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A systematic review on nano-delivery systems enriched with aromatic compounds: Flavor, odor, and chemical quality perspectives in fish

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ABSTRACT

The distinct fishy odors found in fish products are mainly linked to the surrounding environment (eg, algae, water, and feed). These odor compounds can be intensified during processing and storage as a result of lipid autoxidation, enzymatic reactions, degradation of TMAO, and Strecker degradation. For this purpose, the area of nanoapplication methods is attracting attention because of their potential to play a crucial role in maintaining the quality and odor properties of fish, allowing the inhibition of the formation of unpleasant volatile compounds through the oxidation of aroma precursors, such as fatty acids. The nanofibers and NPs the allow carrying fragrances and flavors, resulting in improved performance of the EOs or masking unpleasant volatile compounds that are generated through lipid oxidation. Furthermore, nanovesicles containing aroma and flavor compounds from EOs and microalgae can extend the chemical decomposition with nanocoating methods. The combination of nanomaterials could be one of the promising ways to mask bitter taste and off-odor and delay spoilage in fish products as future trends. In this systematic review, the applications of nanotechnology in recent papers published over the last 10 years related to chemical quality and odor were discussed.

1. Introduction

The taste is the primary factor influencing the purchase of fish products. The unpleasant fishy odorants are associated with the surrounding environment (such as algae, water, and feed) and post-harvest handling storage. There are various applications to control or mitigate fishy odors (Dai et al., 2024). Among these, nanoapplications play a crucial role in mitigating fish odor, from feeding fish to packaging processed fish products. The area of nanotechnology-assisted active food packaging is attracting attention because of its impact on the overall aroma of fish. Furthermore, the type of feed provided to the fish can influence their odor. During the last decade, the demand for fish meals has increased by 300 %, prompting interest in alternative fish feed sources such as microalgae and algal extracts (Coleman et al., 2022; Nagappan et al., 2021; Tayel et al., 2024). These alternatives are rich in ω-3 fatty acids and proteins (28–71 % dry weight) (Coleman et al., 2022; Nagappan et al., 2021).

Despite these advances, the aroma of various species of fish remains relatively unexplored. Most studies on fish neglected flavor and aroma perspectives. However, plant-based nanomaterials, suitable for fish plating and active food packaging, could impact the overall aroma of fish. Therefore, nanotechnology plays a crucial role in flavor release and odor management.

Flavor and aroma compounds are essential components of seafood. Controlled release of flavors in the mouth, triggered by stimuli such as hear bursting or chewing, dissolves upon contact with saliva (Ahmed et al., 2023; Perez & Gaonkar, 2014). Furthermore, acidulants like citric, acetic, malic, and fumaric acids contribute to both taste and aroma (Bratovcic & Suljagic, 2019; Hsueh et al., 2017; Ozogul et al., 2017). However, despite their strong aroma/flavor EOs, face challenges due to

Abbreviations: CD, cyclodextrins; EO, essential oil; FFA, free fatty acid; H_2S, hydrogen sulfide-; NP, nanoparticle; PLA, polylactic acid; PUFA, polyunsaturated fatty acids; PV, peroxide value; PVA, polyvinyl alcohol; SSO, specific spoilage microorganisms; TBA, thiobarbituric acid value; TBARS, thiobarbituric acid reactive substances; TMA, trimethylamine; TMAN, trimethyl-amine nitrogen; TMAO, trimethylamine N-oxide; TVBN, total volatile basic nitrogen; WPI, whey protein isolate; 2-MIB, 2-methylisoborneol.

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low water solubility and light sensitivity when applied to fish. Therefore, nanoencapsulation is a promising practice in the seafood industry for enhanced retention and controlled release of aromatic compounds (Rathod et al., 2023; Saifullah et al., 2019).

Nanocoating applications using nanofibers, nanocapsules, or nanoemulsions can delay rapid deterioration and maintain the aroma of raw or cooked fish products (Cetinkaya & Wijaya, 2024; Durmus, 2020; Durmuş et al., 2020). The antimicrobial mechanism of nanomaterials is attributed to their contact with bacterial cell membranes. Due to their small size, nanomaterials can generate reactive oxygen species that cause damage to bacterial cells and disrupt bacterial cell functions. Furthermore, nanomaterials can retain the water required for microorganisms, inhibiting their biochemical reactions (Cetinkaya & Wijaya, 2024; Çiçek & Özoğul, 2022). Consequently, enzyme activity and the generation of volatile odor compounds slow down, which helps inhibit the off-odor and flavor in the product.

Nanoencapsulation approaches show promise in preventing the release of unwanted flavors, such as bitterness, from fish products. They lead to the protection of flavor from oxidative and thermal degradation and improve odor properties (Ahmed et al., 2023; Tayel et al., 2019). For instance, nanoliposomes or nanocapsules form a protective layer around the flavor droplets, controlling their release, and effectively masking undesirable odor. Therefore, the incorporation of plant extracts and EOs into nanomaterials can mask unpleasant aromas or tastes (Fig. 1).

Nano-sized flavoring particles can activate taste receptors in the human tongue and mask bitterness (Aguilar-Pérez et al., 2023). For this purpose, nanoemulsions made with EO, fabricated by nano-emulsified olive, cinnamaldehyde, orange, grapefruit, mandarin, and lemon have been reported (Durmus, 2020; Durmus et al., 2020; Fajardo et al., 2022). Edible packaging materials or films based on bioactive nanomaterials could also be used to preserve fish by blocking volatile gases (Laorenza et al., 2022; Ponnusamy et al., 2024). Therefore, nanotechnology includes improving active packaging techniques and enhancing the quality in terms of flavor, odor, and taste, as well as the absorption of nutrients from fish (Fajardo et al., 2022). Furthermore, novel approaches using ozone nanobubbles with aromatic compounds to oxygenate water open new frontiers to improve sensory properties (Dien et al., 2023).

In addition to changes in aroma during cooking, flavor perception can be affected by volatile protein interactions. Consequently, sulfur-containing compounds, volatile acids, saturated fatty acids, carbonyl compounds, and amines can also be generated, affecting the final flavor of the fish meat (Durmus et al., 2020; Durmuş & zoul, 2018; L. Liu et al., 2024).

Biodegradable proteins can be considered a reliable source for nanodispersal of food flavors. Investigating the effects of biobased nanocoating materials on changes in taste and flavor precursors of fish products before and after processing is required, to improve the understanding of aroma compound interactions (Eranda et al., 2024). With this background in mind, the purpose of nano-encapsulating aroma compounds should be explained, and biopolymer-based nano-delivery systems to minimize undesired odor and maintain the organoleptic properties of fish products should be introduced. Therefore, in this systematic review, the nano-feeding, and nanoapplications in raw or cooked fish species are discussed. Furthermore, the aroma compounds and precursors of the most common nanomaterials used in the industry for fish plating are briefly discussed, and major conclusions based on prospects are elucidated.

2. Literature search strategy

The Web of Science and Google Scholar databases were simultaneously searched for this systematic review. The most recent search was conducted on June 2024. A list of search terms, including keywords, synonyms, singular and plural forms, and alternative phrases such as “fish nano feed”, ‘nanotechnology AND fish packaging”, “fish volatiles AND nanotechnology”, “nanoemulsion AND fish quality”, “nanocomposite AND fish quality”, “nanotechnology and fish packaging”, “nanoemulsion AND fish fillet”, “fish off-odor”, “nanoliposome AND fish”, “fish fillet AND nanoapplication”, “nanofiber AND active packaging AND fish”, “nanoemulsion AND fillet spoilage’ was utilized. The Mendeley software was employed to organize bibliographic references.

2.1. Inclusion, exclusion criteria and study selection

This individual search strategy contains publications published between January 1, 2014, and June 1, 2024. Studies were classified as evaluations (minimum, comprehensive, systematic), research articles, and book chapters. Only the English language was considered as the search criteria.

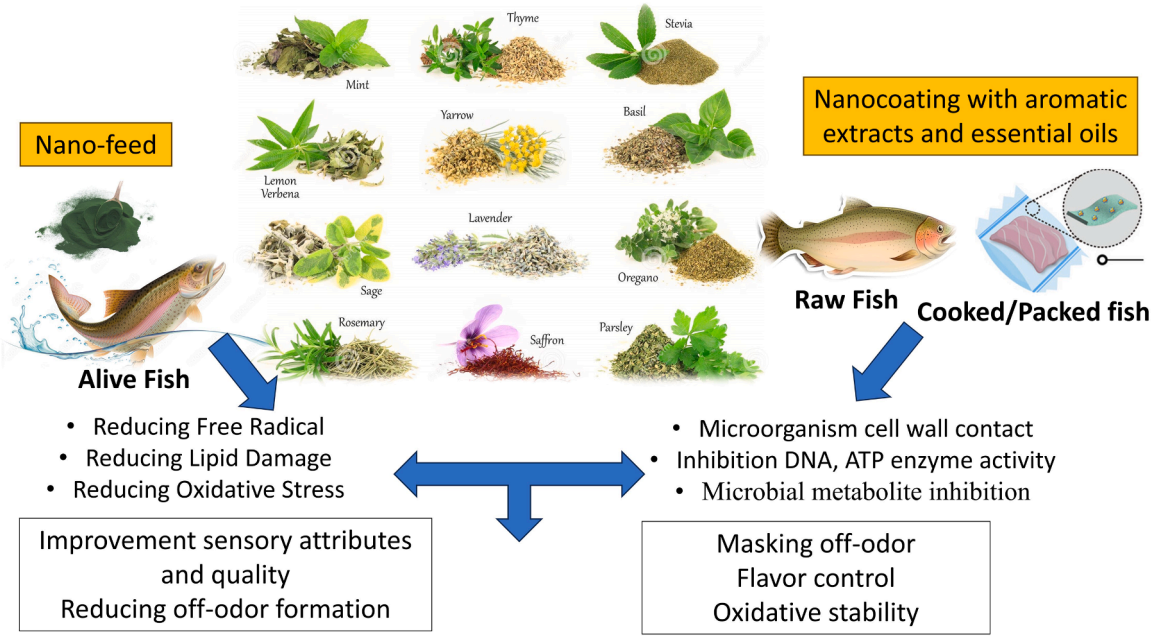


Fig. 1. Graphic illustration showing the nano-feeding and nanocoating delivery systems containing aromatic compounds.

According to all search results in the database, a total of 1240 publications were identified, excluding duplicate and irrelevant publications. Fig. 2 illustrates the concepts of this approach protocol for systematic literature search and online search.

2.2. Data extraction, quality assessment, and reporting phase

The data from the studies include information extracted by the authors, indexed by Web of Science and Google Scholar based on the following information. The authors, year of publication, type of study, reported data, and quarter. However, the following sections mention the developed categories and their respective components. The authors evaluated the quality of the data collected from reviews and research articles.

The authors identified 535 research articles, reviews, and book chapters for complete reading, excluding 7 self-studies. All these studies met the eligibility criteria, and were published between 2014 and 2024. Most studies on fish have overlooked shelf life and microbiological aspects. However, the effect of nanomaterials on improving the flavor and chemical quality of fish products has not been explored in depth. The collected data provide valuable insight into understanding how nanomaterials affect the sensory attributes of raw or cooked fish products. On the basis of the evidence proposed so far, the following sections are briefly discussed.

3. Microorganism-related metabolites that cause off-flavors

SSO can dominate and produce metabolites that directly affect the odor of fish. As is known, TMAO is a microbial metabolite derived from nutrients such as choline, L-carnitine, ergothioneine, and betaine. *Escherichia coli*, Citrobacter, *Klebsiella pneumonia*, Shigella, and Achromobacter have enzymes that can convert chemical compounds into TMA which generally contributes to an unpleasant smell (Tacconi et al., 2023). After the death of aquaculture species, TMAO can lead to the formation of TMA, dimethylamine, and formaldehyde which are responsible for the pungent and fishy odor, similar to that of ammonia. Degradation of TMAO with activation of microbial enzymes increases the levels of these molecules (Ahmed et al., 2023). TBARS is another important assay to measure the lipid peroxidation product malondialdehyde. When the level of malondialdehyde exceeds 5 mg/kg, it can affect the odor characteristics of fish (Nabati et al., 2023). Secondary autoxidation products cause significant odor changes. Lipid autoxidation or lipoxygenase action causes fatty acids to oxidize, resulting in the formation of 2,4-heptadienal, which contributes to a strong rancid odor or the characteristic fishy smell (Chuesiang et al., 2023; Ponnusamy et al., 2024; Zhao et al., 2023). Aldehydes (hexanal, pentanal, heptanal), alcohols (1-penten-3-ol and 1-octen-3-ol, 1-hexanol), esters, ketones, hydrocarbons, and acids produced during lipid oxidation result in an unpleasant odor, alter the flavor, reduce nutritional value and acceptability by consumers. Hexanal and pentanal cause mushroom-like, pungent odor, while heptanal and nonanal are related to a nutty and plastic-like odor (Chuesiang et al., 2023; Ponnusamy et al., 2024). Protein degradation and excessive oxidation of proteins can also cause off-flavor (Liu et al., 2021b; Qiu et al., 2023; Rathod et al., 2023). Further decarboxylation and deamination reactions may generate fishy odorants, such as δ-aminovaleric acid, δ-aminovaleraldehyde and hexahydroxy pyridine (Wang et al., 2023). Putrescine, cadaverine and acetic acid are other microbial metabolites associated with fish spoilage (Chuesiang et al., 2023; Kosker, 2020; Mohammadi et al., 2021).

As is well-known, volatile sulfur compounds are typical compounds in spoiled fish products. Many bacteria such as *S. putrefaciens* and Vibrionaeae identified as SSO can produce H_2S from the sulfur-containing amino acid cysteine, resulting in sulfur and rotten odors in fish species (Bergstedt & Skov, 2023). Dimethylsulfide is also produced by methionine amino acids, which contribute to the unpleasent rotten egg odors, also resembling H_2S. *S. putrefaciens* can form biofilms that lead to spoilage in fish. In seafood processing plants, physical methods for removing biofilms are not ideal for many aquatic products. However, chemical reagents can negatively impact the sensory attributes of aquaculture products (Yan & Xie, 2021). Therefore, environmentally friendly nanoapplications appear promising for biofilm removal.

Functional changes in smart nanomaterials based on the adsorption

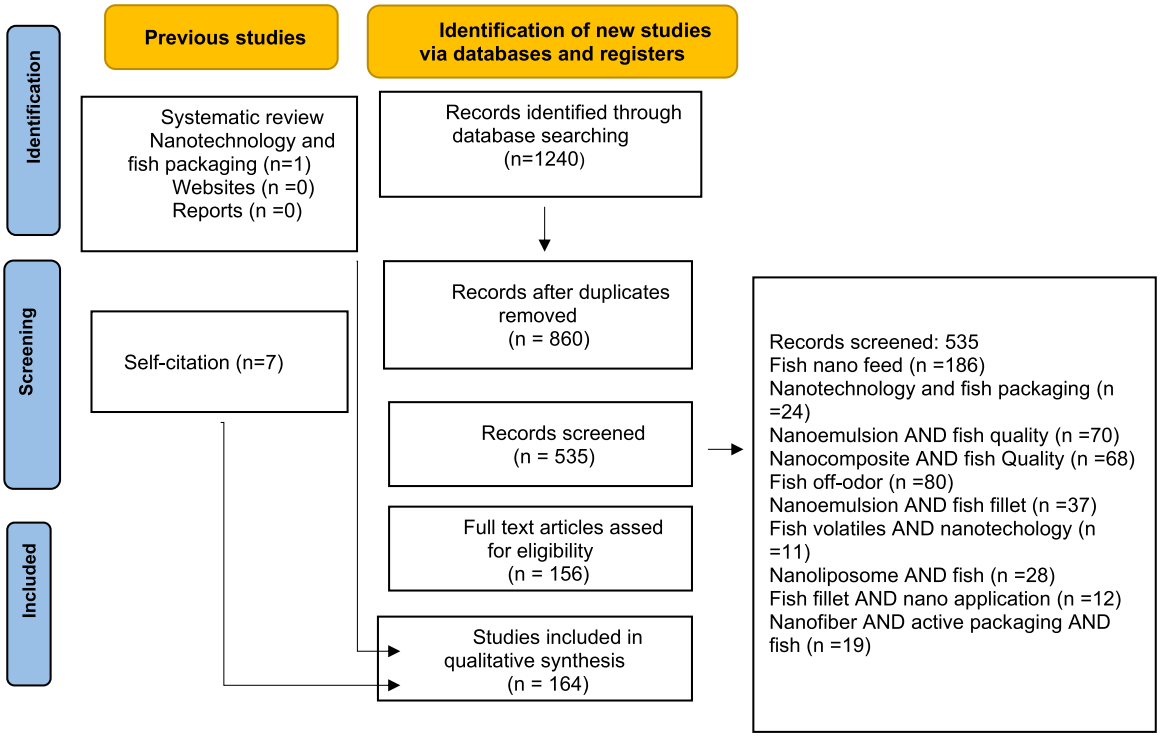


Fig. 2. PRISMA flow diagram of the literature.

of volatiles that cause off-odors, released from fish products, are also gaining interest (Amaregouda et al., 2022; Cetinkaya, 2024, 2024; Ge et al., 2020; Naghdi et al., 2022). Andre et al. (2022) stated that the development of e-nose for fish quality control can be remarkably effective considering the emission of unpleasant odor. For this purpose, nanofiber-based electronic noses have been generated that sense volatile gases released from raw salmon. Furthermore, a portable off-odor sensing nanofiber platform for tilapia fish, by mimicking human olfaction, has recently been developed (Jiang et al., 2024).

Pseudomonas spp. produces volatile aromatic compounds such as ketones, aldehydes, and sulfurs, mainly H_2S. According to Ayseli and Coskun (2022), unsaturated aldehydes are generated by enzymatic oxidation of lipids, such as PUFA-containing lipids which are widely found in many species of fish. The off-flavor of PUFA is described as 'rancid' in fish. Along with this, lipid-derived odor compounds, such as aldehydes, are often associated with algae, in particular cryophytes and diatoms, with a high cellular PUFA content (Cetinkaya et al., 2023). The preparation of edible nanocoatings/films demonstrated a notable efficacy in reducing off-flavor (Zhou et al., 2024b). The energy of UV and visible light can cause oxidation reactions in fish resulting in an off-flavor, and therefore blocking the damaging wavelength of light is an important property for packaging materials of fish integrated with nanomaterials to be used as absorption barriers against UV light (Ge et al., 2020).

Similarly, *Hafnia paralvei* and *Serratia spp*. are considered important SSOs in seafood. The results of Borém et al. (2021) and Silbande et al. (2018) contribute to our understanding of volatile compounds as important spoilage indicators in tuna fish. *Hafnia paralvei* and *Serratia spp*. were demonstrated to produce strong off-odors (pyrrolidine, sulfur/crab) in tuna fish.

2-MIB and geosmin (trans-1,10-dimethyl-trans-9-decalol) are other important volatile terpenoids that contribute to earthy and muddy flavors in fish species (Mohammadi et al., 2021). Both volatiles have a highly negative impact on the sensory profile of fish species because of their low odor threshold. For instance, if the concentration of geosmin or 2-MIB exceeds 8 ng/l, sensory problems are observed in drinking water (Cetinkaya et al., 2023). Therefore, the quality of water is very critical toprevent off-flavor formation in fish species. Two groups of aquatic microorganisms produce a musty and earthy smell as secondary metabolites: (i) Anabaena for Geosmin and (ii) *Phormidium* spp. for 2-MIB. Asghar et al. (2015) have found that metal-doped TiO_2 NPs are effective for the removal of 2-MIB and geosmin that cause off-flavors in the water. In general, these studies suggest that nanotechnological treatments in water to reduce microorganism-based off-flavors will gain more attention as a future trend for fish species (Cetinkaya et al., 2023).

4. Fish feed containing nano-encapsulated aromatic compounds

Feed additives are essential raw materials in the fish feed industry to improve nutritional value and quality (Mishra et al., 2023). Feeds with nanosized particles that have aroma-actives can be used to delay the oxidation of fish products (Ahmed et al., 2023). Therefore, the use of nanotechnology in feeding has become crucial in recent years (Table 1). NPs can alter feeding consumption patterns by adding flavor compounds. Aromatic compounds combined with NP can pass through cells more easily than their larger counterpart, accelerating their assimilation (Dar et al., 2019; Sarkar et al., 2022). The delivery of aromatic compounds through nano-feeding applications may mask an unpleasant taste after fish species are caught (Ahmed et al., 2023). Given that fish products have aromatic phenolic compounds, bioactive compounds such as catechins, caffeic acids, tannic acids, and ferulic acids can be improved by incorporating nanoforms of plant extracts or EOs into feeds.

As stated above, NPs provide a great opportunity todeliver nutraceuticals in aquaculture feed (Abdel-Ghany et al., 2023; Sharma et al., 2013). Incorporating a nano-feed formulation for fish species can enhance the bioavailability and bioaccessibility of nutrients. The nano-nutrients, provided by these formulations can penetrate fish cells more efficiently, intensifying nutrient absorption rates in their digestive tracts (Okeke et al., 2022).

These nanomaterials may incorporate a wide variety of additives, such as aromatic derivatives in vitamins. For example, Alishahi et al. (2011) demonstrated immune-inducing activity by feeding rainbow trout (*O. mykiss*) with vitamin C nano-encapsulated chitosan-based nanostructures. Therefore, vitamin-incorporated nanomaterials in feeds may enhance nutritional benefits and impact other physicochemical properties. Nanogels, solid NPs, and pickering emulsions in fish feed, could be used to encapsulate, deliver, and improve the distribution efficiency of bioactive compounds such as phenolics, EOs, and carotenoids (Kuebutornye et al., 2024; Okeke et al., 2022; Shah & Mraz, 2020). Additionally, liposomal nanovesicles and nanoemulsions, utilizing chitin/chitosan, could enhance the efficacy of EOs to carry flavoring agents, allowing for lower doses (Ahmed et al., 2024; Kuebutornye et al., 2024).

5. Nanocoating for chemical quality and odor improvement

Nanoencapsulation is a promising practice in the seafood industry for enhanced retention and controlled release of flavor and aroma (Saifullah et al., 2019). Nanofibers, NPs, and nanocapsules or nanoemulsions can delay chemical deterioration and preserve the aromatic components. By encapsulating active ingredients, nanoencapsulation reduces issues related to aroma and flavor, as well as the potential side effects of compounds used for production (Baldissera, Souza, Velho et al., 2020). Traditional food packaging is shifting toward active packaging, integrating nanoscience to produce materials with improved bioactive compounds. Active packaging layers for fish products maintain chemical stability and delay oxidation (Çetinkaya, 2022). As shown in Table 2, biodegradable polymer films or coatings are promising for delivering EOs, liquid smoke, aromatic extracts, and other aromatic compounds to fish meat.

EOs are natural volatile antioxidant compounds, generated by aromatic plants as secondary metabolites, characterized by their strong odor (Rossato Viana et al., 2023). For example, the use of coriander and garlic has been reported to remove fishy odor (Zhang & Zhong, 2020). Consequently, EO-containing nanoemulsions can help maintain both the odor and nutritional composition of fish. Aromatic EOs affect fish odor scores, when incorporating different nanoemulsion systems containing clove, thyme, peppermint, cinnamon, etc. (Zhang et al., 2023a).

Nanocapsules have been used as nanosized vehicles for the encapsulation of EOs. Nanocapsules have a vesicular shape with a central core surrounded by a polymeric membrane, onto which chemicals can dissolve or adsorb (Rezaei et al., 2019). The encapsulation of EO within nanocapsules is useful to reduce evaporation during storage and to allow controlled release (Montero et al., 2019). Researchers have explored the incorporation of aroma-containing compounds into nanocomposites, nanofilms, and nanocomplex materials to improve the odor and chemical properties of fish products (Saloko et al., 2016). Notably, nano-encapsulated liquid smoke has demonstrated increased bio-preservative activity and the potential to enhance sensory acceptability in smoked products. For instance, nanocapsules created by the encapsulation of the liquid smoke from coconut shells were created under low oxygen conditions with chitosan and maltodextrin and effectively preserved tuna fish at room temperature (Saloko et al., 2014). Swastawati et al. (2018) stated that liquid smoke nanocapsules improved sensory scores in milkfish meatballs (*C. chanos*) and inhibited oxidation in catfish fillets (*Pangasius* sp.) as determined by PV and TBA tests (Swastawati et al., 2019a). In another study, the same group reported that liquid smoke-incorporated nanocapsules can inhibit lipid oxidation by trapping acid compounds and can be absorbed into the tissues of catfish (Swastawati et al., 2019b). In another study, Navarro-Segura et al. (2019) nano-encapsulated bergamot, carvacrol, and grapefruit EO in β-CDs to evaluate the effect on sea bream. The results of

TMAN and odorindicated that seabream stunning/slaughtering and storage using EO/β-CD ice improved chemical quality and sensorial acceptability. In particular, the TMAN values showed significant differences after 17 days of storage.

A nanocomposite is a material with at least one dimension in the nanometer range, consisting of a polymer matrices supplemented with nanofillers (Arfat et al., 2015; de Moura et al., 2008). Alboofetileh et al. (2016) investigated the effect of alginate/EO-based nanocomposites on rainbow trout. The acceptable limit for TVBN values increased by 3 days. Heydari-Majd et al. (2019) developed a PLA-based nanocomposite film enriched with ZnO NP/EO. The tiger tooth croaker fillets wrapped in PLA/ZnO+EO films exhibited reduced lipid oxidation compared to those covered with neat PLA films, with the lowest TVBN values, demonstrating the antioxidant activity of the EOs. Soy protein and montmorillonite-based films demonstrated noticeable antioxidant properties when combined with clove EO. Montmorillonite appeared to facilitate the release of active EO compounds (Echeverra et al., 2016). Echeverra et al. (2018) reported lower TBARS values in bluefin tuna meat wrapped with soy proteins-montmorillonite+clove EO compared to soy proteins-montmorillonite alone, indicating the lipid autoxidation-reducing capacity of clove EO.

Nanofibers, defined as ig-shaped structures (<1 μ in size), are produced by electrospinning with a high voltage at ambient temperature (Feng et al., 2017). These nanomaterials are promising for the controlled release of encapsulated aroma compounds obtained from plant EO or extracts (Rezaei et al., 2019). Coating fish products with nanofibers containing various aromatic compounds has improved their odor scores (Table 2).

It has been reported that nanofibers can also be used to adjust the perception of salty taste in fish. Hsueh et al. (2017) discovered that increasing the concentration of chitosan in nanofibers improves the salty taste of tilapia fillets without altering the NaCl content. Additionally, chitin nanofibers supplemented with appropriate concentrations of citric or malic acid increased the perception of saltiness in cured tilapia fillets, which can contribute to the development of reduced-salt fish products.

NPs are sub-micrometer-sized solid carriers, with a size range of 1 to 1000 nm, and are in the form of nanospheres that could be produced by electrospraying or chemical methods (Cetinkaya et al., 2024; Rezaei et al., 2019). Nanospheres are particles that encapsulate aroma compounds within the matrix or absorb them at their surface (Ahmed et al., 2019). NPs offer several advantages over microparticles, for example, they create a more stable system because of their reduced tendency for particle aggregation or gravitational separation. This stability is especially crucial in the case of emulsification encapsulation. Very small NPs scatter light weakly, resulting in a transparent or less turbid appearance. Consequently, nano-encapsulated flavor and fragrance ingredients are ideal for use in fish species (Saifullah et al., 2019).

Fishy odors can arise with lipid autoxidation, enzyme reactions, degradation of TMAO, and Strecker degradation during transportation, storage, and processing (Dai et al., 2024). Hydrolysis and glycolysis of sugars also occur, and their main derivatives are organic acids and alcohols, which are responsible for off-odors of fish (Liu et al., 2023). Aromatic compound-reinforced NPs are generally applied to seafood to mask undesirable odors or flavors, mitigate chemical interactions and control release. To further improve the odor properties and maintain the chemical quality of fish products, a combination of nanomaterials can be an alternative way (Rezaei et al., 2019). New nanoscale materials can be developed by incorporating capsules or NPs into nanoemulsions (Esquerdo et al., 2015; Mehraie et al., 2023), by reinforcing the nanocomposite with nanofibers (Gopi et al., 2019), and incorporating aromatic compounds such as curcumin in NPs (Xiao et al., 2021). Pretreatment, such as ultrasound, can also be applied to nanomaterials to reduce bitterness or the formation of unpleasant volatile compounds (Wang et al., 2022).

When all of these studies are evaluated together, nanomaterials enriched with various aromatic bioactive agents could effectively slow chemical deterioration and preserve the organoleptic properties of raw or cooked fish during the storage process by taking advantage of the larger contact area feature.

6. Conclusions and future aspects

Nanomaterials and their combinations hold promise for the protecting of aroma compounds and flavor substances, and the controlled delivery of them. Nanoencapsulation of fish-based raw materials could enhance the organoleptic properties of finished dietary supplements. Additionally, this technique can prevent fish flavor substances from being affected in plant or microalgae-based matrices, whch leads to improved stability of feed materials. Therefore, chemical interactions between acids such as tannic acid, microalgae-based carrier material, and flavor substances should also be investigated.

Enzyme-or probiotic/postbiotic-containing nanomaterials could be promising for improving odor properties. The nanocoating of fish with EOs limits deterioration by slowing oxidation and upholding the flavor of fish, resulting in an improved odor quality. Immersing in nanoemulsions or applying nanofiber coatings with appropriate biopolymers may even help arrange salty, bitter, and sour tastes in the mouth.

Dealing with fish odor during cooking or frying is quite challenging. Consumers often try to reduce the smell of fish by using additives such as daphne, cinnamon, and vanilla when frying fish with oil, but some residual smell still remains. Industrial nanoemulsion, nanoliposome, or

Table 1
Nano-feeding materials that contain aroma compounds and their effects on nile Tilapia fish (*O. niloticus*).

Feed Nanocarrier Material	Key Findings	Refs.
Quercetin loaded chitosan NP feeds (12 weeks feeding trial)	NPs had the potential to improve quality as reflected by alterations on meat fatty acid profiles and antioxidant activity	Ibrahim et al. (2021)
Feed that contained 0.5 and 1 mL of nanoencapsulated nerolidol/Kg	Significant reduction in reactive oxygen species and lipid peroxidation levels at 1.0 mL Nerolidol. Nanospheres (133 nm) suggested a lower free radical content and reduced lipid damage	Baldissera et al. (2020c)
Nerolidol	Nanoencapsulation of nerolidol reduced free radical production and lipid damage	Baldissera et al. (2020a)
Curcumin loaded liposome NPs at levels of 35 mg/kg	Inclusion of NPs at higher concentrations reduced the malondialdehyde contents. DPPH scavenging ability was increased	Alhawas et al. (2023)
Nano-curcumin supplements under chronic low temperatures	Antioxidant responses	El Basuini et al. (2024)
Vitamin C—Nano-selenium	Catalase, superoxide dismutase, glutathione peroxidase, glutathione S-transferase antioxidant assays improved. Oxidative stress reduced	Rathore et al. (2023)
Se-NPs and *Citrullus colocynthis* extract	Enhanced antioxidant status, biochemical indices, serum lysozymes and respiratory burst. Positive effects on antioxidant enzymes	Ayoub et al. (2021)
Vitamin C—Nano-selenium	Nitro-blue tetrazolium level, superoxide dismutase, glutathione peroxidase, catalase, the phagocytic index, and lysozyme and phagocytic activities increased. Positive effects on antioxidant status	Dawood et al. (2020)
Nelumbo nucifera synthesized selenium NPs	Oxidative stress, hydogyene peroxide, malondialdehyde levels reduced	Ibrahim et al. (2024)

Table 2
Nano-delivery systems containing aromatic compounds and their effects on the sensory and/or chemical quality of fish products.

Fish Product and Storage Conditions	Nano-delivery system	Aromatic compound	Effects on sensory and/or chemical quality*	Literature
Rainbow trout at +4 °C for 16 days packed in polyethylene bags	Chitosan, 1 % sterile glacial acetic acid + *Ferulago angulata* EO and tween-80 as an immersing solution	Ferulago angulata EO nanoemulsion 1, 2, and 3 %	TVBN↓ TBARS↓ Acceptable odor scores even after 16 days	Shokri et al. (2020)
Rainbow trout fillets packed in sterile stomacher bags at +4 ºC for 14 days	ZnO NPs (0.2 and 0.4 %) added edible coating composed of chitosan as an immersing solution	*Mentha spicata* EO (0.2 and 0.4 %)	TVBN↓ TBARS↓ pV↓ Sensory attributes↑	Shahbazi and Shavisi (2018a)
Raw trout fillets +4 ºC for 13 days	Sodium caseinate-gelatin nanofiber mats encapsulated with EO and MgO (0 and 0.1%) NPs	*Mentha spicata* L. EO (0, 0.5, and 1 %)	TVBN↓ TBARS↓ Odor scores↑	Eghbalian et al. (2021)
Raw common carp in polyethylene bags at 4 °C for 12 days	Nanocomposite wrapping films based on carboxymethyl cellulose, myrrh gum, TiO_2 NPs and EO	Dill EO	TVBN↓ TBA↓ Odor scores↑	Eshaghi et al. (2024
Rainbow trout at +4 °C for 21 days	Whey protein coating containing nanoliposome	Dill (*Anethum graveolens* L.) EO	TVBN↓ TBARS↓ pH↓ Off-odor↓	Azizi et al. (2024)
Raw Huso huso fillets at 0–4 °C for 27 days in packaging system (80 % CO_2, 19 % N_2, 1 % O)	Chitosan NP (1 % and 1.5 %) prepared with acetic acid (1 % v/v) as an immersing solution	Fennel (*Foeniculum vulgare* L.) EOs (1 %v/v)	TVBN↓ TBA↓ PV↓ Acceptable odor scores until 18th day	Maghami et al. (2019)
Rainbow trout in polyethylene packs at +4 °C for 16 days	Nanocoatings of basil seed gum, *Lepidium perfoliatum* and their combination (1:1 ratio)	*Bunium persicum* EO (1 %, 1.5 %, and 2% w/v)	TVBN↓ TBA↓ PV↓ pH↓	Sayyari et al. (2021)
Rainbow trout in stomacher bags at +4 °C for 15 days	Gamma irradiated basil seed mucilage-chitosan films containing EO and MgO (0, 0.1, and 0.2 %) NPs	*Ziziphora clinopodioides* EO (0, 1, and 2 %)	TVBN↓ pV↓ Odor and overall acceptability scores↑	Naeeji et al. (2020)
Sauced silver carp (immersed in marinade) fillets at +4 °C for 14 days in sterile polyethylene bags	Alginate, carboxy methyl cellulose, ZnO NP (0 and 0.5 %), by direct addition to traditional sauce, solution immersing, or composite film coating	*Ziziphora clinopodioides* EO (0 and 0.5 %), apple peel extract (0 and 1 %)	TVBN↓ TMA↓ pH↓ PV↓ Odor and overall acceptability scores↑	Rezaei and Shahbazi (2018)
Raw Sea Bass fillet at +4 °C for 15 days packed into aseptic bags	Carboxymethyl chitosan/ locust bean gum nanoemulsions as an immersing solution	*Melissa officinalis* L. EO (2 %)	TBARS↓ Protein oxidation↓ sulfhydryl and carbonly contents↓	Xie et al. (2023)
Sea Bass stored at +4 °C for 15 days in polyethylene bags	Carboxymethyl chitosan-locust bean gum supplemented with nanoemulsion as soaking solution	*Melissa officinalis* L. EO nanoemulsion at 0.5 %, 1 % and 2 %	TMA↓ TVBN↓ pH↓PV↓ free amino acid↓ hypoxanthine↓ hypoxanthine riboside↓ Off-flavor compounds↓	Yu et al. (2023)
Raw salmon fillet at +4 °C for 8 days in glass plate	Xanthan gum+soy lecithin and cholesterol based nanoliposomes as an immersing solution	*Litsea cubeba* EO	TVBN↓ pH↓ Fatty acid oxidation↓	Cui et al. (2022)
Grass carp fillets in ziplock bags at +4 °C for 8 days	Tween, co-surfactants, EO based nanoemulsions	*Litsea cubeba*/oregano (4:6) EOs	TVBN↓ pH↓ TBA↓	Yang et al. (2024)
Beluga sturgeon fillet at +4 °C for 15 days	Nanoemulsions from jujube gum (4, 8, and 12 %) and EOs as edible coatings	Nettle EOs (2, 3.5, and 5 %)	TVBN↓ TBA↓ PV↓ FFA↓	Gharibzahedi and Mohammadnabi (2017)
Tiger tooth croaker fillet placed into sterile petri dishes at +4 ºC for 16 days	PLA containing ZnO NPs (1.5% w/w)	*Zataria multiflora* Boiss. and *Menthe piperita* L. EOs (0.5, 1, 1.5% w/w)	TVBN↓ Lipid peroxidation↓	Heydari-Majd et al. (2019)
Rainbow trout in polyethylene bags at +4 ºC for 15 days	Sunflower oil-based nanoemulsion EO	*Zataria multiflora* Boiss. (0.5 and 1 %) EO	TVBN↓ TBA↓ FFA↓ Odor scores↑	Shadman et al. (2017)
Asian sea bass in polyethylene bags at +4 ºC for 16 days	Chitosan-based nanocomposite containing ZnO (5 % of dry chitosan) NPs and EO	*Zataria multiflora* EO	TVBN↓ TBARS↓ FFA↓	Mosavinia et al. (2022)
Starry sturgeon fillet at +4 and +10 °C for 14 days in glass plate	Tween 80, tween 20, span 80 based nanoemulsions as a floating solution	Rosemary, Zataria, and Cuminum EOs at 3 % and 5 %	TBARS↓ PV↓	Nasiri et al. (2020)
Rainbow trout at +2 °C for 24 days in styrofoam box	Nanoemulsions as immersing solutions	Rosemary, laurel, thyme and sage EOs	TVBN↓ TBA↓ pH↓ FFA↓ PV↓	Ozogul et al. (2017)
Silver carp at +4 ºC for 16 days	Chitosan, nanoclay, Tween 80, EO mixture as an immersing solution	Rosemary EO (1.5 % v/v)	Lipid oxidation↓ Odor scores↑	Abdollahi et al. (2014)
Red sea bream fillet at +4 °C for 16 days Red sea bream fillet at +4 °C for 14 days	Nanocomposite films based on chitosan NPs containing EO nanoemulsion as a wrapping Chitosan NPs (3 %, w/v), collagen (3 %, w/v) and anthocyanidin (0.4 %, w/v) nanocomposite with EO nanoemulsion as a wrapping	Cinnamon-perilla EO Cinnamon-perilla EOs (0–3 %)	TVBN↓ TBA↓ Odor scores↑ TVBN↓	Zhao et al. (2022a, 2022b)
Asian seabass fillet in polyethylene bags at +4 ºC for 8 days	Medium-chain triglyceride oil based nanoemulsion as a dipping solution	Cinnamon bark oil	Cinnamon oil-like odour scores↑ Major volatile amounts↓ Lipid oxidation↓	Chuesiang et al. (2023)
Rainbow trout in polyethylene packs for 28 days at 4 °C	Nanocoating of basil seed gum, *Lepidium perfoliatum*, and their combination	Fennel EO oil (1–2 % w/v)	TVBN↓ TBA↓ PV↓ pH↓	Sayyari et al. (2021b)
Minced rainbow trout at +4 °C for 12 days packed and encoded in polyethylene bags	S. aegyptiaca (10% w/w), Tween 80 (2% w/w) and water (88% w/w) nanoemulsion	Kakol (*Suaeda aegyptiaca*) EO	TVBN↓ TBARS↓ PV↓	Zibaee and Shamekhi (2023)
Rainbow trout in ice for 12 days	Laurel oil+2 % ethanol+2 % Tween 80	Laurel EOs (1 and 2 %)	TVBN↓ pH↓	Sharma et al. (2023)
Rainbow trout enclosed with polyethylene films at +4 ºC for 14 days	Whey protein nanofibrils and mung bean protein NPs reinforced with EO	Hemp (*Cannabis sativa* L.) EO	TVBN↓ TBA↓ PV↓	Majidiyan et al. (2022)

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Table 2 (*continued*)

Fish Product and Storage Conditions	Nano-delivery system	Aromatic compound	Effects on sensory and/or chemical quality*	Literature
Golden pompfret fillet at +4 °C for 15 days in sterile polyethylene bags	Fish gelatin chitosan-based films with EO as a wrapping material	α-tocopherol/thyme (*Thymus vulgaris)* nanoemulsified EO	TVBN↓ Putrescine, tyramine, hypoxanthine, hypoxanthine riboside production↓	Liu et al. (2023)
Silvery pomfret +4 °C for 16 days packed in air-proof polyethylene pouches	Chitosan	Citrus EO	TVBN↓ TBARS↓ Odor scores↑	Wu et al. (2016)
Fried common carp burger for 18 days of refrigerated storage	Chitosan: modified starch-based EO nanocapsules added to minced meat	Lemon EO	PV↓ TVBN↓ FFA↓ Odor scores↑	Hasani et al. (2019)
Rainbow trout on styrofoamplates covered with plastic wrap at +4 °C for 15 days	4 % EO, 3 % ethanol, and 3 % Tween 80 based nanoemulsion as a dipping solution	Orange, lemon, mandarin, grapefruit EOs	Putrescine, cadaverine, spermidine, and spermine↓	Kosker (2020)
Rainbow trout in petri dishes at +4 °C for 15 days	Nanochitosan with EO, nanochitosan with nanliposomes of EO	Golpar (*Heracleum persicum* L.) EO	TBARS↓ PV↓ Off-odor delayed until 15th day	Abdollahzadeh et al. (2023)
Atlantic salmon 15 days, European seabass 16 days, Nile tilapia 18 days, and Rainbow trout fishes stunned with crushed ice at −0.2 °C	β-cyclodextrins containing nanocapsules applied as anesthetic in the stunning bath	Clove EO nanocapsules	Odor scores↑ Shelf life ↑ by five, six, six, and eight days for Atlantic salmon, Nile tilapia, European seabass, and Rainbow trout, respectively	López-Cánovas et al. (2020)
Raw Gilthead seabream stored on ice	β-cyclodextrins	Clove, carvacrol, bergamot and grapefruit oils	Shelf-life ↑ by 4 days, TMAN↓	Navarro-Segura et al. (2019)
Grey mullet fish steaks +4 °C for 24 days	Nanochitosan+oil	Clove oil	TVBN↓TBA↓ pH↓ PV↓ Odor scores↑	Aref et al. (2022)
Chilled Norwegian salmon cut at +4 °C for 12 days in cling film	WPI-tannin acid conjugated NPs in pickering W/O/W nanoemulsion co-encapsulating lysozyme as a soaking solution	Perilla leaf oil	TVBN↓ pH↓	Wang et al. (2024)
Sea bass at +4 °C for 9 days in polystyrene styrofoam plates, wrapped with cling film	Roseship seed oil 25 %+oil Tween 80 75 % nanoemulisons as an immersing solution	Roseship seed oil	TVBN↓ pH↓	Çorapci (2022)
Chilled flathead mullet fillets at +2 °C for 14 days	Deinized water, plant EO, ethanol, Tween 80 as an immersing solution	Grape seed and cinnamon nanoemulsions	Raw: TVBN↓TBARS↓ FFA↓ PV↓, Odor scores↑ 2 min 600 W microwave cooked: Odor scores↑	Ameur et al. (2022)
Rainbow trout burgers in polyethylene film stored at 4 °C for 12 days	Alginate coating combined with free and nano-encapsulated EO	*Carum copticum* in free form (0.5 %) and encapsulated form (5 %)	TBA↓ pH↓ Antioxidant activity↑	Hashemi et al. (2023)
Cooked salmon at +3 °C for 43 days in pouches under vacuum	Coating with PVA (10 %) nanofibers containing black seed and black seed+curcumin then sous vide cooking	Black seed oil and curcumin	TBA↓ Flavor and odor scores↑	Ceylan et al. (2022)
Cooked golden pomfret fish sausage +4 °C for 16 days	Canola oil, Tocopherol, Tween 80 nanoemulsion	Canola oil	pH↓ PV↓ FFA↓	Feng et al. (2020)
Cooked mackarel at +4 °C for 11 days in polyethlyne packs	Maltodextrin containing nanoemulsion dropping to the surface of fillets, then oven-baking	Wheat germ oil (3.63 %)	TBARS↓ FFA↓ PV↓ Odor scores↑	Ceylan et al. (2020)
Rainbow trout fillet in sterile polyethylene bags at +4 °C for 12 days	Gelatin-chitosan edible coating containing Brazamble EO nanoemulsion as an immersing solution	*Perovskiaabrotanoides Kar.* EO (1 %)	TVBN↓ pH↓ Peroxide index↓ Sensory scores↑	Ahmadi and Mohsenzadeh (2023)
Beluga sturgeon fillet inoculated with *Listeria monocytogenes* at +4 °C for 16 days	Chitosan nanocomposite	Rosemary (*Rosmarinus officinalis* L.) extract	TVBN↓ TBARS↓ PV↓ Lipid oxidation↓	Jafari et al. (2017)
Raw rainbow trout fillet at +4 °C for 12 days in sterile bags	Chitosan-ZnO nanocomposite	Pomegranate peel extract (0.5 %, 1 %, and 1.5 %)	Odor scores↑	Shahbazi and Shavisi (2018b)
Washed raw silver carp meat at +4 °C for 12 days	Glycerol+chitosan NP solution immersing	Orange (*C. sinensis*) and pomegranate (*P. granatum*) peel extract powders (1% w/v)	TVBN↓ TBARS↓ pH↓ Sensory scores↑	Zarei et al. (2015)
Rainbow trout in polyethylene bags at +4 °C for 6 days	Solution containing extract microcapsules and quince seed mucilage-based chitosan nanofiber (6% w/w)	Orange peel extract	TVBN↓ TBA↓ la Odor scores↑	Sarmadikia et al. (2022)
Salmon at +4 °C for 9 days	Polypropylene nanocomposites containing 4A zeolite, ZnO (3–6 %) NPs	Green tea extract	PV↓ TBA↓ pH↓ Odor scores↑	Azizi-Lalabadi et al. (2020)
African catfish in polyethylene bags at +4 °C for 25 days	Selenium NPs (2 %, w/v)	*Lepidium sativum* seed mucilage extract	TVBN↓ TBARS↓ pH↓	Shehab et al. (2022)
Rainbow trout fillets at +4 °C for 15 days in polyethlene bags	Maltodextrin/whey-protein concentrates-based coating nanomaterials as a soaking solution	Saffron (*Crocus sativus* L.) petal extract (10% w/v)	TVBN↓ TBARS↓ Odor scores↑	Khalili et al. (2021)
Raw sea bass fillet at +2 °C for 9 days in bags	Zein nanofiber with aluminum foil as a wrapping	Saffron *(Crocus sativus* L.*)* extract (5 % and 10% w/w)	TVBN↓ pH↓ PV↓ FFA↓	Najafi et al. (2022)
Smoked salmon at +4 °C for 8 days	Extract films containing ZnO (1 %, 3 %, 5 %) NPs	*Gracilaria vermiculophylla* extract	TBARS↓ PV↓	Baek and Song (2018)
Nile tilapia slices in bags at +4 °C for 15 days	PLA film coated with gelatin/chitosan nanofiber	Betel leaf extract	TVBN↓ TBARS↓ pH↓ PV↓	Tagrida et al. (2022)
Raw rainbow trout fillet at +4 °C for 15 days in polyethylene bags	Glycerol+WPI dipping solutions and/or poly (ε-caprolactone) nanofibers coating	Stinging nettle *(Urtica dioica* L.*)* extract (60 % in nanofiber)	TVBN↓ TBA↓ pH↓	Erbay et al. (2017)

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Table 2 (*continued*)

Fish Product and Storage Conditions	Nano-delivery system	Aromatic compound	Effects on sensory and/or chemical quality*	Literature
Raw rainbow trout fillet at +4 °C for 12 days in low-density polyethylene bag	Polycaprolactone nanofibers as a wrapping	Ganoderma lucidum powder extract (1, 2, 4, 8 %)	TVBN↓ TBARS↓ pH↓ PV↓ Oxidative stability↑	Nabati et al. (2023)
Washed and minced kilka at +4 °C for 16 days in freezer bags	NPs incorporated maltodextrin, carrageenan, gelatin mixed	Acorn fruit (*Quercus persica)* extract NPs (0.5 % and 1 %)	TVBN↓ TBARS↓ FFA↓ PV↓	Rabiee et al. (2020)
Raw rainbow fillet at +4 °C for 15 days in vacuum package	Chitosan nanocoating	Green cumin (*C. cyminum*) extracts	TVBN↓ TBA↓ PV↓ Sensory scores↑	Zamani et al. (2022)
Raw rainbow trout fillets frozen for 6 months and refrigerated for 12 days packed in sterile stomacher bags	Curcumin NPs (0, 0.1 and 0.2 %) incorporated glycerol+sodium alginate-based coating solution immersing	*Prosopis farcta* extract (0 and 0.5 %)	TVBN, TBARS, PV, TMA, protein carbonyl content changes↓	Zhaleh et al. (2019)
Rainbow trout at +4 °C for 14 days	Chitosan-zein nanoliposomes as an immersing solution	*Pulicaria gnaphalodes (Vent.) Boiss*. extract	TBA↓ PV↓ Odor scores↑	Mehdizadeh et al. (2021)
Raw Pike-perch fillet at +4 °C for 14 days sealed in sterile petri dishes	Chitosan NP prepared with acetic acid (1 % v/v) as an immersing solution	Spirulina extract (0, 25, 50, 75, 100% w/w with respect to chitosan)	TVBN↓ TBA↓ pH↓ Odor and overall acceptability scores↑	Karimzadeh et al. (2022)
Aseptic washed rainbow trout fillet at +4 °C for 12 days in low-density polyethylene bags	Electrosprayed zein NPs on the substrate of nanofibers (Zein/PVA) as a wrapping	Resveratrol (2% w/w, with respect to zein) Thymoquinone (4% w/w concerning Zein/PVA)	TVBN↓ TBARS↓ FFA↓ PV↓ Decrease in sensory attributes was slower, overall acceptability score>4 on final day	Ahmadi et al. (2024)
Salmon slices sealed and stored at 4 °C for 20 days	Polycaprolactone coaxial electrospinning film	Linalool	TVBN↓ TBARS↓ Hardness decreased more slowly	Li et al. (2022)
Washed hairtail at +4 °C for 18 days and sealed after totally immersing	0.5 % chitosan-acetic acid solution and 1 wt/v% Tween 20+eugenol+ 0.1 vol% sodium tripolyphosphate as an immersing solution	Eugenol (100 % based on chitosan)	TVBN↓ TBA↓ pH↓ Lipid and protein oxidation↓	Liu et al. (2021)
Rainbow trout in a polyethylene terephthalate container at +4 °C for 16 days	Nano-gelatin coating containing thymol and nisin	Thymol	TBARS↓ PV↓ FFA↓	Hashemi et al. (2022)
Salmon fillet at +4 °C for 15 days	Nisin based double-emulsion-incorporated chitosan film as a dipping solution	Carvacrol in $W_1/O/W_2$ emulsion	TVBN↓ TBARS↓ pH↓	Yuan et al. (2022)
Rainbow trout fillet wrapped ans stored at +4 °C for 16 days	Cinnamaldehyde-loaded chitosan NPs doped into PVA/fish gelatin nanocomposite films	Cinnamaldehyde	TBARS↓ pH↓	Hosseini et al. (2022)
Mandarin fish at +4 °C for 7 days	Anthocyanin and cinnamaldehyde in NP-filled carrageenan films	Cinnamaldehyde	TVBN↓	Zhou et al. (2024)
Grass carp at +4 °C for 8 days	Chitosan/alginate dialdehyde trilayer films with cinnamaldehyde nanoemulsions	Cinnamaldehyde 2, 4, 6, 8, and 10 %	TVBN↓ TBARS↓ pH↓	Dong et al. (2024)
Dry-salted liquid-smoked salmon vacuum-packed and stored at 4 °C up to 49 days	Nanoemulsion containing enterocin Gr17 and EO	Cinnamaldehyde EO	TVBN↓ TBARS↓ Odor scores↑	Duan et al. (2023)
Washed grass carp fillet at +4 °C for 10 days packaged with polyethylene and composite films	Zein solution added chitosan/NP bilayer film packing	Curcumin/nisin-loaded pectin-based NPs	TVBN↓ TBARS↓ pH↓ Lipid oxidation retarded Off-odor released 4 days later than control	Zhang et al. (2023b)
Ya-fish fillet at +4 °C for 15 days in acrylic plates or in polyethylene	Chitosan/curcumin NPs based zein and potato starch composite films as a wrapping	Curcumin	TVBN↓TBARS↓ Odor scores↑	Xin et al. (2020)
Minced rainbow trout fillet at +4 °C for 10 days in nylon bags	Curcumin+Span 80 and Tween 80 nanoemulsion mixing	Curcumin (0 %, 1 %, 3 %, and 5 % (w/w with respect to meat)	TVBN↓ pH↓ FFA↓ Odor scores↑	Khoshbouy Lahidjani et al. (2020)
Small yellow croaker at +4 °C for 8 days	Curcumin-loaded nano-silica material and its aqueous solution	Curcumin	TVBN↓ pH↓ Odor scores↑	Jiao et al. (2024)
Asian sea bass at 25–28 °C for 30 days in pouches bilayer films	Chitosan-fish gelatin-based nanofibers containing epigallocatechin gallate deposited over the PLA film	Epigallocatechin gallate (2% w/w)	PV↓ TBARS↓ Conjugeted diens↓ Volatile compounds↓	Ponnusamy et al. (2024)
Tuna stored at +4 °C for 12 days in low-density polyethylene bag	Zein/gelatin nanofibers loaded with ε-polylysine	Gallic acid	TVBN↓ Oxidative stability↑	Li et al. (2024)
Salmon fillets +4 °C for 15 days packed in homogeneous bags	Nanocomplexes film composed of gallic acid loaded ovalbumin/chitosan NPs and pectin as a soaking solution	Gallic acid	TVBN↓ pH↓ Biogenic amine↓ histamine↓	Liu et al. (2024b)
Rainbow trout at 4 °C for 18 days packaged under a modified atmosphere (40 % CO_2+30 % O_2+30 % N_2)	Chitosan+TiO_2+rosmarinic acid nanocomposite films	Rosmarinic acid	TVBN↓ TBARS↓ pH↓	Kizilkaya and Kaya (2023)
Minced tuna fish at ambient temperature for 48 h	9.5 % Maltodextrin, chitosan, acetic acid 1 % based nanocapsules containing liquid smoke from coconut shell	Liquid smoke (0 %; 2.5 %; 5.0 %; 7.5 % and 10% w/w)	TVBN↓	Saloko et al. (2014)
Catfish fillet Catfish at +4 °C for 12 days	Corncob and coconut shell, maltodextrin, gum arabic, Na-alginate Maltodextrin, Arabic gum	Liquid smoke	TVBN↓ Lipid oxidation↓	Swastawati et al. (2019a, 2019b)
Milkfish meatballs at +4 °C for 12 days	–	Powder liquid smoke (0 %, 1 %, 3 % and 5 %)	Odor scores↑	Swastawati et al. (2018)

* The upside arrows indicate the increase; downward arrows indicate reduction in parameter.

nanogel formulations could be applied to avoid unwanted odor release during frying or baking. It is essential to explore functional nanomaterials that release aroma when fish products are fried or baked. It is necessary to study the impact of air fryer cooking, boiling, grilling, microwave cooking, and sous vide cooking on nanocoated fish flavor/aroma.

Looking ahead, the development of nano-formulation methods based on fish analogs to mimic the taste of fish, will likely become important. However, the development of vegan seafood is still in its infancy.

Investigating the effects of biobased nanocoating materials on the changes in flavor and flavor precursors of fish products before and after cooking is required, to improve our understanding of aroma compound interactions. In this way, new nanomaterial-based approaches and methods will lead to the development of functional nanocoating systems containing aroma compounds with antioxidant properties and adjust the perception of taste for consumers.

CRediT authorship contribution statement

Turgay Cetinkaya: Writing – original draft, Writing – review & editing, Investigation, Conceptualization. **Mehmet Turan Ayseli:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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