technology*, *50*, 131–143.

Hall, G. M. (2011). Freezing and chilling of fish and fish products. In G. M. Hall (Ed.), *Fish processing – sustainability and new opportunities*. Blackwell Publishing Ltd., 77–97.

Hassoun, A., & Karoui, R. (2016). Monitoring changes in whiting (*Merlangius merlangus*) fillets stored under modified atmosphere packaging by front face fluorescence spectroscopy and instrumental techniques. *Food Chemistry*, *200*, 343–353.

Hassoun, A., & Karoui, R. (2017). Quality evaluation of fish and other seafood by traditional and nondestructive instrumental methods: Advantages and limitations. *Critical Reviews in Food Science and Nutrition*, *57*, 1976–1998.

Hernández, A., García García, B., Jordán, M. J., & Hernández, M. D. (2015). Study of the dose of thyme essential oil in feed to prolong the shelf life of gilthead seabream (*Sparus aurata*). *Aquaculture Nutrition*, *21*, 740–749.

Hsu, C. P., Huang, H. W., & Wang, C. Y. (2014). Effects of high-pressure processing on the quality of chopped raw octopus. *LWT - Food Science and Technology*, *56*, 303–308.

Huang, H.-W., Wu, S.-J., Lu, J.-K., Shyu, Y.-T., & Wang, C.-Y. (2017). Current status and future trends of high-pressure processing in food industry. *Food Control*, *72*, 1–8.

Hyldgaard, M., Mygind, T., & Meyer, R. L. (2012). Essential oils in food preservation: Mode of action, synergies, and interactions with food matrix components. *Frontiers in Microbiology*, *3*, 1–24.

Jayasena, D. D., & Jo, C. (2013). Essential oils as potential antimicrobial agents in meat and meat products: A review. *Trends in Food Science and Technology*, *34*, 96–108.

Jayasena, D. D., & Jo, C. (2014). Potential application of essential oils as natural antioxidants in meat and meat products: A review. *Food Reviews International*, *30*, 71–90.

Jessen, F., Nielsen, J., & Larsen, E. (2014). Chilling and freezing of fish. In I. S. Boziaris (Ed.), *Seafood processing: technology, quality and safety*. John Wiley& Sons, Ltd, 98–118.

Kaale, L. D., Eikevik, T. M., Rustad, T., & Kolsaker, K. (2011). Superchilling of food: A review. *Journal of Food Engineering*, *107*, 141–146.

Kapetanakou, A. E., & Skandamis, P. N. (2016). Applications of active packaging for increasing microbial stability in foods: Natural volatile antimicrobial compounds. *Current Opinion in Food Science*, *12*, 1–12.

Karoui, R., & Hassoun, A. (2017). Efficiency of rosemary and basil essential oils on the shelf-life extension of atlantic mackerel (*Scomber Scombrus*) fillets stored at 2 °C. *Journal of AOAC International*, *100*, 335–344.

Karoui, R., Hassoun, A., & Ethuin, P. (2017). Front face fluorescence spectroscopy enables rapid differentiation of fresh and frozen- thawed sea bass (*Dicentrarchus labrax*) fillets. *Journal of Food Engineering*, *202*, 89–98.

Kaur, B. P., Srinivasa Rao, P., & Nema, P. K. (2016). Effect of hydrostatic pressure and holding time on physicochemical quality and microbial inactivation kinetics of black tiger shrimp (*penaeus monodon*). *Innovative Food Science & Emerging Technologies*, *33*, 47–55.

Kenar, M., Özogul, F., & Kuley, E. (2010). Effects of rosemary and sage tea extracts on the sensory, chemical and microbiological changes of vacuum-packed and refrigerated sardine (*Sardina pilchardus*) fillets. *International Journal of Food Science and Technology*, *45*, 2366–2372.

Khan, I., Tango, C. N., Miskeen, S., Lee, B. H., & Oh, D.-H. (2017). Hurdle technology: A novel approach for enhanced food quality and safety-A review. *Food Control*, *73*, 1426–1444.

Kostaki, M., Giatrakou, V., Savvaidis, I. N., & Kontominas, M. G. (2009). Combined effect of MAP and thyme essential oil on the microbiological, chemical and sensory attributes of organically aquacultured sea bass (*Dicentrarchus labrax*) fillets. *Food Microbiology*, *26*, 475–482.

Kuorwel, K. K., Cran, M. J., Sonneveld, K., Miltz, J., & Bigger, S. W. (2011). Essential oils and their principal constituents as antimicrobial agents for synthetic packaging films. *Journal of Food Science*, *76*, R164-R177.

Kykkidou, S., Giatrakou, V., Papavergou, A., Kontominas, M. G., & Savvaidis, I. N. (2009). Effect of thyme essential oil and packaging treatments on fresh Mediterranean swordfish fillets during storage at 4 °C. *Food Chemistry*, *115*, 169–175.

Li, T., Li, J., Hu, W., Zhang, X., Li, X., & Zhao, J. (2012). Shelf-life extension of crucian carp (*Carassius auratus*) using natural preservatives during chilled storage. *Food Chemistry*, *135*, 140–145.

Liu, X., Zhang, Y., Li, D., & Luo, Y. (2017). Characterization of the microbiota in lightly salted bighead carp (*Aristichthys nobilis*) fillets stored at 4 °C. *Food Microbiology*, *62*, 106–111.

Lucera, A., Costa, C., Conte, A., & Del Nobile, M. A. (2012). Food applications of natural antimicrobial compounds. *Frontiers in Microbiology*, *3*, 1–13.

Lv, F., Liang, H., Yuan, Q., & Li, C. (2011). In vitro antimicrobial effects and mechanism of action of selected plant essential oil combinations against four food-related microorganisms. *Food Research International*, *44*, 3057–3064.

Mahmoud, B. S. M., Yamazaki, K., Miyashita, K., Il-Shik, S., Dong-Suk, C., & Suzuki, T. (2004). Bacterial microflora of carp (*Cyprinus carpio*) and its shelf-life extension by essential oil compounds. *Food Microbiology*, *21*, 657–666.

Mahmoud, B. S. M., Yamazaki, K., Miyashita, K., Shin, I., & Suzuki, T. (2006). A new technology for fish preservation by combined treatment with electrolyzed NaCl solutions and essential oil compounds. *Food Chemistry*, *99*, 656–662.

Maisanaba, S., Llana-Ruiz-Cabello, M., Gutiérrez-Praena, D., Pichardo, S., Puerto, M., Prieto, A. I., … Cameán, A. M. (2017). New advances in active packaging incorporated with essential oils or their main components for food preservation. *Food Reviews International*, *33*, 447–515.

Makri, M. (2013). Effect of oregano and rosemary essential oils on lipid oxidation of stored frozen minced gilthead sea bream muscle. *Journal of Consumer Protection and Food Safety*, *8*, 67–70.

Mann, C. M., & Markham, J. L. (1998). A new method for determining the minimum inhibitory concentration of essential oils. *Journal of Applied Microbiology*, *84*, 538–544.

Maqsood, S., Benjakul, S., & Shahidi, F. (2013). Emerging role of phenolic compounds as natural food additives in fish and fish products. *Critical Reviews in Food Science and Nutrition*, *53*, 162–79.

Maqsood, S., Benjakul, S., Abushelaibi, A., & Alam, A. (2014). Phenolic compounds and plant phenolic extracts as natural antioxidants in prevention of lipid oxidation in seafood: A detailed review. *Comprehensive Reviews in Food Science and Food Safety*, *13*, 1125–1140.

Masniyom, P., Benjama, O., & Maneesri, J. (2012). Effect of turmeric and lemongrass essential oils and their mixture on quality changes of refrigerated green mussel (*Perna viridis*). *International Journal of Food Science and Technology*, *47*, 1079–1085.

Mastromatteo, M., Conte, A., & Del Nobile, M. A. (2010a). Combined use of modified atmosphere packaging and natural compounds for food preservation. *Food Engineering Reviews*, *2*, 28–38.

Mastromatteo, M., Danza, A., Conte, A., Muratore, G., & Del Nobile, M. A. (2010b). Shelf life of ready to use peeled shrimps as affected by thymol essential oil and modified atmosphere packaging. *International Journal of Food Microbiology*, *144*, 250–256.

Milne, D., & Powell, S. M. (2014). Limited microbial growth in Atlantic salmon packed in a modified atmosphere. *Food Control*, *42*, 29–33.

Noseda, B., Vermeulen, A., Ragaert, P., & Devlieghere, F. (2014). Packaging of fish and fishery products. In I. S. Boziaris (Ed.), *Seafood processing: Technology, quality and safety*. John Wiley, 237-261.

Ojagh, S. M., Rezaei, M., Razavi, S. H., & Hosseini, S. M. H. (2010). Effect of chitosan coatings enriched with cinnamon oil on the quality of refrigerated rainbow trout. *Food*

Chemistry, 120*, 193–198.

Ozogul, Y., Yuvka, I., Ucar, Y., Durmus, M., Kosker, A. R., Oz, M., & Ozogul, F. (2017). Evaluation of effects of nanoemulsion based on herb essential oils (rosemary, laurel, thyme and sage) on sensory, chemical and microbiological quality of rainbow trout (*Oncorhynchus mykiss*) fillets during ice storage. *LWT - Food Science and Technology, 75*, 677–684.

Patel, S. (2015). Plant essential oils and allied volatile fractions as multifunctional additives in meat and fish-based food products: A review. *Food Additives & Contaminants: Part A, 32*, 1049–1064.

Perricone, M., Arace, E., Corbo, M. R., Sinigaglia, M., & Bevilacqua, A. (2015). Bioactivity of essential oils: A review on their interaction with food components. *Frontiers in Microbiology, 6*, 1–7.

Pezeshk, S., Ojagh, S. M., & Alishahi, A. (2015). Effect of plant antioxidant and antimicrobial compounds on the shelf-life of seafood - A review. *Czech Journal of Food Sciences*, *33*, 195–203.

Provincial, L., Gil, M., Guillén, E., Alonso, V., Roncalés, P., & Beltrán, J. A. (2010). Effect of modified atmosphere packaging using different CO_2 and N_2 combinations on physical, chemical, microbiological and sensory changes of fresh sea bass (*Dicentrarchus labrax*) fillets. *International Journal of Food Science and Technology*, *45*, 1828–1836.

Pyrgotou, N., Giatrakou, V., Ntzimani, A., & Savvaidis, I. N. (2010). Quality assessment of salted, modified atmosphere packaged rainbow trout under treatment with oregano essential oil. *Journal of Food Science, 75*, 406–411.

Rastogi, N. K., Raghavarao, K. S. M. S., Balasubramaniam, V. M., Niranjan, K., & Knorr, D.

(2007). Opportunities and challenges in high pressure processing of foods. *Critical Reviews in Food Science and Nutrition*, *47*, 69–112.

Ribeiro-Santos, R., Andrade, M., Melo, N. R. de, & Sanches- Silva, A. (2017). Use of essential oils in active food packaging: Recent advances and future trends. *Trends in Food Science & Technology*, *61*, 132–140.

Rode, T. M., & Hovda, M. B. (2016). High pressure processing extend the shelf life of fresh salmon, cod and mackerel. *Food Control*, *70*, 242–248.

Rodrigues, B. L., Alvares, T. da S., Sampaio, G. S. L., Cabral, C. C., Araujo, J. V. A., Franco, R. M., … Conte Junior, C. A. (2016). Influence of vacuum and modified atmosphere packaging in combination with UV-C radiation on the shelf life of rainbow trout (*Oncorhynchus mykiss*) fillets. *Food Control*, *60*, 596–605.

Rodriguez-Garcia, I., Silva-Espinoza, B. a., Ortega-Ramirez, L. a., Leyva, J. M., Siddiqui, M. W., Cruz-Valenzuela, M. R., … Ayala-Zavala, J. F. (2016). Oregano essential oil as an antimicrobial and antioxidant additive in food products. *Critical Reviews in Food Science and Nutrition*, *56*, 1717–1727.

Sallam, K. I. (2007). Chemical, sensory and shelf life evaluation of sliced salmon treated with salts of organic acids. *Food Chemistry*, *101*, 592–600.

Sampels, S. (2015a). The effects of processing technologies and preparation on the final quality of fish products. *Trends in Food Science & Technology*, *44*, 131–146.

Sampels, S. (2015b). The effects of storage and preservation technologies on the quality of fish products: A review. *Journal of Food Processing and Preservation*, *39*, 1206–1215.

Sánchez-González, L., Vargas, M., González-Martínez, C., Chiralt, A., & Cháfer, M. (2011).

Use of essential oils in bioactive edible coatings. *Food Engineering Reviews*, *3*, 1–16.

Santos, J., Lisboa, F., Pestana, N., Casal, S., Alves, M. R., & Oliveira, M. B. P. P. (2013). Shelf life assessment of modified atmosphere packaged turbot (*Psetta maxima*) fillets: Evaluation of microbial, physical and chemical quality parameters. *Food and Bioprocess Technology*, *6*, 2630–2639.

Secci, G., & Parisi, G. (2016). From farm to fork: Lipid oxidation in fish products. A review. *Italian Journal of Animal Science*, *15*, 124–136.

Shahidi F, Wanasundara UN. 2002. Methods for measuring oxidative rancidity in fats and oils. In C. C.Akon and D. B. Min (Eds.), *Food Lipids: Chemistry, Nutrition and Biotechnology*. Marcel Dekker, New York, 387-403.

Shahidi, F., & Zhong, Y. (2005). Lipid oxidation: measurement methods. In F. Shahidi (Ed.), *Bailey's industrial oil and fat products*. John Wiley & Sons, Inc, 357–385.

Sivertsvik, M., Jeksrud, W. K., & Rosnes, J. T. (2002). A review of modified atmosphere packaging of fish and fishery products - Significance of microbial growth, activities and safety. *International Journal of Food Science and Technology*, *37*, 107–127.

Solórzano-Santos, F., & Miranda-Novales, M. G. (2012). Essential oils from aromatic herbs as antimicrobial agents. *Current Opinion in Biotechnology*, *23*, 136–141.

Stonehouse, G. G., & Evans, J. A. (2015). The use of supercooling for fresh foods: A review. *Journal of Food Engineering*, *148*, 74–79.

Sugumar, S., Ghosh, V., Mukherjee, A., & Chandrasekaran, N. (2016). Chapter 9 - Essential oil-based nanoemulsion formation by low- and high-energy methods and their application in food preservation against food spoilage microorganisms. In *Essential oils* *in food preservation, flavor and safety*. Elsevier Inc. 93–100.

Suppakul, P., Miltz, J., Sonneveld, K., Bigger, S. W., & Qd. (2003). Antimicrobial properties of basil and its possible application in food packaging. *Journal of Agricultural and Food Chemistry, 51*, 3197–3207.

Swamy, M. K., Akhtar, M. S., & Sinniah, U. R. (2016). Antimicrobial properties of plant essential oils against human pathogens and their mode of action: An updated review. *Evidence-Based Complementary and Alternative Medicine*, ID 3012462, 21.

Tajkarimi, M. M., Ibrahim, S. A., & Cliver, D. O. (2010). Antimicrobial herb and spice compounds in food. *Food Control*, *21*, 1199–1218.

Tongnuanchan, P., & Benjakul, S. (2014). Essential oils: Extraction, bioactivities, and their uses for food preservation. *Journal of Food Science*, *79*, 1–19.

Truong, B. Q., Buckow, R., Stathopoulos, C. E., & Nguyen, M. H. (2014). Advances in high-pressure processing of fish muscles. *Food Engineering Reviews*, *7*, 109–129.

Vatavali, K., Karakosta, L., Nathanailides, C., Georgantelis, D., & Kontominas, M. G. (2013). Combined effect of chitosan and oregano essential oil dip on the microbiological, chemical, and sensory attributes of red porgy (*Pagrus pagrus*) stored in ice. *Food and Bioprocess Technology*, *6*, 3510–3521.

Xu, J. L., Riccioli, C., & Sun, D. W. (2015). An overview on nondestructive spectroscopic techniques for lipid and lipid oxidation analysis in fish and fish products. *Comprehensive Reviews in Food Science and Food Safety*, *14*, 466–477.

Yuan, G., Chen, X., & Li, D. (2016). Chitosan films and coatings containing essential oils: The antioxidant and antimicrobial activity, and application in food systems. *Food*

Research International, *89*, 117–128.

Yuan, G., Lv, H., Tang, W., Zhang, X., & Sun, H. (2016). Effect of chitosan coating combined with pomegranate peel extract on the quality of Pacific white shrimp during iced storage. *Food Control*, *59*, 818–823.

Zhang, Y., Li, D., Lv, J., Li, Q., Kong, C., & Luo, Y. (2016). Effect of cinnamon essential oil on bacterial diversity and shelf-life in vacuum-packaged common carp (*Cyprinus carpio*) during refrigerated storage. *International Journal of Food Microbiology*, *249*, 1–8.

Zhu, Y., Ma, L., Yang, H., Xiao, Y., & Xiong, Y. L. (2016). Super-chilling (-0.7 °C) with high-CO_2 packaging inhibits biochemical changes of microbial origin in catfish (*Clarias gariepinus*) muscle during storage. *Food Chemistry*, *206*, 182–190.

Figure and Table Captions

Figure 1: Effect of *Zataria multiflora* Boiss essential oil added at concentration of 0.2 % (0.2 ZMEO) and 0.4 % (0.4 ZMEO) on (**A**) peroxide value (PV) and (**B**) thiobarbituric acid (TBA) of catfish burgers during storage at 4 °C.

Figure 2: Effect of sage essential oil in combination with vacuum packaging on (**A**) total aerobic mesophilic bacteria and (**B**) Psychrophilic bacteria of rainbow trout stored in air without sage essential oil (control), vacuum packaged (VP), vacuum packaged combined with 2% (VP-EO2) or 4% (VP-EO4) sage essential oil.

Table 1: Summary of some relevant research results testing the antimicrobial and antioxidant activities of common essential oils or their components in fish and other seafoods

Table 2: Relevant examples of antimicrobial and antioxidant properties of some common essential oils combined with other preservation methods in fish and other seafoods

Figure 1: Hassoun and Emir Coban (2017)

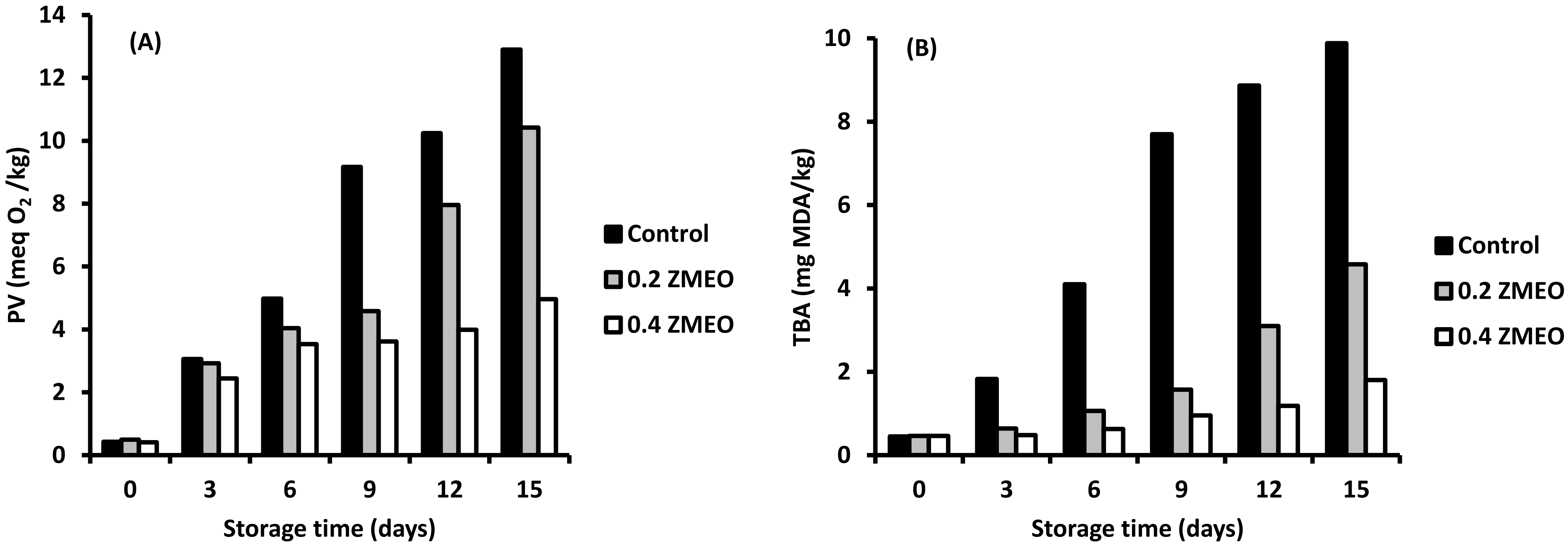

Figure 2: Hassoun and Emir Coban (2017)

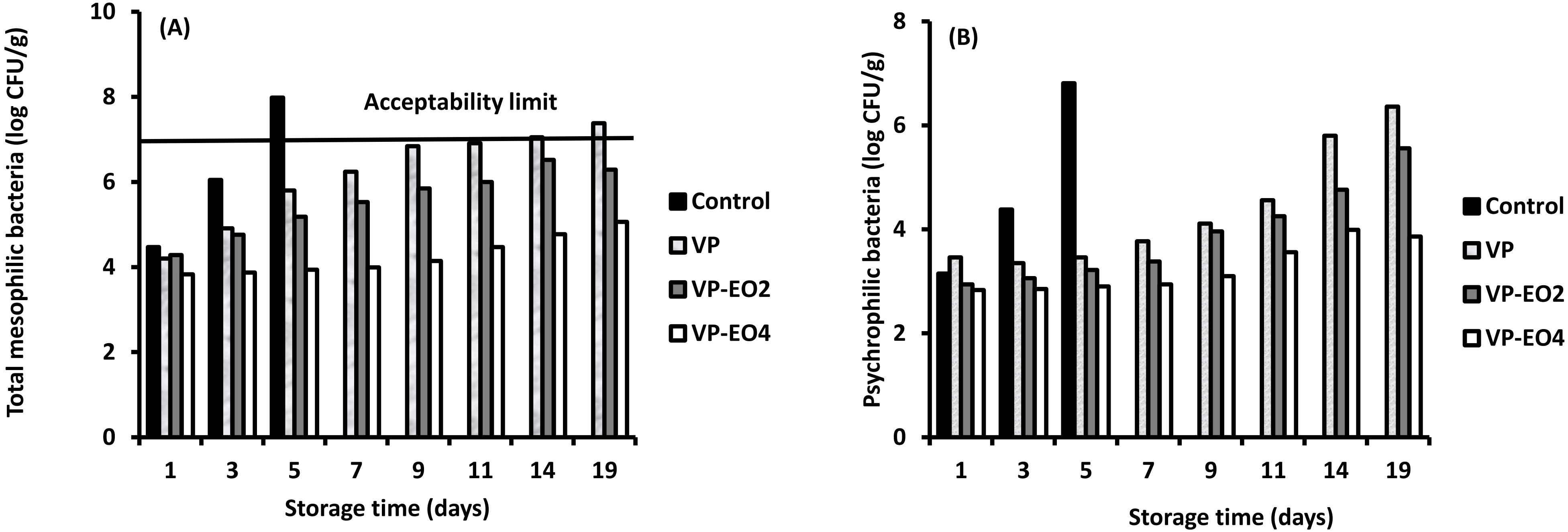

Table 1: Hassoun and Emir Coban (2017)

Seafood product	EOs or their compounds	Mode of application	Antimicrobial and antioxidant effects	Reference
Atlantic Mackerel (*Scomber scombrus*)	Rosemary and basil	Immersion (1%)	Treatment with these EOs resulted in lower contents of volatiles compounds and primary and secondary oxidation products, with a shelf life extension of 2-5 days compared to the control samples	(Karoui & Hassoun, 2017)
Carp (*Cyprinus carpio*)	Garlic EO and different constituents of EOs	Immersion (1% and 2%)	Dipping fish fillets into a solution containing both carvacrol and thymol led to a remarkable reduction in the microbial growth, consequently extending the shelf life of the fish	(Mahmoud et al., 2004)
Bluefish (*Pomatomus saltatrix*)	Thyme and laurel	Immersion (1%)	Treatment with both EOs resulted in a reduction of microbial growth and lower lipid oxidation rates, extending the shelf life from 9 days for the control to 13 days for treated samples	(Erkan, Tosun, Ulusoy, & Üretener, 2011)
Sarda sarda	Ginger	Direct addition (0.5% and 1%)	Treatment of fish fingers with 1% EO extended shelf life up to 17 days compared to only 5 days for untreated samples	(Emir Çoban, 2013)

Seafood product	EOs or their compounds	Mode of application	Antimicrobial and antioxidant effects	Reference
Rainbow trout (*Oncorhynchus mykiss*)	Clove	Immersion (0.1%, 0.5%, and 1%)	Treatment of smoked fillets with 0.5% and 1% clove EO decreased spoilage bacterial growth (TVC and psychrotrophic bacteria) and lipid oxidation (PV and TBA) and extended shelf life by 4–5 weeks compared to the control samples	(Emir Çoban & Patir, 2013)
Rainbow trout (*Oncorhynchus mykiss*)	Rosemary, laurel, thyme, and sage	Nanoemulsion	In addition to their antimicrobial and antioxidant properties, the encapsulation of these EOs, in particular rosemary and thyme ones, into nanoemulsions enhanced organoleptic quality of fish, giving a bitter taste	(Ozogul et al., 2017)
Shrimps (*Parapenaeus longirostris Lucas 1846*)	Orange	Coating (0.5%, 1%, and 2%)	Gelatin coating enriched with 2% orange leaf EO showed significant antioxidant and antimicrobial activities, achieving a shelf life extension in shrimps of about 10 days	(Alparslan et al., 2016)

EO: Essential Oil; MAP: Modified Atmosphere Packaging; PV: Peroxide Value; TBA: Thiobarbituric Acid; TVC: Total Viable Count

Table 2: Hassoun and Emir Coban (2017)

Seafood product and storage conditions	EOs or their compounds	Main results	Reference
Rainbow trout fillets packaged under vacuum in combination with salt	Oregano (0.2%, 0.4%)	The combination of oregano (0.2%) and vacuum packaging achieved a significant shelf life prolongation of fish fillets (11–12 days) compared to control samples packaged in air (5 days)	(Frangos et al., 2010)
Smoked and vacuum packed rainbow trout fillets	Rosemary, sage, thyme, and clove (0.06%)	In particular, the results demonstrated that the addition of clove EO had the highest preservation impact, resulting in a significant extension of shelf life of the product of about 6-7 weeks.	(Emir Çoban, Patir, & Yilmaz, 2012)
Common carp stored under vacuum packaging	Cinnamon (0.1%)	Based on sensory, microbial, and some physico-chemical parameters, it was reported that the combined treatment maintained good quality shelf life was extended by 2 days compared to untreated samples	(Zhang et al., 2016)
Sea bass fillets packaged under different MAP	Thyme (0.2%)	The use of this EO improved the quality of fish fillets when applied in combination with 60% CO_2, 30% N_2, and 10% O_2, extending the shelf life to 17 days compared to only 6 days for control samples	(Kostaki et al., 2009)
Mediterranean Swordfish fillets packed under MAP	Thyme (0.1%)	The combination of thyme EO and MAP reduced the TVC and H_2S-producing bacteria and inhibited lipid oxidation, extending the shelf life to about 20 days compared to 8 days for the control	(Kykkidou et al., 2009)

Seafood product and storage conditions	EOs or their compounds	Main results	Reference
Salted rainbow trout fillets stored under MAP	Oregano (0.2%, 0.4%)	The use of 0.2% oregano EO in combination with MAP reduced the main spoilage microorganisms and the content of some biochemical parameters (TVB-N, TMA-N) and extended the shelf life of the fish up to 21 days	(Pyrgotou et al., 2010)
Salted sea bream fillets stored under MAP	Oregano (0.4%, 0.8%)	The combination of oregano EO (0.8%) and MAP exhibited a strong antioxidant (measured as TBA value) and antimicrobial (estimated as volatile amines contents) activities, which extended the shelf life of fish fillets by more than 17 days	(Goulas & Kontominas, 2007)
Peeled shrimps packaged under MAP	Thymol (0.05%, 0.1%, 0.15%)	The authors obtained a shelf life of about 14 days for the active coating (0.1%) packaged under MAP compared to the samples stored in air (5 days)	(Mastromatteo, Danza, Conte, Muratore, & Del Nobile, 2010b)
Carp fillets pre-treated with electrolyzed NaCl solutions	Carvacrol and thymol (0.5%)	The combined treatment resulted in a significant reduction in the total microbial count and content of lipid oxidation products (determined by PV and TBA) which prolonged the shelf life of the treated fillets to 16 days compared to 4 days for the control	(Mahmoud, Yamazaki, Miyashita, Shin, & Suzuki, 2006)
Whole red Porgy coated with chitosan	Oregano (0.1 %)	The combination of oregano EO and chitosan improved antimicrobial and antioxidant properties of fish and achieved a shelf life extension of about 8 to 9 days	(Vatavali et al. 2013)

EO: Essential Oil; MAP: Modified Atmosphere Packaging; PV: Peroxide Value; TBA: Thiobarbituric Acid; TMA-N: Trimethylamine Nitrogen; TVB-N: Total Volatile Base Nitrogen