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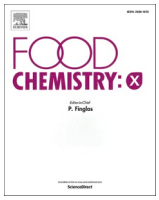

Enhancing the lipid stability of foods of animal origin using edible packaging systems

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ABSTRACT

Foods of animal origin are prone to oxidation due to their high lipid content and fatty acid profile. Edible packaging systems have evolved as a new way of preserving animal-derived foods and have been reported to retard lipid oxidation using antioxidant molecules from side-streams, waste, and agricultural by-products. Studies have evaluated previously undocumented film materials and novel bioactive molecules as additives for edible packaging for animal-derived foods. However, none of the studies is specifically focused on evaluating the packaging systems available for enhancing lipid stability. This paper thoroughly examines and discusses the application of edible packaging containing novel antioxidant molecules for controlling the lipid oxidation of animal-derived foods. The paper analyses and interprets the main findings of the recently published research papers. The materials and active principles used for enhancing lipid stability have been summarised and the underlying mechanisms discussed in detail. Studies should aim at using cheaper and readily available natural ingredients in future for the production of affordable packaging systems.

Introduction

Foods of animal origin, such as seafood, fish, eggs, and meat, are generally rich in unsaturated fatty acids including PUFA (poly-unsaturated fatty acids) which renders them highly prone to oxidation and related off-flavour development (Bhat et al., 2021; Bhat, Morton, Bekhit, et al. 2021a, b). Oxidation of lipids is the main non-microbial cause that is responsible for the deterioration of foods of animal origin. This cascade process involves complex reactions which are influenced by different factors and pathways and produce rancidity and related off-flavours and odours which have a negative impact on the sensory attributes, nutritive value, and shelf life of fat-rich animal foods (Bhat et al., 2023). Free radicals, the intermediate product of lipid oxidation, and reactive aldehydes, the end products, can interact with other constituents of animal foods, such as pigments, sugars, vitamins, and proteins, and negatively affect their characteristics (Mozuraityte et al., 2016). Both enzymatic and non-enzymatic factors alter the rate and mechanisms of fat oxidation, such as the presence of prooxidants or antioxidants (e.g., ascorbic acid, nitrite, phenolic compounds, α-tocopherol, H_2O_2, heme/nonheme-iron, or salts), lipid/fatty acid composition (e.g., phospholipids, triacylglycerols, and others/saturated, unsaturated and polyunsaturated fatty acids), and storage conditions (e.g., light, temperature, oxygen availability, water activity, and packaging system). The oxidation of monounsaturated fatty acids and PUFA in animal food matrices results in the production of primary oxidation compounds of which hydroperoxides (tasteless, odourless, unstable and reactive) constitute the major product (Dua et al., 2015a). Further decomposition of lipid hydroperoxides produces secondary oxidation

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compounds mainly aldehydes such as hydroxylated α,β-unsaturated aldehydes [e.g. HNE {4-Hydroxy-2-(E)-Nonenal} and HHE {4-Hydroxy-2-(E)-Hexenal}] and malondialdehyde (MDA) which is the main aldehyde and whose concentration is commonly measured by TBARS (thiobarbituric acid reactive substances) assays to estimate the rate of oxidation of lipids in animal foods during storage (Bhat & Pathak, 2009; Zargar et al., 2017). Other secondary oxidation compounds are alcohols, ketones, esters, epoxides, hydroxy compounds, lactones, furans, oligomers, polymers, etc. Although it is not officially reported, the EFSA Scientific Committee (European Food Safety Authority) has propounded a maximum exposure limit of 1.5 μg/kg body weight/day for HNE and HHE and 30 μg/kg body weight/day for MDA for humans (Papastergiadis et al., 2014). The lipid stability of animal foods is generally determined using four commonly reported assays viz. TBARS [mg malondialdehyde (MDA)/kg, indicator of secondary oxidation products], free fatty acids (FFA, % oleic acid, indicator of microbial or enzymatic lipolysis), peroxide values (meq/kg, indicator of primary lipid oxidation) and conjugated dienes (% CD, indicator of primary lipid oxidation) (Ahmed et al., 2014; Kalem et al., 2017; Bhat, Morton, Bekhit, et al., 2021). Among these assays, the TBARS value is the most commonly used and highly reliable marker of fat oxidation in animal food matrices (Bhat & Pathak, 2012; Kaur et al., 2015). However, different studies have reported different threshold values for TBARS for the same food products and caution should be applied while comparing the values derived using different methods to avoid misinterpretation. While McKenna et al. (2005) considered TBARS levels higher than 1.0 as unacceptable for a fresh beef product, Campo et al. (2006) and Hughes et al. (2015) reported values greater than 2.28 and 2.60, respectively, as unacceptable to consumers. It is important to mention that each of these studies used unique methods to determine TBARS values indicating that the protocol selection can influence the interpretation. A large number of studies on meat and meat products using the protocol of Witte et al. (1970) or Tarladgis et al. (1960) have used a maximum permissible limit of 2.0 mg MDA/kg and 1.0 mg MDA/kg, respectively, to interpret their results. Johnson et al. (2015) reported a value of 1.3 mg MDA/l as the limiting sensory threshold for oxidized milk. A TBARS value of less than 3 mg MDA/kg with an upper limit of 7–8 mg MDA/kg has been reported for egg, fish and seafood products (Bekhit et al., 2022; Faitarone et al., 2016; Jo et al., 2022; Cadun et al., 2005). However, a large number of studies have reported that a value of up to 0.5 mg MDA/kg indicates a tolerable level of oxidation whereas a value above 1.0 mg MDA/kg is an index of oxidation (Warriss, 2000; Wood & Enser, 2017).

Due to the negative effect of lipid oxidation on food quality and human health (Bhat et al., 2019), food processors use different strategies to control it in animal foods during storage. These range from the traditional way of mixing antioxidants with food matrices during processing to packaging interventions, such as CAP (controlled atmosphere packaging), MAP (modified atmosphere packaging), and VP (vacuum packaging), and quite recently the application of bioactive edible packaging (for example coatings and films) (Noor et al., 2022). Numerous studies have reported bioactive coatings and films utilizing a wide array of biopolymers and bioactive ingredients that can efficiently retard the fat oxidation of animal foods during their shelf life. This paper examines the main findings of the recently published research papers (last 5 years) which have designed edible packaging systems for controlling lipid oxidation of various animal-derived foods such as eggs, seafood and fish, meat and meat products, and milk and dairy products. The materials and active principles used to augment the lipid stability of foods of animal origin have been summarised and the underlying mechanisms have been explicitly deliberated.

Milk and dairy products

The major results of various studies and the bioactive agents and materials evaluated for the production of edible-grade packaging for enhancing the lipid stability of dairy products, milk and eggs are presented in Table 1.

Cheese

A large number of research papers have reported the development of edible coatings and films using plant extracts with antioxidant phytochemicals to enhance the stability of lipids in stored cheese. For example, Kouser et al. (2023) prepared an edible film utilising 1 % powder of *A. vera* gel and carrageenan for *kalari*, a traditional cheese. The samples of *kalari* enclosed within the edible packaging manifested significantly lowered means for peroxide-values, TBARS, and FFA in comparison to the control *kalari* kept under refrigerated conditions for 4 weeks. This beneficial influence of the edible packaging on the lipid stability of the *kalari* during storage was credited to various antioxidant compounds present in the gel such as α-tocopherol, phenolic compounds, organic acids, carotenoids, ascorbic acid, and tannins. The incorporation of the gel markedly enhanced the antioxidant activities of the edible film as shown by significantly augmented total flavonoids and phenolics and radical scavenging activities (ABTS and DPPH) in comparison to the control film. In a much similar work, Kouser, Kumar, Bhat, Noor, et al. (2023) prepared a film using carrageenan containing extract (0.5 %) derived from the fruit of *Terminalia bellerica* as a bioactive additive to enhance the stability of lipids in stored *kalari* cheese. This extract contains large amounts of antioxidant phytochemicals, such as vitamin C, ellagitannins, and polyphenols, attributed to its antioxidant and radical scavenging properties. The inclusion of the extract enhanced the antioxidant potential of the film assessed in terms of flavonoids, phenolics, and radical scavenging properties (DPPH and ABTS) and significantly affected the lipid stability of the stored *kalari*. The cheese wrapped within the edible packaging exhibited significantly reduced peroxide values, TBARS, and FFA during the whole four-week trial compared to the control product.

Recently published research papers have investigated the utilization of several plant extracts and essential oils, such as *Moringa oleifera,* green tea, red cabbage, and cumin essential oil, to develop bioactive coatings and films for cheese. Robalo et al. (2022) prepared an edible packaging using whey protein as a base material loaded with extract (2.5 %) obtained from *Camellia sinensis* L. (Portuguese green tea) to enhance the lipid stability of fresh cheese [Latin-style from goat milk and mixture (sheep and goat milk)] during one week of storage (5 °C). The cheese (goat and mixture) packed within the edible packaging exhibited markedly reduced TBARS values (3.2 and 3.7 mg MDA/kg) after one week compared to the cheese wrapped within control films without any extract (4.2 mg MDA/kg and 4.4 mg MDA/kg, respectively). All the samples wrapped within the edible packaging exhibited TBARS values lower than 0.5 MDA/kg, the threshold limit to perceive the off flavours (Andrade et al., 2019). Mezhoudi et al. (2022) used extract from leaves (20, 10, and 5 μg/ml) of *Moringa oleifera* to prepare a film using gelatin as a base material to augment the lipid stability of ricotta cheese. The fresh cheese samples were packaged with the edible film [control (no extract) and extract-including (20 μg/ml)] and maintained for 6 days at 4 °C. The extract-including film significantly lowered the lipid oxidation of the ricotta cubes. Markedly lower means were recorded for TBARS for the treated ricotta in contrast to the unpacked ricotta cubes and the cubes packed within the control film. Veiga-Santos et al. (2022) prepared a corn-starch-based (5 %, w/w) coating utilizing extracts from jaboticaba (*Myrciaria cauliflora*, 0.0–6.2 %, w/w) and red cabbage stirs (*Brassica oleracea*, 0.0–4.0 %, w/w) for improving lipid stability of stored Minas Frescal cheese (9 days at 10 °C). The film exhibited a positive impact on lipid oxidation and significantly lowered values were recorded for the peroxide index for the treated cheese samples in comparison to control cheese without any coating. The film offered a maximum of 8.5 times more protection towards oxidation compared to the untreated cheese due to a synergistic reaction of the extracts. Esparvarini et al. (2022) developed wheat starch (5 %) and gelatin (10 %) based edible coatings incorporated with 0.5 % cumin EO and 3 %

Table 1
Edible coatings and films with different bioactive agents for enhancing the lipid stability of milk, dairy products and eggs.

Coating and film material	Bioactive ingredients	Storage conditions and product packaged	Major results	Citation
Cheese				
Glycerol as a plasticiser and carrageenan as a film material (1.5 % w/v)	*A. vera* gel powder (1 % w/v) was frozen-dried	The film was used to wrap the samples of *kalari,* a hard and dry cheese, and stored at 4 °C for 4 weeks	The incorporation of the gel significantly enhanced the antioxidant potential of the film. Stored samples packaged within the film showed significantly lower free fatty acids (%), TBARS (mg MDA/kg), and peroxide values (meq/kg)	Kouser, Kumar, Bhat, Hassoun, et al. (2023)
Glycerol (1:1 = protein: glycerol) and whey protein concentrate in H_2O (8 %, w/w protein)	Portuguese green tea (*Camellia sinensis* L.) extract (2.5 %, w/w)	Latin-style fresh cheese [goat and a mixture (goat and sheep milk)] was packaged within the films and kept for one week at 5 °C	The cheese samples (goat and mixture) wrapped with the bioactive packaging showed significantly reduced TBARS values (3.2 and 3.7 mg MDA/kg) after one week in comparison to the cheese wrapped within control films without any extract (4.2 and 4.4 mg MDA/kg, respectively)	Robalo et al. (2022)
Corn starch (5 %, w/w) and sucrose (1.4 %, w/w) as a plasticizing additive	Extracts of jaboticaba (*Myrciaria cauliflora,* 0.0–6.2 %, w/w) and red cabbage stirs (*Brassica oleracea,* 0.0–4.0 %, w/w)	The dipping method was followed to coat the *Minas Frescal* cheeses which were kept at 10 °C for 9 days	Significantly lower values were recorded for the peroxide index for the coated cheese in comparison to uncoated cheese. The film offered a maximum of 8.5 times more protection against oxidation in comparison to the uncoated samples	Veiga-Santos et al. (2022)
The glycerol (15 % v/v) was used as a plasticizer and the gelatin (3 % w/v) as film material that was obtained from co-products of grey triggerfish	The extract was developed from leaves of *Moringa oleifera* Lam. (20, 10, and 5 μg/ml) extracted using water, ethanol, and water/ethanol (1:1, v/v)	The fresh and traditional ricotta cheese samples were packed with the films and kept at 4 °C for 6 days	Significantly reduced values were observed for TBARS for the cheese wrapped with the extract-based film (20 μg/ml) after 6 days compared to the unwrapped samples and the samples wrapped with the control film	Mezhoudi et al. (2022)
The film was developed using 1.5 % (w/v) carrageenan	0.5 % (w/v) of the *T. bellerica* extract was used which was obtained from the fruit	The film was used to wrap *kalari* cheese and kept at 4 °C for 28 days	*T. bellerica* extract increased the antioxidant potential of the film significantly. *Kalari* packaged within the film exhibited significantly reduced TBARS, FFA and peroxide values	Kouser, Kumar, Bhat, Noor, et al. (2023)
The coating solution was developed using wheat starch (5 %), gelatin (10 %), and glycerol (10 %)	Cumin essential oil (0.5 %) and cucumber peel extract (3 %)	The solutions were used to coat ultrafiltered cheese slices by dipping method and stored at 4 °C for 56 days	Significantly lower TBARS values were recorded for the slices with a coating and the lowest values were found for the coated cheese with both the antioxidants	Esparvarini et al. (2022)
The coating solution was developed using glycerol (0.1–0.6 %, w/v) and residue from the pulp of *Ziziphus joazeiro* fruit (1 %, w/v)	The bioactive ingredient used was residue from the fruit pulp of *Z. joazeiro* (1 %, w/v)	The dipping method was followed to coat the *Coalho* cheese which was kept for 21 days at 4 °C	Significantly lower TBARS values were observed for coated samples on day 7 of storage in comparison to the uncoated cheese	Leandro et al. (2021)
10 ml of polyvinylalcohol (10 % w/v) was mixed with 0.5 ml of pomegranate seed oil and 0.1 ml of tween 20 and used for preparing nano-mats by electrospinning method	Pomegranate seed oil	*Karish* cheese samples were wrapped with nano-mats and stored for 20 days at 4 °C	In comparison to the uncoated samples, significantly reduced TBARS was recorded for the cheese with a coating during the whole 20 days of storage	Kutlu et al. (2022)
Frozen dairy products				
Three levels (1.0, 1.5 and 2.0 % w/v) of carrageenan were used	Three levels (9, 12, and 15 % w/v) of *Aloe vera* gel were used	An Indian ice cream known as kulfi was kept for 6 months at −18 °C	The film significantly reduced the TBARS, FFA and peroxide values of Indian ice cream during frozen storage for six months	Mahajan et al. (2022)
Three levels (1.0, 1.5 and 2.0 % w/v) of carrageenan were used	Three levels (9, 12, and 15 % w/v) of *Aloe vera* gel were used	An Indian ice cream known as kulfi was kept for 6 months at −18 °C	The film significantly improved the stability of lipids (TBARS and FFA) of samples during the entire storage time	Mahajan, Kumar, Bhat, Naqvi, Mungure, et al., (2021)
The film was developed using 1.5 % carrageenan	15 % of *Aloe vera* gel was used	Fig-enriched functional kulfi was kept for 6 months at −18 °C	The film significantly improved the lipid stability (in terms of TBARS, FFA and peroxide values) of the product during the entire storage time	Mahajan et al. (2021)
Other dairy products				
Furcellaran (2.5 g/400 ml H_2O) and glycerol (4 ml)	Protein hydrolysates from soyabean bran (5 g)	Butter samples (50 g) packaged within single and double-layered films were stored at room and refrigeration temperatures (4 and 25 °C) for 12 days	The film manifested no significant impact on the lipid oxidation of butter during the entire 12 days	Jamroz et al. (2022)
The films were developed using glycerol (3 %) and corn starch (5 %)	Bioactive agents used were natamycin (35 and 30 μg/ml of film solution) and nisin (7500,	*Doda burfi,* which is a popular Indian sweetmeat, was stored under MAP (CO_2 and N_2 =	The films significantly decreased the free fatty acid values of the product during storage. Both the films	Chawla et al. (2021)

(*continued on next page*)

Table 1 (*continued*)

Coating and film material	Bioactive ingredients	Storage conditions and product packaged	Major results	Citation
	5000, and 1000 IU/ml of film solution)	30:70) followed by refrigerated storage (4 ± 2 °C)	prolonged the shelf life of burfi to 42 days in comparison to control samples which stayed fresh for 21 days	
Egg and egg products				
Soy protein isolates [3 g of glycerol was mixed with 5 g of soy protein isolates and dissolved in 92 ml water], whey protein isolates [18 % aqueous solution of isolates was added to glycerol in a ratio of 2.5:1] and chitosan [2 % acetic acid solution was used to dissolve 1 % chitosan]	Chitosan, whey protein isolates and soy protein isolates	The coated boiled duck eggs were kept at 30 ± 2 °C for 15 days	The boiled eggs coated with whey protein isolates showed significantly lower TBARS values compared to uncoated eggs during the whole 15 days storage time	Venkatachalam et al. (2019)
Carboxymethyl cellulose (3 %) in an ethyl alcohol-water mixture (1:3 v/v) and 2 % propylene glycol (plasticizer)	Barnûf leaf extract (2, 4, and 6 %, w/w)	The coated eggs were stored for five weeks at 25 ± 2 °C	Significantly lower TBARS values (mg MDA/kg yolk) were observed for the eggs with a coating containing 6 % extract in comparison to the uncoated eggs	Elsebaie & Essa (2022)

extract from cucumber peel to enhance the lipid stability of ultrafiltered cheese kept in a refrigerator for 56 days. The coatings reduced the lipid oxidation of the slices of cheese significantly throughout 56 days' storage time. Markedly lower means were found for TBARS for the treated slices in comparison to the ones without any coating and the lowest values were found for the coatings with both the antioxidants (cumin EO and the peel extract).

Other published papers have documented a desirable influence of edible coatings and films on the lipid stability of the stored cheese, such as Leandro et al. (2021) found a favourable impact of a coating developed from the fruit pulp of *Ziziphus joazeiro* on the lipid oxidation (TBARS) of Coalho cheese during the first 7 days under refrigeration and Kutlu et al. (2022) documented a favourable impact of nanomats developed using polyvinylalcohol and pomegranate seed oil (encapsulated) on the lipid oxidation (TBARS) of *Karish* cheese kept in a refrigerator for 20 days.

Frozen dairy products

A small number of research papers have analysed the impact of bioactive and edible films on the lipid oxidation of frozen dairy products such as ice cream. Mahajan et al. (2022) prepared a film using carrageenan and improved its antioxidant properties using *Aloe vera* gel at different levels (9, 12, and 15 % w/v). The efficiency of the prepared film was examined using Indian ice cream, kulfi, as a model of study stored at −18 °C for six months. The film positively impacted the stability of lipids in ice cream assessed in terms of peroxide values, FFA, and TBARS. The kulfi packaged within the edible films manifested significantly lowered TBARS, FFA, and peroxide values on days 45, 90, 135, and 180. The lowest means were exhibited for 15 % gel for all these lipid stability parameters. This favourable effect of the packaging on lipid stability was credited to different antioxidant phytochemicals, such as vitamins E and C, carotenoids, and phenolic compounds, present in the gel (Hęś et al., 2019). The same research group further used the carrageenan film to enhance the stability of lipids in fig powder-enriched ice cream stored for six months at −18 °C (Mahajan et al., 2021). The enrichment of *A. vera* gel (15, 12, and 9 % w/v) significantly enhanced the phenolic compounds (mg GAE/100 g) of the film and the highest concentrations were found for the highest level of the gel (15 %). These results aligned with the results of lipid stability and markedly lower means were documented for FFA and TBARS for the ice cream packaged with the edible packaging. The lowest means were reported for the edible packaging prepared with 15 % gel on days 45, 90, 135, and 180. These findings indicated that the film enriched with 15 % *A. vera* gel showed optimum antioxidant properties and significantly enhanced the stability of lipids in stored ice cream. The same research group studied the characteristics (physicomechanical) of the optimum film (containing 15 % gel) and evaluated its efficacy using kulfi enriched with fig powder stored frozen for six months (Mahajan, Kumar, Bhat, Naqvi, & Jayawardena, 2021). As expected, the film significantly reduced the FFA, TBARS, and peroxide values of the kulfi during the entire time of six months. These parameters provide indispensable data with respect to the stability of lipids in the food matrices during storage. The lipolysis of neutral and polar lipids produces FFA whereas the oxidation of lipids, especially PUFA, increases TBARS and peroxides content during storage and are important indicators of lipid stability in animal products. These reactions are influenced by different factors including length of storage and the presence of packaging, moisture, ions (metallic), and enzymes (lipases).

Other dairy products

The edible grade packaging materials with bioactive properties have been developed to enhance the stability of lipids in stored milk products. An edible film was prepared by Chawla et al. (2021) utilizing corn starch to enhance the lipid stability and storage life of a composite dairy product of India namely *Doda burfi*. The bioactive properties of the edible packaging were enhanced using natamycin (35 and 30 μg/ml) and nisin (7500, 5000, and 1000 IU/ml) as bioactive agents. The *burfi* pieces were enveloped within the edible packaging and stored at 4 °C in a refrigerator. The films significantly increased the lipid stability of the *burfi* kept at refrigeration temperature compared to the unwrapped *burfi* samples. The mean FFA values increased from 0.60 μeq/g for all samples on the 0th day to 1.01 μeq/g for control samples on day 21. The mean FFA values of the treated burfi wrapped within the films loaded with nisin and natamycin rose to 1.08 and 1.15 μeq/g on day 42, respectively. The efficacy of both the bioactive agents was the same and equally controlled the lipolytic changes in the *burfi* during storage. Jamróz et al. (2022) developed a furcellaran (2.5 g/400 ml H_2O) based bioactive film containing protein hydrolysates from soybean bran (5 g) for improving the storage quality of butter. Single and double-layered films were developed and used for packaging butter samples (50 g) stored at room and refrigeration temperatures (4 and 25 °C) for 12 days. The butter was evaluated for lipid oxidation (TBARS, peroxide and acid values) in comparison with the butter covered within synthetic LDPE packaging. It is important to note that LDPE is not generally used for packaging butter and is not a good choice as a control. No difference was recorded in the lipid oxidation between the samples within LDPE films and the bioactive films. The mean TBARS and peroxide and acid values of all the stored samples were comparable. The short period of study might be responsible for this non-significant impact on the stability of lipids in butter.

Egg and egg products

The major results of various studies and the bioactive agents and materials evaluated for the development of edible-grade packaging for augmenting the lipid stability of egg products and eggs are presented in Table 1. Recent research papers have assessed the impact of coatings on the lipid oxidation of eggs and egg products. Venkatachalam et al. (2019) evaluated the impact of different coatings (chitosan, soy protein isolates, whey protein isolates) on the oxidation of lipids in boiled (20 min) duck eggs kept under ambient (30 ± 2 °C) conditions. The boiled eggs were coated by a dipping method [soy protein isolates (3 % glycerol and 5 % isolates in water), chitosan {chitosan (1 %) in acetic acid (2 %)} and whey protein isolates {aqueous solution of isolates (18 %) and glycerol in a ratio of 2.5:1}]. A positive influence of the coating made of whey protein isolates was found on lipid oxidation and the treated eggs manifested significantly lower values for TBARS in comparison to uncoated samples stored for 15 days. The means for TBARS for the eggs coated with other coatings (chitosan and soy protein isolates) were comparable with uncoated control samples. Elsebaie & Essa (2022) documented a desirable effect of coatings on the lipid stability of stored eggs and used an extract from barnûf leaf to enhance the bioactive characteristics of the coatings applied on chicken eggs. The coating solution was developed using 3 % CMC (w/v), different levels of leaf extract (6, 4, and 2 % w/w) and 2 % plasticizer (propylene glycol). The eggs were coated by the emersion method (2 min) followed by drying (30 min at room temperature) and five weeks (25 ± 2 °C) of storage. A favourable effect of the treatment was found on the oxidation of lipids in stored eggs and manifested significantly lower TBARS (mg MDA/kg yolk) for the eggs with a coating containing 6 % extract. The MDA content at higher levels can affect the aroma and flavour of the stored food products. This favourable influence of the coating on the oxidation of lipids in eggs was imputed to various phytochemicals of the leaf extract with antioxidant properties as indicated by a significant rise in total phenolic and total flavonoid contents of the coated egg samples. Further, the biochemical evaluation of the leaf extract showed appreciable amounts of several antioxidant compounds and organic acids, such as ellagic, benzoic, catechin, chlorogenic, gallic, caffeic, cinnamic, vanillic, ferulic, β-coumaric, and salicylic acids, which have potential to neutralise free radicals and break chain reactions. While designing films for the preservation of eggs it is important to consider the maximum daily intake of such active compounds and their impact on the taste of the eggs.

Meat and meat products

Numerous studies have examined the application of edible coatings and films to control the oxidation of lipids which can adversely influence the colour and flavour of meat, especially red meat. These are two important sensory attributes of meat which can directly affect consumer acceptance and purchasing decisions (Morton et al., 2018). The secondary lipid oxidation metabolites produced in meat and muscle foods, e.g., hexanal, glutaral, and 2,4-decadienal, can give rise to undesirable odours such as rancid, sour, fatty, and oily. The free radicals generated during the oxidation of lipids can accelerate the rate of oxidation of myoglobin which can affect the attractive meat colour. These two processes (oxidation of lipids and myoglobin) seem to be interlinked and the oxidation of one promotes that of the other and exhibits a joint influence on meat flavour (X. Wang et al., 2021). Several end products of the oxidation process have the capacity to negatively influence the flavour of the meat. The aldehydes generated during oxidation of the fats can react with lysine (amino acid) and produce Schiff base whereas the sulphur compounds produced from sulphur-containing amino acids during Strecker degradation react with free radicals to produce hydrogen sulphide. These affect the flavour of meat and add rancid and pungent odours. Further, hydroxyl radicals produced during lipid oxidation can promote the oxidation of proteins which can cause the release of non-heme and heme–iron during storage and in turn promote the oxidation of fats.

Frozen and fresh meat

The bioactive agents and materials evaluated for the production of edible packaging systems for enhancing the lipid stability of frozen and fresh meat and the major results of various studies are presented in Table 2.

Beef

Edible packaging (coatings and films) prepared using EO (essential oils) and flavonoids have been observed to enhance the lipid stability of beef. For example, a film was developed by B. Zhang et al. (2023) using agar and alginate (4:1) and ginger EO (0–4 %) to augment the lipid stability of stored (18 days at 5 °C) beef samples. Samples covered with the films containing ginger EO, particularly 4 and 3 %, exhibited markedly lower peroxide and TBARS values in comparison to the beef packed within films containing 0 % EO (blank) from days 0 to 18. It is noteworthy that the beef packed within the polyethylene films manifested the lowest means for peroxide and TBARS from days 0 to 18. This positive influence of the agar and alginate-based composite film on the lipid stability of fresh meat samples was ascribed to the antioxidant properties of ginger EO. A similar favourable effect of a film made of CMC (carboxymethyl cellulose), zinc oxide nanoparticles (1–3 % of CMC) and extract from grape seeds (5 % of CMC) has been reported on oxidation of lipids in beef kept for 15 days in a refrigerated environment (Priyadarshi et al., 2021). The peroxide values of 10.55, 9.92, and 1.2 meq/kg were found after a week's time for the samples packed within films made of CMC only (blank), containing zinc oxide nanoparticles (3 %) and both the additives (extract from grape seeds and 3 % zinc oxide nanoparticles), respectively. The peroxide values increased further on day 15 to a value of 16.66 meq/kg, 14.50 meq/kg, and 2.08 meq/kg, respectively. The contact with the film loaded with both bioactive additives decreased the peroxide value of beef by 88 % after 15 days. Dini et al. (2020) documented a favourable influence of a film made of chitosan and cumin EO nanoemulsion (1 %) on lipid oxidation of stored beef loins (21 days at 3 °C). Significantly lower TBARS (mg MDA/kg) means were found for the beef enveloped within the films made of nanoemulsion in comparison to the control beef from days 0 to 21. Chang et al. (2019) recorded a favourable influence of a film made of chitosan on the oxidation of lipids of fresh beef during 10 days of storage in a refrigerator. Markedly lower means were recorded for TBARS for the beef enveloped within the chitosan-based films in comparison to the beef packaged within LDPE films or without any films from days 0 to 10. A similar favourable influence of the citrus-pectin and fish gelatin-based film incorporated with 3,4-dihydroxyphenylglycol and hydroxytyrosol (0.1 and 0.5 %) extracted from the olive byproduct has been reported on the stability of the lipids of fresh beef during 6 days storage in a refrigerator (Bermúdez-Oria et al., 2019). The study (Bermúdez-Oria et al., 2019) also examined the effect of the beeswax-based film containing these antioxidants during 7 days of storage in a refrigerator. Markedly lower means were found for TBARS for the beef packed within the pectin-gelatin-based edible packaging from days 1 to 7 in comparison to the control beef and the beef packed within the commercial LDPE film. The positive effect observed on lipid oxidation was more prominent for the films containing hydroxytyrosol, especially 0.5 %. A similar positive impact was also found for the beeswax-based films containing these antioxidants. This positive effect was ascribed to the oxygen barrier properties of the films and the ion-reducing and radical scavenging activities of the olive antioxidants used.

Chicken

Khan et al. (2023) prepared a film using gum from *Artemisia sphaerocephala* and different levels (3, 5 and 7 %, w/w of gum) of curcumin/β-cyclodextrin inclusion complex to enhance the stability of

Table 2
Edible coatings and films with different bioactive agents to enhance lipid stability of frozen and fresh meat.

Coating and film material	Bioactive agents	Storage conditions and product packaged	Major results	Citation
The film was prepared using 25% glycerol (on the basis of alginate and agar weight), tween 80 (1% v/v), and agar and sodium alginate (4:1 w/w in H_2O)	Five levels (0, 1, 2, 3, and 4%) of ginger essential oil were taken	The edible films were used to wrap the fresh beef samples and were kept for 18 days at 5 °C	Beef wrapped within the edible films containing ginger essential oil, especially 3 and 4%, showed significantly lower peroxide and TBARS values in comparison to the beef packaged within blank films (0% oil) during the entire 18 days storage time	B. Zhang et al. (2023)
The film was prepared using CMC (carboxymethyl cellulose, 2.66%, w/v) and glycerol (30 wt% of CMC)	The bioactive agents used were ZnO nanoparticles (3, 2, and 1% of CMC) and extract from grape seeds (5% of CMC)	Beef loin samples were packaged within the film and kept for 15 days at 4 °C	The film containing both bioactive agents (grape extract and 3% ZnO nanoparticles) decreased the peroxide value of beef by 88% after 15 days of storage	Priyadarshi et al. (2021)
The film was prepared using glycerol (0.25 g/g chitosan) and chitosan (1%, w/v) prepared in 1% glacial acetic acid	The bioactive agent used for the film was 1% (w/v) nanoemulsion containing cumin essential oil	The film was used to wrap the beef loin samples which were kept for 21 days at 3 °C	Significantly lowered TBARS (mg MDA/kg) values were recorded for the beef enclosed within the nanoemulsion films in comparison to control beef during the entire 21 days storage time	Dini et al. (2020)
The film contained 10% glycerol (w/w, chitosan basis) and chitosan (1%) prepared in 0.5% acetic acid	Films were soaked in NaOH (0, 1, 5, and 10% w/w) for 10, 50 or 90 s	Meat samples with the films were examined for 10 days at 4 °C and compared with LDPE films (control)	Significantly lowered TBARS values were observed for the meat with chitosan films during the entire 10 days storage time	Chang et al. (2019)
Citrus pectin (0.5 g) and fish gelatin (0.5 g) in water (20 ml) and glycerol (0.5 g/g) were used. For beeswax-based film 0.4 g/g beeswax was used	Hydroxytyrosol and 3,4-dihydroxy-phenylglycol (0.1 and 0.5%, w/w of dry polymers) from the olive byproduct	The films were used to enclose the fresh beef samples (Topside) and kept at 4 °C for 6 (pectin-gelatin film) or 7 (beeswax) days	Significantly lowered values for TBARS were observed for the beef wrapped within pectin-gelatin or beeswax films from day 1 to storage end in comparison to the control samples and the beef packaged within the commercial film made of LDPE	Bermúdez-Oria et al. (2019)
The film contained 40% of glycerol (w/w, gum basis) and an aqueous solution of *Artemisia sphaerocephala* gum (6 g in 800 ml)	Bioactive agents used were curcumin/β-cyclodextrin inclusion complexes (7, 5, and 3%, w/w, gum basis)	The films were used to enclose chicken and lamb samples and kept at 4 °C for 9 days	The TBARS values lowered significantly for all the meat samples enclosed within the films during the entire 9 days storage time compared to the control samples	Khan et al. (2023)
The film contained calcium chloride (2%, w/v), tween 80 (0.25%) and sodium alginate (2%, w/v)	Bioactive agents used were oregano essential oil (0.39% w/v) and curcumin (250 μg/ml)	The coated chicken breast was kept within shrink film-covered plastic trays and kept at 4 °C for 7 days (illuminated display for 12h/day to imitate commercial display conditions)	The TBARS values lowered significantly for the coated breast from days 5 to 7 in comparison to the uncoated breast	de Moraes Pinto et al. (2023)
The film contained glycerin (15 mg/ml), cassava starch (15 mg/ml), and sodium carboxymethyl cellulose (15 mg/ml)	Apple polyphenols (70 mg/ml)	The film was used to wrap the chicken and kept at 4 °C for 7 days	The TBARS values lowered significantly for the chicken wrapped within the polyphenol-based film in comparison to the control film from days 1 to 7	(Lin et al. (2022)
The film contained 0.3% glycerol (w/v) and 3% (w/v) starch powder	Four levels (0.1, 0.2, 0.4, and 0.8%, w/v) of the essential oil obtained from Torch ginger (*Etlingera eliator*) inflorescence were used as bioactive agents	The film was used to wrap chicken samples and kept at 3 °C for 6 days	The TBARS values lowered significantly (0.212 mg MDA/kg) for the chicken wrapped within the polyphenol-based film in comparison to the unpackaged chicken (0.475) and the chicken enclosed within the control films (0.350) on day 6 of the storage	Marzlan et al. (2022)
The film contained glycerol (30% w/w, dry matter basis) and *Alyssum homolocarpum* seed gum (5 g)	The phytosomes developed using *Echinacea purpurea* (L.) extract and phospholipids were used as bioactive agents (1, 5, 10 and 20%, w/w)	The film was used to wrap the chicken and was kept at 4 °C for 14 days	The TBARS value of the chicken wrapped within the film containing 20% phytosomes was 2.7 mg MDA/kg on day 14 in comparison to a value of 5.5 mg MDA/kg for the chicken wrapped within control film	Molaveisi et al. (2022)
The film contained glycerin (35%, w/w), lily polysaccharide and sodium alginate solutions (1:0, 1:1, 1:2, 1:3, 1:4, and 1:5, v/v)	Lily polysaccharide (100–16%)	Chicken breasts were inoculated with *S. aureus* and *E. coli* O157:H7 (10^3 CFU/ml) and packaged with the films and kept at 4 °C for 7 days	The TBARS values lowered significantly for the coated chicken from day 1 onwards and reached a value of 0.114 mg MDA/kg on day 7 compared to 0.173 for the uncoated samples	Cui et al. (2022)
The film contained chitosan (20 g/kg) mixed with lauric arginate (20 g/kg) or chitosan (20 g/kg) only	Bioactive agents included lauric arginate with chitosan or only chitosan	The coated chicken drumsticks were kept at −18 °C for 90 days	The TBARS values lowered significantly for the coated drumsticks from days 0 to 90 in comparison to the control drumsticks	Abdel-Naeem et al. (2021)

(*continued on next page*)

Table 2 (*continued*)

Coating and film material	Bioactive agents	Storage conditions and product packaged	Major results	Citation
A konjac solution was prepared initially for the coating emulsion using glycerol (30% w/w of dry matter), carrageenan (0.5 g/100 ml) and konjac glucomannan (0.5 g/100 ml). This konjac solution was used for preparing emulsion using tween 80 (10%, w/w of oil) and camellia oil	Five different levels (0.0, 2.0, 2.5, 3.0, and 3.5%, w/v) of camellia oil were used as a bioactive agent	The coated chicken samples were kept at 4 °C for 10 days	Significantly lowered TBARS values were observed for coated samples from days 2 to 10 in comparison to uncoated chicken	Zhou, Zong, et al. (2021)
The film contained glycerol (0.5–1.0%, w/v), cross-linked maize starch (3–5%, w/v), and grape juice (juice: water volume ratio of 10:90–50:50)	Grape juice	The coated chicken breast samples were kept at 4 °C for 8 days	The TBARS values lowered significantly for the coated chicken from days 1 to 8. The values for TBARS on day 8 for uncoated and coated chicken were 1.98 and 0.91 mg MDA/kg, respectively	Yıldırım-Yalçın et al. (2021)
The film contained montmorillonite (0.1%), carboxymethyl cellulose (1%, w/v), chitosan (2% w/v, in 1% acetic acid solution), tween 80 (0.25 ml/100 ml) and glycerol (0.75 ml/g) as a plasticizer	The bioactive agents used were *Ficuscarica extract* (1.0%) and *Ziziphora clinopodioides* essential oil (ZCEO, 0.5, 1.0 and 2.0%) together or ZCEO alone	The nanocomposite chitosan and carboxymethylcellulose films were used to wrap the fresh camel meat (*Semimembranosus*) mince and kept at 4 °C for 14 days	The TBARS and peroxide values lowered significantly for the camel meat wrapped within the developed films from days 2 to 14	Khezrian and Shahbazi (2018)
Lecithin: cholesterol (60:0, 50:10, 40:20, and 30:30) in dichloromethane/methanol (1:1) and 60 mg *Satureja khuzestanica* essential oil were used to prepare nanoliposomes. The coating solution was prepared using nanoliposomes (50:10, 1% v/v), glycerol (25%, w/w) and 2% (w/v) chitosan (in 1% acetic acid)	Nanoliposomes were developed using *Satureja khuzestanica*	The coated meat steaks from fresh lamb leg were kept at 4 °C for 20 days	The TBARS values lowered significantly for the coated steaks from days 1 to 20	Pabast et al. (2018)
The film contained cellulose nanofibers (7.5%, w/w), glycerol (6%, w/v), and whey protein isolates (10% w/v)	The bioactive agents used were rosemary oil (2%, w/v) and TiO_2 particles (1% w/w)	The nanocomposite films were applied to Lamb samples from *Semimembranosus* and were kept at 4 °C for 15 days	Significantly lower TBARS, FFA and peroxide values were recorded for the lamb wrapped within nanocomposite films from days 3 to 15 in comparison to the lamb stored within polyethylene bags	Alizadeh-Sani et al. (2020)
The film contained starch aldehyde-catechin conjugate (0.06 g) and chitosan solution (20 g/l, in acetic acid)	A conjugate developed using starch aldehyde and catechins was used as a bioactive agent	The coated fresh pork loins were kept at 4 °C for 14 days	The TBARS values lowered significantly for the coated pork from days 2 to 14 in comparison to uncoated pork	Hu et al. (2022)
The film contained chitosan (1%) and gelatine (3%)	Grape seed extract (0.5%) and nisin (0.1%)	The coated fresh pork loins were kept at 4 °C for 20 days	The TBARS values lowered significantly for the coated pork from days 5 to 20 in comparison to uncoated pork	Xiong, Chen, et al. (2020)
The film contained tween 80 (20% dry matter), thyme essential oil, polyvinyl alcohol (Pva, 5%), curdlan (4:1 = Pva:curdlan), and glycerin (20% of dry matter)	Three levels (1.0, 1.5 and 2%) of thyme essential oil were used	The coated fresh pork tenderloin was kept at 4 °C for 20 days	The TBARS values lowered significantly for the coated pork from days 2 to 20 in comparison to uncoated pork	Y. Zhang et al. (2020)
Pectin (2.25%), oregano essential oil (0.5%) and resveratrol (200 mg/l) nanoemulsion, and tween 80 (1.25%)	Oregano essential oil (0.5%) and resveratrol (200 mg/l) nanoemulsion	Coated fresh pork loins were kept at 4 °C for 20 days	The TBARS values lowered significantly for the coated pork from days 5 to 20 in comparison to uncoated pork	Xiong, Li, et al. (2020)
The film contained glycerol (30%) as a plasticizer and 2% gelatin: agar solution (1:1) as a base	Zinc oxide nanoparticles (2 and 1%) and 10% of a Pickering emulsion prepared using clove essential oil	The film-wrapped pork loin samples were kept at 10 °C for 15 days	While no difference was observed during the first week of storage, significantly lower peroxide values were found for wrapped pork in comparison to the unwrapped pork on the 15th day of storage	Roy et al. (2022)
The blended film was developed using 2% curdlan and nanocellulose (0, 2, 5, 8, and 10%). 5% (w/v) microcrystalline cellulose in NaOH (7%, w/w) and urea solution (12%, w/w) was used to prepare nanocellulose	Nanocellulose (0, 2, 5, 8, and 10%)	The film-wrapped pork samples were kept at 4 °C for 12 days	The TBARS values lowered significantly for the film-wrapped pork from days 3 to 12 in comparison to unwrapped pork	Y. Qian et al. (2021)

lipids of fresh lamb and chicken stored for 9 days in a refrigerator. Markedly lower means were manifested for TBARS for all the meat samples packed within the edible packaging during storage (9 days) in contrast to the meat without any edible packaging. A significant impact of the concentration of the inclusion complex was found and the films containing a 7 % concentration showed the lowest TBARS values. The mean values rose from the initial value of 0.65 and 0.31 to 1.148 and 0.71 mg MDA/kg for lamb and chicken, respectively, wrapped within 7 % film on day 9. Other studies, such as de Moraes Pinto et al. (2023), have documented a desirable effect of curcumin-based films on the

oxidation of lipids in fresh chicken breast. Films were prepared using sodium alginate and curcumin (0.025 %) and essential oil from oregano (0.39 %) as bioactive agents to improve the lipid stability of chicken maintained under a simulated market environment (12 h illumination per day) at 4 °C for 7 days (de Moraes Pinto et al., 2023). The coated chicken samples were packaged within shrink-film-covered plastic trays. Markedly lower means were recorded for TBARS for the coated chicken from day 5 to day 7 in comparison to the uncoated chicken and the lowest means were found for the coatings with both the antioxidants. A significant impact of an edible film towards the storage end has been observed by other research works such as Marzlan et al. (2022) who observed a favourable impact of a starch-made edible packaging on the oxidation of lipids in chicken towards the storage end (6 days). The chicken wrapped within the film incorporated with EO (0.8 %) derived from torch ginger inflorescence (*E. eliator*) manifested significantly lower TBARS (0.212 mg MDA/kg) in comparison to the unpackaged (0.475) and the chicken samples within control films (0.350) on day 6. A similar favourable influence of a composite film prepared from cassava starch and carboxymethyl cellulose was documented by Lin et al. (2022) on the oxidation of lipids of fresh chicken during storage under refrigerated conditions. The film contained apple polyphenols (40–80 mg/ml) as a bioactive ingredient and the fresh chicken packed within the optimum film (70 mg/ml) was evaluated for 7 days. Markedly lower means were found for TBARS for the chicken packed within the optimum film from day 1 to day 7 in contrast to the chicken wrapped within the packaging film without polyphenols. The mean values for TBARS rose from the initial value of 0.033 to 0.092 and 0.178 mg MDA/kg for optimum and control film on day 7, respectively. Another study (Molaveisi et al., 2022) has demonstrated a significant favourable impact of a film made of seed gum on the oxidation of lipids in chicken kept for 2 weeks under refrigeration. The gum-based film was developed using phytosomes (1–20 %) prepared from an extract of *E. purpurea* which is a rich source of bioactive compounds, such as polyphenols, with antioxidant properties. Markedly lower means were recorded for TBARS for the chicken packed within the films, especially the films incorporated with 10 and 20 % phytosomes, from days 7 to 14. The mean values for TBARS increased from the initial value of 1.7 to 5.5 and 2.7 mg MDA/kg for the chicken packed within 20 % film and control film, respectively, on the 14th day.

Several other researchers have found a desirable effect of edible-grade packaging on the oxidation of lipids in stored chicken, such as Abdel-Naeem et al. (2021) demonstrated a significant effect of chitosan with lauric arginate or chitosan on the lipid oxidation (TBARS) of chicken during 90 days of storage at −18 °C. Cui et al. (2022) observed a significant favourable impact of a film made of lily polysaccharide and sodium alginate on the lipid oxidation (TBARS) of fresh chicken kept for 7 days under a refrigerated environment. Yıldırım-Yalçın et al. (2021) found a marked desirable influence of a coating developed from grape juice and maize starch on the lipid oxidation (TBARS) of fresh stored refrigerated chicken (8 days). Zhou, Zong, et al. (2021) recorded a significant favourable influence of a coating developed using carrageenan/konjac glucomannan and 0–3.5 % camellia oil on the oxidation of lipids (TBARS) of chicken kept under a refrigerated environment for 10 days.

Pork

Recent studies have investigated the potential of edible packaging containing flavonoids and essential oils to enhance the lipid stability of pork. Roy et al. (2022) prepared a multifunctional film using gelatin and agar as a base material and two bioactive agents (ZnO nanoparticles and Pickering emulsion of clove EO) to enhance the stability of lipids of pork stored for 15 days (8 °C). No significant impact was observed on the peroxide values of the samples during the first week of the storage, however, significantly lower means were recorded for the pork packaged within the film on the 15th day in contrast to the pork with no edible packaging. The means of 16 and 22 meq/kg were reported for treated and control samples on the 15th day, respectively. A favourable impact was also reported by Hu et al. (2022) on the lipid stability of loins of pork coated with chitosan containing a starch aldehyde-catechin conjugate during two weeks of storage in a refrigerator. Markedly lower means were found for TBARS for coated pork from days 2 to 14. In another study, Y. Qian et al. (2021) documented a favourable impact of a film made of curdlan (2 %) and nanocellulose (0–10 %) on the lipid oxidation of fresh pork kept under a refrigerated environment for 12 days. Markedly lower TBARS values were recorded for the pork covered with the film in comparison to the pork without edible packaging from days 3 to 12. The TBARS values for control pork surpassed the maximum permissible limit of 1 mg MDA/kg on the 12th day. Xiong, Li, et al. (2020) recorded a positive influence of a film made of pectin and a nanoemulsion [prepared from resveratrol (200 mg/ml) and 0.5 % oregano essential oil] on the lipid stability of loins (fresh pork) preserved for 20 days in a refrigerator. In contrast to the control pork (uncoated), all the treated pork exhibited significantly reduced means for TBARS from days 5 to 20. Some other research papers have reported a desirable influence of bioactive coatings on the lipid stability of pork such as Xiong, Chen, et al. (2020) found a positive influence of a coating prepared from chitosan, gelatine, and grapeseed extract or nisin on the stability of lipids of pork loins kept for 20 days under a refrigerated environment. Y. Zhang et al. (2020) documented a favourable influence of polyvinyl alcohol and a curdlan-based film containing 1–2 % thyme EO on the stability of lipids of pork (tenderloin) kept for 20 days under a refrigerated environment.

Other meats

Studies have reported edible-grade materials with the potential to augment the lipid stability of other meats such as lamb and camel meat. Alizadeh-Sani et al. (2020) used a film made of cellulose nanofibers and whey protein incorporated with 1 % TiO_2 particles and 2 % rosemary oil to augment the stability of lipids of lamb meat (*Semimembranosus*) kept inside a refrigerator for 15 days. A desirable influence of the packaging was found and significantly lower FFA, peroxide, and TBARS values were observed for the lamb wrapped with the edible packaging in comparison to the lamb covered with pouches of polyethylene from the 3rd to 15th day. The values of 1.46 meq/kg, 1.23 mg MDA/kg, and 1.70 % (% oleic acid) were found for lamb wrapped within the edible packaging compared to 3.81, 3.12, and 3.26 for control samples for peroxide values, TBARS, and FFA, respectively, on the 15th day. Other published papers have found a favourable influence of nanocomposite materials on the lipid stability of fresh meat. Khezrian and Shahbazi (2018) developed films from nanocomposite chitosan and carboxymethylcellulose base material incorporated with *Ficuscarica extract* (1.0 %) or *Ziziphora clinopodioides* EO (2.0, 1.0, and 0.5 %) or both to augment the lipid stability of stored camel meat kept for 14 days at 4 °C. A favourable influence of the film was recorded on the oxidation of lipids and markedly lower TBARS and peroxide values were found for the meat wrapped within the nanocomposites in contrast to the control camel meat (unwrapped) from days 2 to 14. The lowest means were found for the camel meat covered within the edible packaging loaded with both the bioactive agents. A similar study (Pabast et al., 2018) reported a significant favourable influence of coatings made of chitosan and *S. khuzestanica* EO in the form of nanoliposomes (1 %) or through direct addition on lipid stability of lamb leg meat steaks kept under refrigerated environment for 20 days. Markedly lower means were recorded for TBARS for the lamb with coatings in comparison to the uncoated lamb from days 1 to 20. While TBARS values of uncoated lamb rose from a value of 0.33 (day 0) to 5 mg MDA/kg (day 20), the value of less than 2.5 mg/kg was observed for nanoliposomes coated lamb on day 20. This favourable influence of the coating on the lipid oxidation of lamb was imputed to various antioxidant compounds, such as carvacrol, present in the EO which have radical scavenging capacity by donating electrons or hydrogen atoms. The large surface area of the nanoliposomes which was available for interaction was considered as the main reason for higher antioxidant activity.

Meat products

The major results of various studies and the bioactive agents and materials evaluated for the production of edible materials for packaging for enhancing the lipid stability of meat products and processed meat are presented in Table 3.

Meat nuggets

Research works have evaluated the application of edible coatings and films to prevent lipid oxidation in stored meat nuggets. A significant favourable influence of a coating developed from 1.5 % pomegranate peel powder and sodium alginate was found on the stability of lipids of chicken nuggets kept in a refrigerated environment (Bashir et al., 2022). Significantly lower TBARS and peroxide means were recorded for the coated nuggets in comparison to the samples without coating during 21 days of storage time. The mean values for uncoated and coated nuggets reached 1.62 and 0.86 for TBARS (MDA/kg) and 0.92 and 0.63 for peroxide values (meq/kg), respectively, on day 21. This favourable influence of the coating on the oxidation of lipids in chicken nuggets was attributed to various phenolic compounds and phytochemicals naturally present in pomegranate peel (Dua et al., 2016). A similar positive impact was recorded by Sharma et al. (2021) who investigated the use of a film made of alginate and maltodextrin to augment the stability of lipids in chicken nuggets packaged under vacuum and kept in a refrigerator (60 days). The antioxidant capacity of the edible packaging film was improved using *Commiphora wightii* extract (0–0.75 %). The extract significantly enhanced the total-phenolic and total-flavonoid contents and the highest values were found for the film incorporated with 0.75 % *C. wightii* extract. The film-wrapped samples manifested significantly lower means for FFA and TBARS during the 60 days of refrigerated storage and the lowest means were documented for the films incorporated with 0.75 and 0.50 % extract. This desirable influence of the film on lipid stability was imputed to different compounds of the extract with antioxidant activities which have the ability to inhibit the chain reactions of oxidation. The *C. wightii* extract contains various antioxidant compounds such as terpenoids, phenolic acids, flavonoids, guggulsterones, and guggultetrols (Bhardwaj & Alia, 2019). Other published papers have observed a favourable influence of edible materials on the lipid oxidation of meat nuggets. Sharma et al. (2021) reported the beneficial effect of the film containing a high concentration of phenolics on lipid oxidation. The film prepared from maltodextrin, sodium alginate and root extract (0–1.0 %) from *Rubia cordifolia* effectively enhanced the stability of lipids in chicken nuggets kept under a refrigerated environment for 60 days. The film-wrapped nuggets manifested significantly lower means for FFA and TBARS during the 60 days of storage and the lowest means were recorded for the films loaded with 1.0 and 0.75 % extract. The *R. cordifolia* extract is rich in bioactive phytochemicals with strong radical scavenging activities and retard lipid oxidation in meat products (Sharma et al., 2021). These phytochemicals enhanced the total phenolics and flavonoids and antimicrobial activities of the film and thereby reducing lipolysis and FFA production during storage. A similar favourable influence of the packaging on the stability of lipids in chicken nuggets has been documented by Ozvural (2019) who investigated the effect of hazelnut skin and olive leaf extract-based films on lipid oxidation of nuggets kept at −18 °C and 4 °C for 90 and 21 days, respectively. Significantly lower means were found for TBARS for the coated nuggets in comparison to uncoated nuggets during both refrigerated and frozen conditions. This favourable influence of the packaging materials on the oxidation of lipids was ascribed to the antioxidant activities of the phenolic compounds, mainly proanthocyanidins and flavan-3-ols in hazelnut skin and oleuropein present in olive leaf (Dua et al., 2015b).

Sausages

Several edible packaging materials have been developed to enhance the lipid stability of stored meat sausages. A gelatin-based coating incorporated with green tea extract (1.0 %) was developed to augment the stability of lipids in fresh pork sausages kept at 4 °C for 76 days (Hamann et al., 2022). The coatings significantly enhanced the stability of lipids in stored sausages. The TBARS, peroxide values and FFA for the coated samples (0.27, 13.7 and 9.7 on day 69) were significantly lower compared to uncoated samples (0.53, 20.7 and 11.3 on day 69, respectively) till 69 days of the storage. The rate of lipid oxidation (k, Weibull model) was determined and indicated that the oxidative process was 12 times slower for the coated sausages in comparison to the control sausages during storage. Dong et al. (2020) prepared a coating from chitosan (0–3 %) for a Chinese pork-based speciality, Harbin red sausages, to improve its lipid stability at room temperature. The TBARS for the coated sausages were significantly lower from 6 days onwards till day 12 in contrast to the sausages with 0 % chitosan (control). This effect was more prominent for coatings prepared with 2 and 3 % chitosan. Some other scientific works have used polyphenols and flavonoid-rich plant extracts, such as *Tinospora cordifolia*, *Terminalia arjuna,* and *Asparagus racemosus,* as antioxidant agents to augment the stability of lipids in stored meat sausages. *A. racemosus* root extract (0–2 %) was used for the development of a film from sodium alginate and maltodextrin for enhancing the stability of lipids in chevon sausages (Noor et al., 2018). The film significantly reduced the TBARS and FFA values of the sausages kept under a refrigerated environment for 21 days. The extract contains various molecules with antimicrobial and antioxidant activities such as terpenoids, phenolic compounds, anthraquinones, tannins, diosgenin, coniferin, vanillin, alkaloids, proteins, and triterpene sterols and saponins. These phytochemicals purge out of the film material at a controlled rate and neutralize the free radicals produced during the oxidation of lipids and inhibit these chain reactions and can also reduce microbial and enzymatic lipolysis of meat products (Noor et al., 2018). *Terminalia arjuna*, another plant with bioactive properties, was used to prepare a bioactive film to enhance the lipid stability of the sausages prepared from Chevon (Kalem et al., 2018). Samples stored within the film (0.5 and 1.0 % extract) showed a significant decline in FFA and TBARS values during 21 days of storage compared to the sausages with control films. This favourable influence of the film material on lipid stability was attributed to bioactive molecules having the capacity to slow down oxidation and lipolysis during storage. *Tinospora cordifolia*, a plant rich in various bioactive principles, has been linked with antioxidant, reducing power, metal chelating, and antimicrobial activities (Dwivedi & Pa, 2016). *T. cordifolia* stem extract has been explored for the preparation of packaging materials for enhancing the oxidative stability of lipids in meat sausages (Kalem et al., 2018). The sausages stored within the edible packaging loaded with 0.5 and 1.0 % extract manifested a marked decline in FFA and TBARS values during 3 weeks of storage. The lowest means were recorded for the sausages stored with 1 % extract-based films. The bioactive compounds of the extract have the ability to retard the chain reactions of lipid oxidative through direct neutralisation of the free radicals (Dwivedi & Pa, 2016). The extract can potentially reduce the growth of both pathogenic and spoilage microbes, thereby reducing the production of microbial lipases and phospholipases which can split glycerides and produce FFA.

Meat patties

Recent studies have investigated the impact of bioactive edible packaging on the oxidation of lipids in stored meat patties. Qian et al. (2022) documented a favourable influence of a film made of chicken myofibrillar proteins on the oxidation of lipid in beef patties kept under a refrigerated environment for 5 days. The film was exposed to plasma and contained three EOs i.e. 0.2 mg/ml rosemary, 0.1 % oregano and 0.1 % cinnamon as bioactive agents and markedly reduced lipid oxidation induced by plasma as indicated by the reduction of TBARS from 0.16 MDA/kg to 0.06 mg MDA/kg in comparison to the control patties. da Nóbrega Santos et al. (2022) assessed the impact of gelatin-based film incorporated with *M. emarginata* (Acerola cherry) bagasse (2, 4, and 6 %) on the lipid stability of beef patties stored for 60 days at

Table 3
Edible coatings and films with different bioactive agents to enhance lipid stability of processed meat and meat products.

Coating and film material	Bioactive agents	Storage conditions and product packaged	Major results	Citation
Chicken myofibrillar protein (50 mg/ml), Tween 80 (1 %) and glycerol	Oregano (0.1 %), cinnamon (0.1 %), and rosemary (0.2 mg/ml) essential oils	The film-wrapped beef patties were kept at 4 °C for 5 days	The lipid oxidation significantly reduced from 0.16 to 0.06 mg MDA/kg due to the film	Qian et al. (2022)
The film contained glycerol (5 % v/v) and bovine gelatin (5 % w/v)	Three levels (2, 4, and 6 %) of bagasse from acerola cherry (*Malpighia emarginata*) were used as a bioactive agent	The beef patties enclosed within PVC plastic films were considered as control and together with edible film-covered beef patties were kept at −18 °C for 60 days	The 4 % edible film lowered the formation of malonaldehyde and conjugated dienes towards the storage end by 23.58 and 34.46 %, respectively, in comparison to the control	da Nóbrega Santos et al. (2022)
The film was developed using tween 80 (1 % v/v), resveratrol, clove essential oil, and basil seed gum (1 % w/v)	The bioactive agents used were clove essential oil (10 mg/ml) and resveratrol (4 μg/ml)	The raw camel meat patties enclosed within PVC plastic films were considered as control and together with treated patties covered with the edible films were kept at 4 °C for 20 days	The TBARS (mg MDA/kg) and peroxide values (meq/kg) lowered significantly for the patties covered with the film from days 0 to 20 in comparison to the control	Ansarian et al. (2022)
The coating emulsion was prepared from glycerin (1 % v/v), twain-80 (1.5 % v/v), cinnamic aldehyde (1 % v/v), fennel essential oil (1 % v/v), and chitosan (1.5 % w/v, in 1 % glacial acetic acid	The bioactive agents used were cinnamic aldehyde (1 % v/v) and fennel essential oil (1 % v/v)	The emulsion-coated pork meat patties were kept at 4 °C for 12 days	Significantly lower TBARS values were observed for coated samples (both nanoemulsion and crude emulsion) from days 0 to 12	Sun et al. (2021)
The coating solution was prepared using pomegranate peel powder (1.5 %, w/v), $CaCl_2$ (2 %, w/v) and sodium alginate (1.5 %, w/v)	1.5 % powder developed from dried pomegranate peel	The coated chicken nuggets were kept for 21 days at 4 °C	Significantly lower TBARS and peroxide values were found for the coated nuggets in comparison to uncoated nuggets from days 0 to 21	Bashir et al. (2022)
The coating solution was prepared using glycerol (1 %, w/v), calcium chloride (1.5 %, w/v) and sodium alginate (1.5 %, w/v)	Olive leaf (*Olea europea* L.) extract (1 %) and hazelnut skin (2 %), separately	The coated chicken nuggets were kept for 21 days at 4 °C and for 90 days at −18 °C	The coated chicken nuggets exhibited significantly lower TBARS and peroxide values under both the conditions	Ozvural (2019)
The films were developed using sodium alginate, $CaCl_2$, maltodextrin, carboxymethylcellulose and glycerol	Three levels (0.25, 0.50, and 0.75 %) of the extract obtained from the *Commiphora wightii* plant	The film-wrapped chicken nuggets were vacuum-packed and kept at 4 °C for 60 days	The extract significantly increased the bioactive properties of the film. Nuggets stored within the film showed significantly lower TBARS (mg MDA/kg) and FFA (% oleic acid) values during the entire storage time	Sharma, Bhat, Kumar, Kumar, Bekhit, et al. (2021)
The films were developed using sodium alginate, $CaCl_2$, maltodextrin, carboxymethylcellulose and glycerol	Three levels (1.0, 0.75, and 0.50 %) of the extract obtained from *Rubia cordifolia* root	The film-wrapped chicken nuggets were vacuum-packed and kept at 4 °C for 60 days	The extract significantly increased the bioactive properties of the film. The film wrapped-nuggets manifested significantly lowered TBARS and FFA values during the entire storage time	Sharma, Bhat, Kumar, Kumar, Bhatti, et al. (2021)
Gelatin (5–30 % w/v) and glycerol (10–45 % w/w of gelatin)	Green tea extract (*Camellia sinensis,* 0.5, 1.0, 2.5, and 5.0 % of the film-making solution)	Fresh pork sausages coated with 30 % glycerol, 15 % gelatin and 1 % tea extract were kept at 4 °C for 76 days	The TBARS, peroxide values and free fatty acids were significantly lowered for the coated sausages till 69 days of storage in comparison to uncoated sausages	Hamann et al. (2022)
The film contained glycerol (1 % v/v) and chitosan (0–3 % w/w, in 1 % acetic acid solution)	Three levels (1, 2, and 3 % w/w) of chitosan were used	The coated Harbin red pork sausages were kept at 23 °C for 12 days	The TBARS values lowered significantly for the coated sausages from days 6 to 12	Dong et al. (2020)
The film was developed using glycerol, sodium alginate and maltodextrin	Two levels (1.0 and 2.0 %) of extract obtained from *Asparagus racemosus* root were used	The film-wrapped Chevon sausages were kept for 21 days at 4 °C	The extract (*A. racemosus*) significantly increased the bioactivities of the film. Sausages wrapped within the film (1.0 and 2.0 %) manifested significantly lowered values for TBARS and FFA from days 0 to 21 in comparison to the control sausages	Noor et al. (2018)
The film was developed using glycerol, sodium alginate and maltodextrin	Two levels (1.0 and 0.5 %) of extract obtained from *Terminalia arjuna* were used	The film-wrapped Chevon sausages were kept for 21 days at 4 °C	The extract (*T. arjuna*) increased the bioactive properties of the film significantly. Sausages wrapped within the film (0.5 and 1.0 %) exhibited significantly lowered TBARS and FFA values from days 0 to 21 in comparison to the control sausages	Kalem, Bhat, Kumar, Noor, et al. (2018)
The film was developed using glycerol, sodium alginate and maltodextrin	Two levels (1.0 and 0.5 %) of extract obtained from *Tinospora cordifolia* stem were used	The film-wrapped Chevon sausages were kept for 21 days at 4 °C	The extract (*T. cordifolia*) increased the bioactive properties of the film significantly. Sausages wrapped within the film (0.5 and 1.0 %) exhibited significantly lowered TBARS and	Kalem, Bhat, Kumar, Wang, et al. (2018)

(*continued on next page*)

Table 3 (*continued*)

Coating and film material	Bioactive agents	Storage conditions and product packaged	Major results	Citation
			FFA values from days 0 to 21 in comparison to the control sausages	
The film contained tween 80 (1 %, v/v), glycerol (1.5 %, v/v), coconut shell liquid smoke (0–15 %, v/v), and ginger starch (5 %, w/v)	Four levels (0, 5, 10 or 15 %, v/v) of liquid smoke developed from coconut shells were used	The film-covered ground beef patties were kept at 4 °C for 12 days	The TBARS values were lowered significantly for the film-wrapped patties from days 0 to 12	Rahmasari & Yemiş (2022)
The film contained glycerol (30 %, w/w, dry matter basis), gelatin (2.5 %, w/v), chickpea protein isolate (2.5 % w/v), copper nanoparticles after sulfidation (0–0.03 %, w/v), and *Nigella sativa* essential oil encapsulated in sodium caseinate (0–0.5 %)	*Nigella sativa* essential oil (0–0.5 %) and copper nanoparticles (0–0.03 %, w/v)	The film-wrapped ground beef was kept for 14 days at 4 °C	The TBARS values lowered significantly for the wrapped beef from days 1 to 14 in comparison to unwrapped beef	Rasul et al. (2022)
Mung bean protein isolate (5 %), pullulan (5 %), and glycerol (40 %, based on protein)	Marjoram essential oil (9 % v/w)	The film-wrapped ground beef was kept for 14 days at 4 °C	The TBARS values lowered significantly for the film-wrapped beef from days 0 to 14	Haghighatpanah et al. (2022)
The emulsion for coating contained gelatin (2.5 %, w/v), chitosan (0.5 %, w/v), and Tween 80 (25 %, w/w oil)	The bioactive agents used were ε-poly-ι-lysine (0.04 %) and essential oil of rosemary (2 %)	The coated carbonado chicken was kept for 16 days at 4 °C	The TBARS values lowered significantly for the coated chicken from days 0 to 16 in comparison to the uncoated chicken	Huang et al. (2020)
Clove essential oil microencapsulated by cyclodextrin metal–organic frameworks (β-CD-MOFs) which were prepared from β-cyclodextrin and potassium hydroxide	Clove essential oil (inclusion rate was up to 96.07 %, powder with 10:1 wall/mass core ratio)	Fresh pork pieces were rubbed with cyclodextrin frameworks (0.05, 0.1, and 0.2 %) and kept for 18 days at different fermentation temperatures to prepare the Chinese bacon	Significantly lower TBARS (MDA/kg) and peroxide values (g/100 g) were recorded for treated bacon in comparison to untreated bacon from days 3 to 18	Wang et al. (2023)

−18 °C. The edible film-wrapped beef patties with 4 % bagasse exhibited the lowest means for conjugated dienes (%) at the beginning (3.59 %) and the end (7.34 %) of the storage. A reduction of 34.46 % was achieved when compared to the beef patties packed within the PVC plastic films. The highest means were found for the patties packed within PVC film (10.53 %) and the edible film containing 6 % bagasse (11.20 %) on day 60. The absence of antioxidant molecules in the PVC film was responsible for this high increase in conjugated dienes in the control samples whereas the presence of phenolic compounds of bagasse, such as ρ-coumaric, quercetin, ferulic acids, and chlorogenic acids, which can neutralise free radicals and chelate metals (Cruz et al., 2019) was responsible for lowest values for 4 % edible film. High concentrations of polyphenols, such as 6 % bagasse in this case, can initiate a pro-oxidative process in meat products and intensify the action of free radicals and promote lipid oxidation (Aminzare et al., 2019). A similar trend was recorded for TBARS values of the patties on day 60 and the lowest means were observed for the edible film incorporated with 4 % bagasse. A reduction of 23.58 % in lipid oxidation was achieved in comparison to the control patties.

Ansarian et al. (2022) prepared a film using clove essential oil (10 mg/ml), resveratrol (4 μg/ml) and basil seed gum-based nanoemulsion to enhance the stability of lipids in raw camel meat patties. The patties were covered by the films on the bottom and top sides and kept for 20 days at 4 °C. The control patties were wrapped in polyethylene bags. Markedly lower TBARS (mg MDA/kg) and peroxide values (meq/kg) were recorded for the patties with the films from days 0 to 20. The mean TBARS and peroxide values for control and treated samples on day 20 were 1.89 and 1.03 mg MDA/kg and 7.81 and 4.03 meq/kg, respectively. A similar favourable impact of coatings developed using a nanoemulsion loaded with cinnamaldehyde/fennel EO has been documented on the oxidation of lipids in pork patties kept for 12 days in a refrigerator (Sun et al., 2021). Significantly reduced TBARS results were recorded for samples with coatings (crude emulsion or nanoemulsion) from days 0 to 12. The mean value of 0.35 mg MDA/kg was found for all the patties on day 0 for TBARS which increased to 0.85, 0.64, and 0.63 mg/kg for patties without any coating, coated with crude emulsion and nanoemulsion, respectively, on day 12.

Ground meat

The edible and bioactive coatings and films can reduce the oxidation rate in ground meats which are specifically prone to lipid oxidation due to particle reduction/mincing which damages the muscle cell membranes and facilitates oxygen diffusion. Rahmasari and Yemiş (2022) prepared a film from ginger starch and liquid smoke (0–15 %, prepared from coconut shell) to retard the lipid oxidation in ground beef kept for 12 days at 4 °C. The ground beef covered with edible packaging exhibited significantly reduced TBARS from days 0 to 12. The different treatments exhibited no difference. The mean TBARS values on the 0th day were 0.68 mg MDA/kg for all the beef samples which increased to 3.83, 0.81, 0.72, and 0.73 mg MDA/kg on the 12th day for control beef and the beef covered with the packaging loaded with 5, 10, and 15 % liquid smoke, respectively. A similar favourable influence of a chickpea protein and gelatin-based film loaded with *Nigella sativa* EO (0–0.5 %) and copper nanoparticles (0–0.03 %) has been reported on the lipid-oxidation of ground beef kept for 14 days at 4 °C (Rasul et al., 2022). The ground beef enveloped within the film manifested significantly reduced TBARS values in comparison to the unwrapped ground beef from days 1 onwards to 14. The lowest TBARS values were recorded for the beef loaded with both EOs as well as copper nanoparticles. The TBARS values on day 1 were 0.40 mg MDA/kg for all the samples which increased to 2.6, 1.3, 1.6, and 1.1 mg MDA/kg on the 14th day for unwrapped ground beef and the beef enveloped within the packaging loaded with EO, nanoparticles, and both oil and nanoparticles, respectively. Haghighatpanah et al. (2022) observed a favourable impact of a film made from pullulan, mung bean protein and Marjoram EO (9 %) on lipid oxidation of ground beef maintained for 14 days at 4 °C. The beef covered with the film loaded with EO exhibited significantly reduced values for TBARS when compared to the unwrapped beef from days 0 to 14. This favourable influence of the film on the lipid oxidation of ground beef was ascribed to the polyphenolic molecules of the EO which can reduce the ions and scavenge the free radicals.

Other products

Wang et al. (2023) used clove essential oil microencapsulated by cyclodextrin metal–organic frameworks (inclusion rate up to 96.07 %) to enhance the stability of lipids in Chinese bacon. Fresh pork pieces were rubbed with cyclodextrin frameworks (0.05, 0.1, and 0.2 %) and

kept for 18 days at different fermentation temperatures to prepare the Chinese bacon. A positive impact of the treatment was reported on lipid peroxidation and both TBARS (MDA/kg) and peroxide values (g/100 g) recorded were significantly lower for treated bacon samples compared to untreated bacon from days 3 to 18. This positive influence of the treatment on the lipid oxidation of bacon was imputed to the clove EO which has strong antioxidant activities. Huang et al. (2020) prepared a film from gelatin and chitosan-based nanoemulsion containing ε-poly-L-lysine (0.04 % w/v) and rosemary EO (2 % w/w) to enhance the quality of carbonado chicken maintained for 16 days at 4 °C. Markedly lower means were recorded for TBARS for the chicken with coatings from days 0 to 16. The TBARS values increased from 0.77 MDA/kg on day 0 to a maximum value of 2.27 and 1.53 MDA/kg for untreated (uncoated) and treated samples on day 16, respectively. This favourable influence of the nanoemulsion on the oxidation of lipids in chicken was ascribed to the good barrier properties of chitosan and gelatin (reducing oxygen ingress) and the antioxidant activities of rosemary and chitosan.

Fish and seafood

The major results of various studies and the bioactive agents and materials evaluated for the production of edible packaging materials for enhancing the lipid stability of fish and seafood are presented in Table 4. Research papers have documented the favourable impact of edible packaging such as coatings on the lipid stability of stored seafood. For example, Osanloo et al. (2023) prepared a coating from alginate-based nanoparticles incorporated with *Cuminum cyminum* (0.125 %) and *Zataria multiflora* (0.125 %) EOs to enhance the stability of lipids in shrimp maintained at 4 °C for 15 days. Treated shrimp were compared with the shrimp without any coating. The essential oil-encapsulated nanoparticles were developed using $CaCl_2$ and sodium alginate and the shrimps were coated by dipping them for 5 min in the coating solution. A favourable influence of the edible material was recorded on the oxidation of lipids in the stored shrimp and lower TBARS means were found for the coated shrimp from days 0 to 15. This favourable influence of the coatings was imputed to the antioxidant activities of cuminic aldehyde present in *C. cyminum* EO and carvacrol and thymol present in *Z. multiflora* EO. These compounds have the capacity to inhibit oxidation by neutralising the reactive oxygen species (ROS) and free radicals and through ion-chelating action. The stability of lipids in fresh *Litopenaeus vannamei*, a shrimp, has been improved using a coating prepared from nanoemulsion (garlic EO-based) and zein-protein during 2-week storage under a refrigerated environment (Rahnama et al., 2021). Different proportions (6, 12 and 24 %) of nanoemulsion of garlic EO and zein protein (10 %) were mixed to produce different coating solutions. The dipping method was used to coat the shrimp at 4 °C. The stability of lipids in shrimp was measured by determining TBARS and peroxide values. A favourable influence of the coating was recorded on both TBARS and peroxide values and significantly reduced means were reported for the coated shrimp in comparison to uncoated shrimp. The effect of the coatings was more prevalent in the second week of storage and a concentration-dependent response was seen with the lowest means recorded for the shrimp with 24 % EO.

Research publications have documented a desirable influence of edible materials on the lipid stability of different species of both freshwater and marine fish. Tan et al. (2022) prepared a multifunctional coating for augmenting the stability of lipids in fresh fillets from sturgeon (*A. baeri* x *A. schrenckii*) maintained at 4 °C for 16 days. The solutions for coating of the fillets were prepared using sodium alginate (2 %), egg albumin and egg yolk powders, and glycerol and bioactive properties were imparted using various agents with antibacterial activities viz. 0.025 % tea polyphenols, 0.1 % chitosan and 0.05 % ε-polylysine. The coated fillets were evaluated for lipid oxidation (TBARS values). The rate of lipid oxidation was markedly lowered in the fillets with the coatings and the TBARS values rose from 0.23 mg MDA/kg for all samples on day 0 to 1.49 for control samples and 0.87 mg MDA/kg, 0.78 mg MDA/kg, and 0.68 mg MDA/kg for treatment samples on day 16 of storage. The coated fillets exhibited significantly lower TBARS from days 0 to 16 compared to uncoated fillets. This favourable influence of the edible material on the oxidation of lipids was attributed to its barrier properties, minimizing contact with oxygen and light, and the activities of the polyphenol-rich agents. Zhao et al. (2022) prepared a film using anthocyanidin and chitosan nanocomposite to boost the lipid stability of fish fillets (*Pagrus major*) kept at a refrigeration temperature (4 °C) for 14 days. The perilla-cinnamon EOs (9:1) nanoemulsion (1.0 %) with and without anthocyanidin (0.43 %) were used to develop the films which were used to pack the stored fillets. The films showed a marked favourable influence on the stability of lipids and significantly reduced values were recorded for TBARS for the fillets wrapped within the film from days 0 to 14 in comparison to the unwrapped fillets. The lowest TBARS means were found for the film loaded with both anthocyanidin (0.43 %) and nanoemulsion (1.0 %) during the storage. The mean values for TBARS for all the fillets remained lower than the maximum threshold limit for stored fish [frozen (5 mg MDA/kg) and fresh (2 mg MDA/kg)]. The same research group (Zhao, Guan, Zheng, et al., 2022) reported similar findings during a similar study evaluating the impact of the same edible film (chitosan/anthocyanidin-based) on the storage stability of the same fish (*Pagrus major*) kept at 4 °C for 14 days. Markedly reduced values were documented for TBARS for the treated fillets from days 0 to 14. The lowest means were documented for TBARS for the film loaded with both anthocyanidin (0.43 %) and nanoemulsion (1.0 %) and the values of all the fillets remained within the acceptable limit till storage end.

Yuan et al. (2022) prepared a film using chitosan to enhance the stability of lipids in fresh salmon fillets maintained for 15 days at 4 °C. The double emulsion ($W_1/O/W_2$) containing nisin and carvacrol was prepared and used to impart bioactivities to the chitosan-based composite film. The chitosan films were also prepared using carvacrol and nisin (separately and together) without preparing the double emulsion. The salmon fillets wrapped within the edible materials manifested significantly reduced TBARS values compared to the fillets without any edible material from days 0 to 15 of storage. The lowest TBARS values were manifested by the composite film prepared from double emulsion with nisin and carvacrol followed by the film prepared from chitosan loaded with both antioxidants. The highest TBARS value was recorded for unwrapped fillets (3.20 mg MDA/kg) after 15 days whereas the lowest TBARS value was found for the fillets wrapped within the film prepared from double emulsion (1.20 mg MDA/kg). Among the two bioactive agents, carvacrol showed a higher potency than nisin and a synergistic effect existed between the bioactive agents. While Yuan et al. (2022) used double emulsion for the edible films, Chen et al. (2022) developed an edible film which was bilayered using polylactic acid, fish gelatin (tilapia), and sodium alginate, and imparted bioactive properties by incorporating β-cyclodextrin complexes loaded with cinnamaldehyde (1 %) or thymol (1 %). The films were utilised for packaging sea bass (*L. japonicus*) fillets which were kept under a refrigerated environment (4 °C) for 8 days. The films containing cinnamaldehyde and thymol significantly lowered the lipid oxidation (TBARS) of the fillets from days 0 to 8 compared to the films without any bioactive agent. This favourable impact of the edible packaging on the lipid oxidation of the seabass was credited to their good barrier characteristics which can restrict the ingress of oxygen and the radical scavenging ability of the antioxidants. Xiong et al. (2021) prepared a coating solution for salmon fillets using 2 % chitosan and 2 % gelatine derived from Atlantic salmon bone and imparted bioactive properties using 0.5 % clove oil and 0.2 % gallic acid as bioactive agents. The fillets from fresh Atlantic salmon (*Salmo salar*) were maintained for 15 days at 4 °C after coating by a dipping method (60 s). The coated fillets manifested significantly lower TBARS in comparison to uncoated fillets from day 0 onwards. The lowest TBARS values were recorded for the fillets with a coating material containing both the bioactive agents and the highest for the fillets without any coating which exceeded the acceptability limit (1 mg MDA/kg) on the

Table 4
Edible coatings and films with different bioactive agents to enhance lipid stability of fish and seafood.

Coating and film material	Bioactive agents	Storage conditions and product packaged	Major results	Citation
The film contained anthocyanidin (0.4 %), collagen (3 %) and chitosan nanoparticles (3 %)	The bioactive agents used were Pickering nanoemulsion (0–3 %) developed using cinnamon-perilla essential oils (1:9)	The film-wrapped fillets from red sea bream (*Pagrus major*) were kept at 4 °C for 14 days	The TBARS values lowered significantly for the treated fillets from days 0 to 14. The film containing both cinnamon-perilla essential oils nanoemulsion (1.0 %) and anthocyanidin (0.43 %) showed the lowest TBARS values	Zhao et al. (2022)
A composite film was developed using chitosan and a double emulsion	Double emulsion ($W_1/O/W_2$) containing nisin and carvacrol. Films were also prepared through the direct addition of nisin and carvacrol (alone and in combination without double emulsion)	The film-wrapped salmon fillets were kept for 15 days at 4 °C	The fillets packaged within the composite films showed significantly lower TBARS values from days 0 to 15. Among the two bioactive agents, carvacrol showed a higher potency than nisin and a synergistic effect existed between the antioxidants.	Yuan et al. (2022)
The coating solution contained glycerol (30 % of egg white powder), sodium alginate (2 %), egg yolk powder (15 % of egg white powder), and egg white powder (1:10 and 1:15, w/v in water)	The bioactive agents used were tea polyphenols (0.025 %), chitosan (0.1 %), and ε-polylysine (0.05 %)	The coated fillets from sturgeon were kept at 4 °C for 16 days	The TBARS values lowered significantly for the treated fillets from days 0 to 16 in comparison to uncoated fillets	Tan et al. (2022)
The film contained anthocyanidin (0.4 %), collagen (3 %) and chitosan nanoparticles (3 %)	The bioactive agents used were Pickering nanoemulsion (0–3 %) developed using cinnamon-perilla essential oils (1:9)	The film-wrapped fillets from red sea bream were kept at 4 °C for 14 days	The TBARS values lowered significantly for the treated fillets from days 0 to 14. The film containing both cinnamon-perilla essential oils nanoemulsion (1.0 %) and anthocyanidin (0.43 %) showed the lowest TBARS values	Zhao, Guan, Zheng, et al. (2022)
Tilapia fish gelatin (10 %) and sodium alginate (2 %) coating solution was taken twice the mass of polylactic acid preformed film and coated on the surface of the film	β-cyclodextrin inclusion complexes of thymol (1 %) or cinnamaldehyde (1 %)	The film-wrapped fillets of Japanese sea bass (*Lateolabrax japonicus*) were kept at 4 °C for 8 days	The TBARS values lowered significantly for the film-wrapped fillets from days 0 to 8 in comparison to unwrapped fillets	Chen et al. (2022)
Grass carp myofibrillar proteins (2 % w/v), glycerol (1.63 % w/v) and chitosan (2 % in 1 % acetic acid)	Rosemary extract (0.05 %, 0.10 %, 0.15 %, and 0.20 %)	The film-wrapped fillets from grass carp were kept at 4 °C for 10 days	The fillets without films crossed the threshold of 1 mg MDA/kg on day 8 and reached a value of 1.24 on day 10 whereas the TBARS values of the film-wrapped fillets manifested the values less than the limit from days 0 to 10	Du et al. (2021)
The dope solution for electrospinning was prepared using 10 ml of Poly (vinyl alcohol) (10 % w/v) solution, 0.1 g of Tween 20, and 0.5 g of grape seed oil	Grape seed oil (0.5 g/10 ml of dope solution)	The coated fillets from fresh rainbow trout were kept at 4 °C for 9 days	The TBARS values lowered significantly for the coated fillets from days 0 to 9 in comparison to uncoated fillets	Ceylan et al. (2021)
Atlantic salmon bone gelatine (2 %) and chitosan (2 %)	The bioactive agents used were clove oil (0.5 %) and gallic acid (0.2 %)	The coated fillets from Atlantic salmon (*Salmo salar*) were kept at 4 °C for 15 days	The TBARS values lowered significantly for the coated fillets from days 0 to 15 in comparison to uncoated fillets	Xiong et al. (2021)
The coating solution contained glycerol (0.75 %) and chitosan (2 %, in 1 % glacial acetic acid)	The bioactive agents used were lycopene (1.5 and 3.0 %) along with egg yolk antibodies (IgY, anti-*Shewanella putrefaciens* and anti-*Pseudomonas fluorescens*)	The coated fillets from rainbow trout were kept at 4 °C for 16 days	The peroxide (meq O_2/kg), free fatty acids (%) and TBARS values reduced significantly for the coated fillets from days 0 to 16 in comparison to uncoated fillets. TBARS values of 3.34 and 2.02, peroxide values of 9.86 and 5.77 and free fatty acid values of 5.08 and 3.65 were observed for control and coated samples (IgY + lycopene 3 %) on day 16 of storage, respectively	Ehsani et al. (2020)
The coating solution was developed using 10 % fish protein hydrolysates in glycerol and water (1:2) solution	Trout by-products were used to develop fish hydrolysates using an ultrasound-assisted (UA) and a conventional enzymatic (CE) method	The coated fillets from Bonito (*Sarda sarda*) were kept at 4 °C for 15 days	The TBARS values reduced significantly for the coated fillets from days 0 to 15 in comparison to uncoated fillets. TBARS values of 4.26, 4.42, and 7.28 mg MDA/kg were found for UA and CE-coated and uncoated fillets, respectively, on day 15	Balcik Misir and Koral (2019)
The coating solution contained 1.5 % chitosan prepared in 1 % acetic acid and seaweeds or their extracts	The bioactive agents used were two seaweeds viz. *Palmaria palmata* (1 %) and *Himanthalia elongata* (1 %) and their extracts	The coated burgers (50 g) prepared from minced meat of rainbow trout (*Oncorhynchus mykiss*) were kept at 4 °C for 7 days	The TBARS values reduced significantly for the coated (extracts from both seaweeds and *H. elongata*) burgers from days 0 to 7 in comparison to chitosan-coated burgers	Albertos et al. (2019)
The coating solution contained essential oils incorporated nanoparticles developed using sodium alginate (0.25 %)	The bioactive agents used were essential oils from *Cuminum cyminum* (0.125 %) and *Zataria multiflora* (0.125 %)	The coated fresh shrimp were kept at 4 °C for 15 days	The TBARS values reduced significantly for the coated fillets from days 0 to 15 in comparison to uncoated fillets	Osanloo et al. (2023)
The coating solution contained glycerol (2.5 %), ethanol (95 %) and zein-protein (10 %)	Three levels (6, 12, and 24 %) of nanoemulsion were used which was developed using garlic essential oil	The coated fresh shrimp were kept at 4 °C for 14 days	The TBARS and peroxide values reduced significantly for the coated fillets from days 0 to 14 in comparison	Rahnama et al. (2021)

(*continued on next page*)

Table 4 (*continued*)

Coating and film material	Bioactive agents	Storage conditions and product packaged	Major results	Citation
			to uncoated fillets. The lowest values for lipid oxidation were found for 24 % nanoemulsion-coated fillets	

15th day. The fillets coated with bioactive additives never surpassed the limit. This positive effect on lipid oxidation was imputed to the oxygen barrier characteristics of the material and the radical scavenging ability of the bioactive agents, preventing the exposure of the fillets to oxygen and quenching the free radicals generated during the cascade reactions of lipid oxidation.

Du et al. (2021) prepared an edible film using a base material composed of 2 % myofibrillar protein (extracted from grass carp) and 2 % chitosan and used 0.05–0.20 % rosemary extract to impart bioactive properties. The developed films were used to wrap the grass carp fillets and evaluated for lipid stability at 4 °C for 10 days. Significantly reduced means were recorded for FFA (g/100 g) and TBARS (mg MDA/kg) for the fillets wrapped within the extract-based films from 0 days onwards compared to unwrapped fillets. The lowest means were found for the film loaded with 0.2 % rosemary extract for both the parameters (TBARS and FFA) from days 0 to 10. The mean values for TBARS for unwrapped fillets surpassed the maximum-permissible limit (1 mg MDA/kg) on day 8 and rose to a value of 1.24 on day 10 whereas the mean values for treated samples were less than 1 mg MDA/kg on day 10 of storage. A favourable influence of a coating material loaded with grapeseed oil has also been reported by Ceylan et al. (2021) on the lipid stability of rainbow trout kept for 9 days at 4 °C. The bioactive properties were imparted to the coating solution using a 5 % grape seed oil which was incorporated into polyvinyl alcohol-based nanofibers developed by electrospinning method. The fillets coated with the solution showed markedly lower TBARS values from day 1 onwards and the mean values of 0.68, 1.14, and 1.65 were recorded for coated fillets and 0.93, 2.00, and 2.06 were found for uncoated fillets on days 3, 7, and 9, respectively. Other research studies have presented a favourable influence of films and coatings on the lipid stability of stored fish and their products. For example, Ehsani et al. (2020) documented a significant favourable effect of a coating developed from lycopene, chitosan, and egg yolk antibodies on lipid oxidation (FFA, TBARS and peroxide values) of fillets from rainbow trout kept for 16 days in a refrigerator. Albertos et al. (2019) found a favourable impact of a film prepared from chitosan, seaweeds (*P. palmata* and *H. elongata*) and their extracts on lipid stability (TBARS values) of rainbow trout burgers stored for one week. Balcik Misir and Koral (2019) observed a significant favourable effect of a coating made from the hydrolysates obtained from by-products of trout on TBARS values of *Sarda sarda* (Bonito) fillets during 14 days of storage.

Market size, commercial applications and constraints

The global market for edible coatings and films has been projected to grow at a rate of 7.70 % (CAGR) during the next five years to reach a value of 4.54 billion US$ in 2028 (Market Analysis Report, 2023). Some of the key players in this market include DuPont de Nemours Inc., Tate and Lyle PLC, Koninklijke DSM NV, Dohler Group, Ingredion Incorporated, Cargill Incorporated, Nagase America LLC, Lactips, Pace International, Kerry Group plc, Watson Inc., and LLC (Market Analysis Report, 2023). Despite the extensive research over the last many years, there have been limited successful commercial applications in the area of edible packaging especially for animal-derived foods. During the last few years, some edible packaging systems have been launched commercially for animal-derived foods such as meat and dairy products. For example, BioCheeseCoat and BioNutriCoat are two edible packaging systems introduced for cheese and cheese and meat, respectively, by 'Improveat'. Similarly, a bite-sized product (WikiPearls™) in the shape of a grape with an edible gel skin containing cheese, frozen yoghurt or ice cream was introduced by Stonyfield Farm.

Despite several advantages to the food industry in terms of enhanced storage quality and shelf life, some serious barriers and hurdles impede the growth and commercial uptake of this technology. Developing large-size workable films of uniform thickness is difficult, the ingredients are generally expensive and production is time-consuming. Further, most reported formulations produce fragile films with poor mechanical strength, water vapour and gas barrier properties and poor heat sealability compared to petroleum polymer-based films. These films cannot be used on their own and require the use of conventional packaging systems and therefore cannot help reduce the environmental burden of packaging. The use of higher and more effective levels of some bioactive agents has been reported to negatively affect the sensory quality and appearance of foods. A detailed review of the impact of edible packaging systems on the sensory quality of animal-derived foods has been presented in our recently published paper (Bhat et al., 2023). Further, there are some safety issues and toxicological effects of using some materials especially when used in the nano form. The application of coatings on meat and seafood using dipping methods at an industrial scale may lead to microbial build-up and affect the safety and quality of the products. This may necessitate the use of synthetic preservatives in the dipping solutions which are highly discouraged by modern consumers. Some of the animal-derived foods, such as fish, seafood, and meat, do not present a suitable matrix for these types of packaging due to the purge loss. Other barriers such as lack of clarity about consumer acceptance, lack of regulations and standards or differences between the nations, limited engineering developments and availability of automated systems, and sustainability concerns remain among the main hurdles to the wider commercial uptake and applications of this technology.

Conclusions

Lipid oxidation is one of the prime reasons for the degradation in the quality of stored animal-derived foods due to their unsaturated fatty acid profile and high-fat content. While natural preservatives offer a workable solution to reduce lipolysis and lipid oxidation safely, their inclusion may adversely affect the sensory attributes of the foods. Edible packaging systems can control lipid oxidation in combination with good oxygen barrier properties through the controlled release of bioactive principles and their delivery on the food surface. Studies have reported a broad range of biopolymers and bioactive agents which are effective in improving the lipid stability of stored foods of animal origin. Both direct additions of the phytochemicals to the film matrices or in the form of nanoparticles and nanoemulsions were effective in controlling the lipid oxidation of animal-derived foods. Studies should aim to use cheaper and readily available natural ingredients in the future to produce affordable packaging systems for foods of animal origin.

CRediT authorship contribution statement

Zuhaib F. Bhat: Conceptualization, Data curation, Methodology, Visualization, Writing – original draft. **Hina F. Bhat:** Data curation, Validation, Visualization, Methodology, Writing – review & editing. **Mehnaza Manzoor:** Resources, Software, Validation, Writing – review & editing. **Gholamreza Abdi:** Conceptualization, Data curation, Funding acquisition, Methodology, Software, Visualization, Writing – original draft. **Rana Muhammad Aadil:** Methodology, Resources, Software,

Validation, Visualization, Writing – review & editing. **Abdo Hassoun:** Validation, Visualization, Writing – review & editing. **Abderrahmane Aït-Kaddour:** Visualization, Validation, Writing – review & editing.

Declaration of competing interest

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

Data availability

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

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