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Assessment of lipid oxidation in fish and fish products processed by cold plasma technologies

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ABSTRACT

Plasmas generated at or near ambient temperature are emerging as mild, selective and environmentally friendly technologies for extending the shelf-life of perishable fish and fish products. However, the high degree of unsaturation makes fish lipids highly susceptible to the reactive oxygen and nitrogen species (RONS) of plasmas, which can trigger the onset and/or progression of lipid oxidation, leading to the formation of off-flavours, the loss of nutritionally valuable components (polyunsaturated fatty acids, proteins, vitamins) and the formation of risky or toxic substances. Despite numerous experiments on the decontamination effects of cold plasma on fish and fish products, the evaluation of lipid oxidation has been limited to a few parameters. Most studies have focused on measuring global indices of primary and secondary oxidation products (peroxide value and thiobarbituric acid reactive substances, respectively) and some researchers have analysed total fatty acid composition as an indirect measure of the degree of oxidation. However, more advanced analytical methods for the direct quantification of volatile and non-volatile chemical species derived from the oxidation of fatty acids and sterols have been performed only to a very limited extent. The results on the effects of cold plasma on lipid oxidation in fish and fish products are contradictory. Although several studies show a pro-oxidant effect of RONS, others report no significant effects on lipid oxidation and even a lower rate of lipid oxidation during storage of fish products.

1. Introduction

Edible fish, crustaceans and molluscs from marine and freshwater are highly susceptible to chemical, biochemical and microbiological spoilage due to their high water activity, near-neutral pH, high nutrient content and the presence of strong enzymatic (lipoxygenases, microsomal enzymes) and non-enzymatic (emoproteins, transition metals and ascorbate) prooxidants (Undeland et al., 1998). A variety of traditional thermal (sterilisation, pasteurisation, drying, smoking) and non-thermal (low temperature storage, salting, marinating, modified atmosphere packaging, vacuum packaging) preservation strategies have been used to extend the shelf-life of raw, canned and semi-preserved fish products. Thermal sterilisation and pasteurisation offer high reliability in terms of safety and microbiological stability but can lead to significant undesirable physical and chemical changes in the food, which are reflected in the organoleptic and nutritional properties. In addition, the low energy efficiency of conventional heating systems affects the sustainability of the fish processing industry. Other conventional preservation technologies either lead to a short shelf-life extension or to a significant impact on the sensory properties, so that the end products differ from fresh products.

Novel non-thermal technologies (high-pressure processing, pulsed light, ultrasound, pulsed electric field, cold plasma) make it possible to combine treatment selectivity with environmental sustainability and are gaining interest in the food industry as they respond to the growing consumer desire for fresh and healthy food and awareness of environmental issues (Allai et al., 2023; Jadhav et al., 2021; Yudhistira et al., 2023). Cold plasma (CP) is one of the latest technologies being explored for microbial decontamination of a variety of perishable foods (Kaur et al., 2024). Reactive oxygen species (ROS), reactive nitrogen species

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(RNS), charged particles, excited molecules and UV photons present in the plasma matrix are believed to be involved in the mechanisms of microbial inactivation (Liao et al., 2017; López et al., 2019; Moisan et al., 2002). The acronyms CP, CAP (cold atmospheric plasma) and NTP (non-thermal plasma) have become established in the scientific literature to denote plasmas that can be generated under "mild" conditions compatible with food applications, i.e. at or near ambient temperature and atmospheric or reduced pressure (Mandal et al., 2018).

Research on the application of CP technologies in the fish industry has increased exponentially over the last decade, focussing mainly on their effectiveness in the microbial decontamination of fish and fish products. However, fish lipids are expected to be a sensitive target for the reactive species that give plasma its microbicidal activity due to their structural characteristics, which could lead to undesirable effects on the sensory and nutritional properties of the final products and compromise their safety. This article provides a comprehensive review of the available experimental data on the oxidative degradation of the lipid fraction in products treated with direct and indirect CP technologies and critically analyses the parameters used to describe the oxidative state of fish lipids.

The literature search was carried out using the keywords "cold atmospheric plasma" and "plasma activated water" in the fields "Article title", "Abstract" and "Keywords" in the Scopus database (www.scopus.com). Since there is no significant history on the application of CP technologies for food safety and preservation before 2010, the time period was set from 2011 to 2024. The output was further refined using the keyword "lipid AND oxidation", resulting in a total of 99 and 77 references for the searches for "cold atmospheric plasma" and "plasma activated water" respectively. The abstracts were then analysed to select papers and reviews on marine and freshwater products. This resulted in a final selection of 66 references, the main contents of which are summarised in Table 1 and Table 2.

2. Application of cold plasma technologies in the fish industry

Numerous recent reviews (Abel et al., 2022; Conz et al., 2024; Esua et al., 2021a; Mousakhani Ganjeh et al., 2024; Olatunde et al., 2021b; Olatunde & Benjakul, 2018; Rathod et al., 2021, 2022; Tagrida et al., 2024; Ying et al., 2024; Zhao et al., 2018) show the growing interest in the potentialities of CP technologies in the fish industry. Direct and indirect plasma treatments have been tested on marine fish (Atlantic mackerel, chub mackerel, tuna, skipjack tuna, sardine, herring, silverfish, Alaska pollock, blackmouth angler, sea bream, hairtail fish, sea bass, filefish, golden pompano), freshwater fish (black carp, tilapia, bolti fish, silver carp, grass carp, Yellow River carp), catadromous fish (Asian sea bass, Atlantic salmon), crustaceans (Pacific white shrimp, blue swimming crab, whiteleg shrimp, crayfish), molluscs (Korean mud snake, oyster), cephalopods (squid), food preparations (smoked salmon, surimi, ready-to-eat sushi products, gwamegi) and other seafood (dried laver, herring fish oil) (Table 1). In direct treatments, the plasma is generated in the atmosphere surrounding the product. In indirect treatments, the reactive species generated in the gas phase penetrate and diffuse into the liquid medium, triggering a cascade of chemical reactions that leads to the formation of a complex solution of highly reactive chemical species (Gao et al., 2022; Surowsky et al., 2015; Thirumdas et al., 2018). The so-called "activated" or "functionalized" liquid is then used to decontaminate food, process equipment and packaging materials by immersion (washing), spraying or nebulisation (Herianto et al., 2023; Oliveira et al., 2022; Wong et al., 2023). The liquid medium is usually water (plasma activated water, PAW), but aqueous solutions (phosphate buffer, light brine, peracetic acid) have also been tested (Laurita et al., 2015; Perinban et al., 2019; Zhao et al., 2020, 2021). Another type of indirect treatment was developed by Ke et al. (2022a), in which CP treated air was used in the final stage of processing dry-cured black carp (*Mylopharyngodon piceus*).

Most published studies have focussed on the inactivation of natural microflora, which can have a negative impact on the safety and durability of fresh and processed fish products. Microbial group counts (total viable bacteria, total psychrotrophic bacteria, lactic acid bacteria, *Pseudomonas* spp, *Enterobacteriaceae*, hydrogen sulphide producing bacteria, yeasts, moulds) have often been used to evaluate the efficacy of CP treatments, although a number of studies have aimed to collect data on the kinetics of destruction of specific pathogenic and spoilage microorganisms, such as *Staphylococcus aureus* and *Bacillus cereus* (Choi et al., 2020), *Salmonella* spp (Esua et al., 2020; Jeon et al., 2022; Üçok et al., 2024), *Listeria monocytogenes* (Esua et al., 2020; Jeon et al., 2022), *Pseudomonas aeruginosa* (Zhao et al., 2022), *Shewanella putrefaciens* (Hu et al., 2023b; Liu et al., 2021; Qi et al., 2018), and laboratory surrogates for pathogens, such as *Listeria innocua* (Concha-Meyer et al., 2024).

Dielectric barrier discharge (DBD) and plasma jet (PJ) are the most commonly used plasma sources in laboratory experiments that provide data on the oxidation state of fish lipids (Table 1). In particular, DBD sources have been tested for their ability to extend the shelf-life of Pacific white shrimp (*Penaeus vannamei*) (Elliot et al., 2021; Liu et al., 2024b), sea bream (*Sparus aurata*) fillets (Giannoglou et al., 2021; Tappi et al., 2023), bolti fish (*Tilapia nilotica*) (Mohamed et al., 2021), and snakehead (*Ophiocephalus argus* Cantor) surimi gels (Huang et al., 2023). The DBD design offers the possibility to generate the plasma directly in the atmosphere inside the pre-packaged food, providing the opportunity to combine CP with modified atmosphere packaging (MAP) and eliminating the risk of post-process contamination. (Alaguthevar et al., 2024; Pankaj et al., 2018). Air can easily be used as filling gas and has been tested for the in-package DBD treatment of mackerel fillets (Albertos et al., 2017; Chen et al., 2019; Pérez-Andrés et al., 2020b), Atlantic herring (*Clupea harengus*) fillets (Albertos et al., 2019), hairtail (*Trichiurus lepturus*) (Xu et al., 2022), tilapia fillets (Wang, et al., 2022a, 2022b), red shrimp (*Solenocera crassicornis*) (Hu et al., 2023a), oyster (*Crassostrea gigas*) (Zhao et al., 2024), sushi products (Kulawik et al., 2018) and wine-pickled Korean mud snail (*Bullacta exarata*) (Lin et al., 2020). Nitrogen, argon/air mixtures (80:20), argon/oxygen mixtures (90:10 and 80:20), carbon dioxide/oxygen/nitrogen mixtures (80:10:10, 40:10:50 and 40:30:30) and carbon dioxide/argon/oxygen mixtures (60:30:10) were used for packaging Pacific white shrimp, silverfish (*Trachinotus ovatus*) pieces, Asian sea bass (*Lates calcarifer*) slices, blue swimming crab (*Portunus armatus*) meat, tilapia fillets and dried blackmouth angler (*Lophiomus setigerus*) (Cai et al., 2022; Choi et al., 2020; Olatunde et al., 2019a, 2019b, 2019c, 2020a, 2020b, 2021a; Sang et al., 2024; Shiekh et al., 2021a; Shiekh & Benjakul, 2020; Singh et al., 2021; Singh & Benjakul, 2020). Atmospheric pressure plasma jets (APPJ) allow localised treatments with high plasma density and have been used for the treatment of products with low water content, such as dried Alaska pollock (*Theragra chalcogramma*) shreds (Choi et al., 2016), dried and semi-dried squid (*Todarodes pacificus*) shreds (Choi et al., 2017a, 2017b), gwamegi (semi-dried Pacific saury) (Puligundla et al., 2018) and smoked salmon (*Salmo salar*) slices (Colejo et al., 2018). A corona discharge plasma jet (CDPJ) was used for microbial surface decontamination of thin sheets of dried laver, an edible red alga commonly used in ready-to-eat Korean rice rolls (gimbap or kimbab) (Kim et al., 2015).

Plasma jet and DBD are also the most popular plasma sources used in the production of PAW by ionising the atmosphere (air) in direct contact with the liquid phase. The effects of soaking in water activated by air plasmas on shelf-life were investigated on fillets of Yellow River carp (*Cyprinus carpio*) (Liu et al., 2021), golden pompano (*Trachinotus ovatus*) (Gao et al., 2024), tilapia (*Oreochromis mossambicus*) (Huang et al., 2024), grass carp (*Ctenopharyngodon idella*) (Esua et al., 2021b) and Asian sea bass (Wang, et al., 2024d). Different feeding gases were tested by Chanioti et al. (2023) (helium/air mixture) on sea bream fillets and by (Vichiansan et al. (2024)) (argon) on whiteleg Shrimp (*Litopenaeus vannamei*) and splendid squid (*Loligo formosana*). Zhu et al. (2023) used a plasma jet to activate slightly acidic electrolysed water (SAEW) and evaluated the effect of the activated liquid medium on microbial

Table 1
Summary of studies on the effects of CP technologies on the lipid fraction of fish and fish products.

Food matrix	Plasma source	Feed gas	Treatment conditions	Oxidation assays	Key findings in treated samples [1]	Notes	References
Direct treatments							
Atlantic mackerel (*Scomber scombrus*) fillets	DBD	Air (50% RH)	V = 70–80 kV; f = 50 Hz; t = 1–5 min	FA composition, PV, TBARS, Dienes (UV absorbance at 232 nm)	- decrease of DHA for the heavier treatment (80 Kv, 5 min) - significant development of primary oxidation (PV and Dienes)	In-package plasma treatment	(Albertos et al., 2017)
Herring (*Clupea harengus*) fillets	DBD	Air (50% RH)	V = 70–80 kV; f = 50 Hz; t = 5 min	TBARS	- faster increase than in the controls during storage at 4 °C	In-package plasma treatment	(Albertos et al., 2019)
Silverfish (*Trachinotus ovatus*)	DBD	$CO_2/O_2/N_2$ 80:10:10	V = 75 kV; t = 3 min	TBARS	- higher values than controls during 9 days of refrigerated storage	In-package plasma treatment	(Cai et al., 2022)
chub mackerel (*Scomber japonicus*) fillets	DBD	Air	V = 60 kV; t = 1 min	PV, TBARS	- slower increase in PV and TBARS than in the controls during storage at 4 °C	In-package plasma treatment	(Chen et al., 2019)
dried Alaska pollock (*Theragra chalcogramma*) shreds	CDPJ	Air	V = 20 kV; f = 58 kHz; t = 1–3 min	PV, TBARS	- TBARS values increase progressively with increasing exposure time		(Choi et al., 2016)
dried squid (*Todarodes pacificus*)	CDPJ	Air	V = 20 kV; f = 58 kHz; t = 1–3 min	TBARS	- TBARS increases progressively with increasing exposure time		(Choi et al., 2017a)
semi-dried squid (*Todarodes pacificus*)	CDPJ	Air	V = 20 kV; f = 58 Hz; t = 1–10 min	TBARS	- TBARS increases progressively with increasing exposure time		(Choi et al., 2017b)
dried blackmouth angler (*Lophiomus setigerus*)	DBD	N_2	V = 1 kV; f = 43 kHz; t = 1–30 min	TBARS	- higher TBARS		(Choi et al., 2020)
smoked salmon (*Salmo salar*) slices	Plasma jet	Air	P = 1 W; V = 2 kV; f = 1 kHz; t = 1–15 min	TBARS	- time-dependent increase (CP only) - time and energy dependent increase (CP + UV)	Combination of CP an UV	(Colejo et al., 2018)
Pacific white shrimps (*Penaeus vannamei*)	DBD	Air	V = 60 kV; t = 1–2.5 min	TBARS			(Elliot et al., 2021)
sea bream (*Sparus aurata*) fillets	DBD	Air	V = 3 kV; f = 45 kHz; t = 15 min	TBARS	- higher values than controls during 15 days of refrigerated storage		(Giannoglou et al., 2021)
myofibrillar protein isolate from hairtail fish (*Trichiurus lepturus*)	DBD	Air	V = 50 kV; t = 0.5–5 min	PV, TBARS			(Hatab et al., 2022)
snakehead (*Ophiocephalus argus* Cantor) surimi gels	DBD	Air	V = 40 kV; t = 1–2 min	TBARS, volatile substances	- TBARS increases progressively with increasing exposure time - increase in volatile oxidation products		(Huang et al., 2023)
dry-cured black carp (*Mylopharyngodon piceus*)	DBD	Air	V = 20 kV; f = 10 kHz; t = 3–12 min	PV, TBARS, FA composition, volatile and non-volatile markers of lipid oxidation	- CPTA exposure significantly increases PV (0–12 min), TBARS (0–6 min) and 4-OH-2-none-nal (0–12 min) - decrease of MUFAs (oleic acid) and PUFAs (linoleic acid) - increase of volatile oxidation markers	Cold plasma treated air (CPTA)	(Ke et al., 2022a)
ready-to-eat sushi products (nigiri and hosomaki)	DBD	Air	V = 70–80 kV; f = 50 Hz; t = 5 min	TBARS, FA composition	- higher TBARS	In-package plasma treatment	(Kulawik et al., 2018)
Ready-to-eat wine-pickled *Bullacta exarata*	DBD	Air (50% RH)	V = 40–60 kV; f = 36 kHz; t = 3 min	TBARS		In-package plasma treatment	(Lin et al., 2020)
tilapia fillets	DBD		V = 40–80 kV; t = 1–5 min	PV, TBARS	- increasing the voltage and extending the treatment time of CP leads to an increase in PV and TBARS	In-package plasma treatment	(Liu et al., 2023)
Pacific white shrimp (*Litopenaeus vannamei*)	DBD	Air (65% RH)	P = 72–112 W; V = 60–80 kV	TBARS	- higher TBARS		(Liu et al., 2024b)
tilapia fillets	DBD	Air	V = 70 kV; t = 3 min	TBARS	- antioxidants effectively inhibit lipid oxidation caused by CP treatment	In-package plasma treatment	(Liu et al., 2024a)

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Table 1 (*continued*)

Food matrix	Plasma source	Feed gas	Treatment conditions	Oxidation assays	Key findings in treated samples [1]	Notes	References
Direct treatments							
						Combined effect of CP and antioxidants	
bolti fish (*Tilapia nilotica*)	DBD	Air	P = 20.52–46.17 W; V = 40–60 kV; t = 1–4 min	TBARS, PV	- lower increase in PV and TBARS than in the controls during 10 days of storage at 4 °C		(Mohamed et al., 2021)
fresh sea bass (*Dicentrarchus labrax*)	Newly designed device	Air, He	V = 30 kV; f = 20 kHz; t = 0.5–10 min	TBARS	- higher TBARS values in samples exposed to He-plasma for more than 5 min after 5 days of cold storage		(Mol et al., 2023)
Pacific white shrimp (*Litopenaeus vannamei*)	Gliding arc discharge	Ar/air 50:50, 75:25, 100:0	P = 300 W; V = 26 kV; f = 50 Hz, t = 2–10 min	PV	- feeding gas and treatment time significantly influence PV		(Mousavi et al., 2022)
Asian sea bass (*Lates calcalifer*) slices	DBD	Ar/O_2 90:10	V = 16 kV; t = 5 min	TBARS, FA composition	- rapid increase in TBARS levels in slices exoised to CP - decrease of MUFA (oleic acid) and n-3 PUFAs (DHA, EPA) - antioxidants are effective in mitigating the lipid oxidation caused by plasma reactive species	In-package plasma treatment Combined effect of CP and antioxidants	(Olatunde et al., 2019a)
Asian sea bass (*Lates calcalifer*) slices	DBD	Ar/O_2 90:10 and 80:20	V = 8 kV; t = 2.5–10 min	TBARS, FA composition	- TBARS increases with increasing exposure time - n-3 PUFAs (EPA, DHA) and MUFAs (oleic acid) decrease with increasing treatment time	In-package plasma treatment	(Olatunde et al., 2019c)
Asian sea bass (*Lates calcalifer*) slices	DBD	Ar/O_2 90:10	V = 80 kV; t = 2.5–10 min	TBARS, FA composition	- TBARS increases rapidly with increasing exposure time and storage duration - n-3 PUFAs (EPA, DHA) and MUFAs (oleic acid) decreased with increasing exposure time and storage duration	In-package plasma treatment	(Olatunde et al., 2019b)
Asian sea bass (*Lates calcarifer*) slices	DBD	Ar/O_2 90:10 CO_2/Ar/O_2 60:30:10	V = 80 kV; t = 5 min	TBARS	- TBARS increases rapidly with increasing exposure time and storage duration	In-package plasma treatment	(Olatunde et al., 2020b)
Asian sea bass (*Lates calcarifer*) slices	DBD	CO_2/Ar/O_2 60:30:10	V = 80 kV; t = 5 min	TBARS, FA composition	- higher TBARS throughout the storage - lower oleic acid and PUFAs (EPA, DHA) - antioxidants are effective in mitigating the lipid oxidation caused by plasma reactive species	In-package plasma treatment Combined effect of CP and antioxidants	(Olatunde et al., 2020a)
blue swimming crab (*Portunus armatus*) meat	DBD	Ar/O_2 90:10	V = 80 kV; t = 5–15 min	PV, TBARS, FA composition	- PV and TBARS increase with increasing exposure time - higher PV, TBARS in CP-treated samples during cold storage - MUFAs (oleic acid) and PUFAs (linoleic acid, EPA, DHA) decrease with increasing exposure time	In-package plasma treatment	(Olatunde et al., 2021a)
dried filefish (*Stephanolepis cirrhifer*) fillets	UV light	Air	t = 3–20 min	TBARS	- increased TBARS value in fillets exposed to the longest (20 min) treatment time		(Park & Ha, 2015)
mackerel fillets	DBD	Air	V = 80 kV; t = 5 min	TBARS, FA composition		In-package plasma treatment	(Pérez-Andrés et al., 2020b)
gwamegi (semidried Pacific saury)	CDPJ	Air	V = 20 kV; f = 58 kHz; t = 1–10 min	PV, TBARS	- increased TBARS		(Puligundla et al., 2018)

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Table 1 (*continued*)

Food matrix	Plasma source	Feed gas	Treatment conditions	Oxidation assays	Key findings in treated samples [1]	Notes	References
Direct treatments							
semi-dried golden pompano	n.a.	Air	V = 70 V, t = 3 min	PV, TBARS, volatile markers of lipid oxidation	- increased PV and TBARS during 24 days storage at room temperature - increased volatile aldehydes and ketones	In-package plasma treatment	(Qiu et al., 2024)
tilapia fillets	DBD	$O_2/N_2/CO_2$ 10:50:40 Air $O_2/N_2/CO_2$ 30:30:40	V = 70 kV; t = 3 min	PV, TBARS, p-AnV, dienes (UV absorbance at 232 nm); FA composition	- higher PV, TBARS, p-AnV, dienes during 8 days of refrigerated storage - highest loss of PUFAs (linoleic acid) in samples packaged in $O_2/N_2/CO_2$ 30:30:40	In-package plasma treatment	(Sang et al., 2024)
Silver carp (*Hypophthalmichthys sinensis*) fillets	n.a.	Air	V = 65 kV; f = 60 Hz; t = 3–5 min	TBARS	- increased TBARS		(Shen et al., 2023)
Pacific white shrimp	DBD	Ar/O_2 80:20 Ar/Air 80:20	V = 16kV; t = 10 min	PV, TBARS, FA composition	- lower PV, TBARS at the end of storage in samples pre-soaked with antioxidants and treated with Ar/air plasma - lower oxidation of n-3 PUFAs (EPA and DHA) in samples pre-soaked with antioxidants and treated with Ar/Air plasma	In-package plasma treatment Combined effect of CP and antioxidants	(Shiekh & Benjakul, 2020)
Pacific white shrimp	DBD	Ar/Air 80:20	V = 16 kV; t = 10 min	PV, TBARS, FA composition	- lower lipid oxidation in samples treated with 2 % vegetable extract with the aid of PEF and VI and exposed to CP - loss of PUFAs mitigated by PEF/antioxidants pretreatment	In-package plasma treatment Combined effect of CP, PEF, VI and antioxidants	(Shiekh et al., 2021a)
whiteleg shrimp (*Litopenaeus vannamei*)	DBD	Ar/Air 80:20	V = 16 kV; t = 10 min	PV, TBARS, FA composition	- lowest PV and TBARS for the highest PEF energy and antioxidant concentration	In-package plasma treatment Combined effect of CP, PEF and antioxidants	(Shiekh et al., 2021b)
Asian sea bass (*Lates calcarifer*) slices	DBD	Ar/O_2 90:10	V = 16 kV; t = 5 min	PV, TBARS, FA composition	- lower TBARS and PV in samples pretreated with antioxidants throughout the storage - lower oxidation of PUFAs in samples pretreated with antioxidants throughout the storage	In-package plasma treatment Combined effect of CP and antioxidants	(Singh & Benjakul, 2020)
Asian sea bass (*Lates calcarifer*) slices	DBD	Ar/O_2 90:10 and 80:20	V = 16 kV; t = 5 min	PV, TBARS	- lower TBARS and PV in samples pretreated with antioxidants	In-package plasma treatment Combined effect of CP and antioxidants	(Singh et al., 2021)
gilthead sea bream (*S. aurata*) fillets	Newly designed device	Air	f = 1.0–1.5 kHz; t = 5–10 min	TBARS	- lipid oxidation is accelerated, especially under more intensive processing conditions (frequency, exposure time)	In-package plasma treatment	(Spanou et al., 2024)
seabream (*Spaurus aurata*) fillets	DBD	N_2/O_2 80:20 Ar/O_2 80:20	V = 6 kV; f = 5 Hz; t = 10–20 min	TBARS, FA composition	- significantly higher TBARS		(Tappi et al., 2023)
tilapia fillets	DBD	Air	V = 70 kV; t = 1–5 min	TBARS	- TBARS increases with increasing exposure time	In-package plasma treatment	(Wang, et al., 2022b)
golden pompano (*Trachinotus blochii*) fillets	n.a	n.a.	n.a.	PV, TBARS, FA composition	- coating and MAP are effective in retarding the lipid oxidation during storage - coating and MAP are effective in protecting UFAs (oleic acid, linoleic acid, EPA, DHA, DPA) from oxidation	Combined effect of CP, MAP and antioxidant-enriched coating	(Wang et al., 2023)
herring fish oil	DBD	Air	V = 50 V; t = 3 min	PV, TBARS, p-AnV, dienes and trienes (UV absorbance at 232 and	- vitamin E exhibits the most robust antioxidant activity	Combined effect of CP and antioxidants	(Wang et al., 2024a)

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Table 1 (*continued*)

Food matrix	Plasma source	Feed gas	Treatment conditions	Oxidation assays	Key findings in treated samples [1]	Notes	References
Direct treatments							
				268 nm), FA composition; volatile substances			
hairtail (*Trichiurus lepturus*)	DBD	Air	V = 50 kV; t = 2–5 min	TBARS	- lower TBARS during refrigerated storage	In-package plasma treatment	(Xu et al., 2022)
dried silver carp (*Hypophthalmichthys molitrix*)	n.a.	Air	V = 65 kV; t = 3–5 min	volatile substances	- higher content of aldehydes (hexanal, 2-octenal-(E), octanal, nonanal)		(Zhai et al., 2024)
oysters (*Crassostrea gigas*)	DBD	Air	V = 70 kV; t = 5–10 min	PV, TBARS, FA composition	- antioxidants effectively delay lipid oxidation during storage - antioxidants effectively inhibit the UFAs reduction	In-package plasma treatment Combined effect of CP and antioxidants	(Zhao et al., 2024)
PAW treatments							
Asian sea bass *(Lates calcarifer*) steak	RF	O_2, Ar	P = 28 W; V = 10 kV; t = 0.5–4 min	PV, TBARS	- lower PV and TBARS during refrigerated storage		(Chaijan et al., 2021)
Asian sea bass (*Lates calcarifer*) steak	RF	Air	P = 28 W; V = 10 kV; t = 3 min	PV, TBARS	- lower PV and TBARS than untreated and PAW-soaked samples during the 30-day cold storage period	Combined effect of PAW and edible coating enriched with antioxidants	(M. Chaijan et al., 2022)
sea bream (*Sparus aurata*) fillets	Plasma jet	He/Air	V = 7.2 kV; f = 82 kHz; t = 5–20 min	TBARS	- higher TBARS during refrigerated storage		(Chanioti et al., 2023)
grass carp (*Ctenopharyngodon idella*)	DBD	Air	V = 30–70 V; t = 4 min	PV, TBARS, p-AnV, FA composition	- combined treatments increase lipid oxidation (PV, TBARS, p-AnV) compared to single applications	Combined effect of plasma functionalized liquids and US	(Esua et al., 2021b)
golden pompano (*Trachinotus ovatus*) fillets	Plasma jet	Air	V = 65 kV; t = 15 min	TBARS	- higher TBARS during refrigerated storage - antioxidants are effective in mitigating the lipid oxidation induced by plasma reactive species	Combined effect of PAW and antioxidants	(Gao et al., 2024)
whiteleg shrimp (*Litopenaeus vannamei*)	PDDP	N_2/O_2 80:20, 85:15, 90:10, 95:5, and 100:0%	P = 60–70 W	TBARS	- lower rate of TBARS increase during storage	PAW as glazing agent	(Herianto et al., 2022)
tilapia (*Oreochromis mossambicus*) fillets	Plasma jet		P = 750 W; t = 10 min	FA composition			(Huang et al., 2024)
tuna	Corona discharge	Air	V = 20 kV; f = 10 kHz; t = 48 h	TBARS, FA composition	- TBARS decreases when the amount of added PAW increases - loss of MUFAs (oleic acid) and PUFAs (arachidonic acid)		(Ke et al., 2023)
Skipjack tuna (*Katsuwonus pelamis*) meat	Corona discharge	Air	V = 20 kV; f = 10 kHz; t = 5–20 min	TBARS, FA composition	- electrochemical treatment of PAW notably elevated the TBARS - reduction of MUFAs and PUFAs levels	electrochemically treated PAW	(Z. Ke et al., 2024)
shrimps (*Metapenaeus ensis*)	DBD		P = 30 W	TBARS	- lower rate of TBARS increase during storage	storage in PAW ice	(Liao et al., 2018)
Yellow River carp (*Cyprinus carpio*) fillets	Plasma jet	Air	P = 750 W; V = 5 kV; t = 1.5–6 min	TBARS	- significant increase of TBARS for the longest (6 min) dipping time)		(Liu et al., 2021)
sardine (*Sardina pilchardus*) fillets	Pulsed corona discharge	Air	P = 209 W; V = 18 kV; f = 5 kHz; t = 10–30 min	PV, FA composition, volatile markers of lipid oxidation, COPs	- loss of n-3 PUFA - increase in volatile oxidation products (4-heptenal; 2,4-heptadienal isomers; 3,5-octadien-2-one; n-nonanal)		(Mozzon et al., 2023)
sardine (*Sardina pilchardus*) fillets	Pulsed corona discharge	Air	P = 209 W; V = 18 kV; f = 5 kHz; t = 10–30 min	PV, dienes, trienes and tetraenes (UV absorbance at 232, 270 and 315 nm), FA composition, volatile	- increased UV specific absorbances (232, 270 and 315 nm)		(M. Mozzon et al., 2024)

(*continued on next page*)

Table 1 (*continued*)

PAW treatments							
				markers of lipid oxidation, COPs	- increased levels of C5-C9 secondary volatile oxidation products		
crayfish (*Procambarus clarkia*)	Plasma jet	Air	t = 20–60 min	TBARS	- lower TBARS	Combined effect of PAW and US	(Sun et al., 2023)
Asian sea bass (*Lates calcarifer*) fillets	Plasma jet	Air	V = 6.68 kV; f = 21.67 kHz; t = 1–3 min	TBARS	- higher values than PAW and DBD treatment carried our separately	Combined effect of PAW and in-package DBD	(Wang et al., 2024c)
Asian sea bass (*Lates calcarifer*) fillets	Plasma jet	Air	P = 750 W; t = 2.5 min	FA composition, volatile substances	- loss of UFAs (oleic, linoleic, linolenic and arachidonic acids, EPA, DHA) - higher content in aldehydes, ketones, and alcohols	Combined effect of PAW and in-package DBD	(Wang et al., 2024d)
Asian sea bass (*Lates calcarifer*) fillets	Plasma jet	Air	t = 2.5 min	FA composition	- loss of UFAs (oleic, linoleic, linolenic and arachidonic acids, EPA, DHA)		(Wang et al., 2024b)
raw mackerel fillets	Plasma jet	Air	P = 300 W; f = 20 kHz; t = 10 min	PV, TBARS		Combined effect of PAW, US and peracetic acid	(Zhao et al., 2021)
Atlantic salmon fillets	Plasma jet	Air	P = 320 W; t = 20 min	TBARS, p-AnV	- PAW and PASW better inhibit the lipid oxidation than electrolyzed water	Plasma-activated slightly acidic electrolyzed water (PASW)	(Zhu et al., 2023)

[1] Only statistically significant differences between controls and treatments are reported.
t = exposure time (direct treatments) or dipping time (PAW); n.a. = not available.
CDPJ = corona discharge plasma jet; CP = cold plasma; DBD = dielectric barrier discharge; FA = fatty acid; MAP = modified atmosphere packaging; p-AnV = p-anisidine value; PDDP = piezoelectric direct discharge plasma; PEF = pulsed electric fiels; PV = peroxide value; RF = radiofrequency; TBARS = thiobarbituric acid reactive substances; VI = vacuum impregnation.

Table 2
Summary of research articles evaluating lipid oxidation of fish and fish products treated with CP technologies.

Determination	Analytes		No. of references	
			Direct plasma treatments	Plasma functionalised liquids
UV absorption	λ_{max} = 230–232 nm	dienes; α,β-unsaturated carbonyl compounds	2	1
	λ_{max} = 268–270 nm	trienes; bifunctional oxidation products (ethylenic diketones); oxo-dienes	2	1
	λ_{max} = 315 nm	bifunctional oxidation products	-	1
PV	hydroperoxides		20	6
TBARS	carbonyl compounds (MDA, alkanals, alkenals, alkadienals), hydroperoxides, cyclic peroxides		45	14
p-AnV	α- and β-unsaturated aldehydes		2	2
Total fatty acid composition (GC of FAMEs)	MUFAs, PUFAs, EPA, DHA		18	8
GC–MS	volatile markers of lipid peroxidation (C6-C10 aldehydes, alcohols, and ketones)		4	3
COPs (GC–MS)	epoxy-, hydroxy- and keto-derivatives of cholesterol		-	2
Others	non-volatile hydroxylated α,β-unsaturated aldehydes		1	-
	lipidome		-	3

decontamination and physicochemical quality of Atlantic salmon fillets.

The growing knowledge of gas-liquid interactions in the production of PAW opens the way to the development of further applications for PAW and direct CP treatments. In Liao et al. (2018), ice made from frozen water activated by a DBD plasma source was proposed for the preservation of fresh shrimp. Compared to tap water ice, PAW ice significantly delays microbial growth and lipid oxidation and extends the storage time by 4–8 days. Herianto et al. (2022) investigated the effectiveness of PAW produced with a piezoelectric direct discharge plasma (PDDP) system as glazing agent for whiteleg shrimp. The glazing process effectively retards microbial growth and loss of physical (colour and firmness) and chemical properties (pH, total volatile basic nitrogen and thiobarbituric acid reactive substance). Kim et al. (2022) found that activation of rearing water by CP was effective against *Aeromonas hydrophila* without causing significant physiological damage to fish (*Cyprinus carpio haematopterus*), suggesting a promising future for CP technologies in aquaculture. More recently, Zorzi et al. (2023) have shown that the combination of CP and UV-A irradiation effectively inactivates *Listeria monocytogenes* and degrades organic matter without affecting the quality of trout fillet samples, indicating the suitability of the technology as a sustainable and chlorine-free means of decontaminating fish processing water.

3. Fish lipid oxidation

The reactive species responsible for microbial decontamination could cause undesirable changes in the food components, leading to the formation of off-flavours and/or hazardous substances that could limit the acceptability of the final products and jeopardise their safety. In particular, the oxidation of lipids has been observed in milk, vegetable products (wheat flour, nuts, vegetable oils), meat products (pork, beef and chicken) and fish products processed with CP technologies (Ganesan et al., 2021; Pérez-Andrés et al., 2018). The consequences of lipid oxidation can be potentially problematic in food matrices that are susceptible to this spoilage due to the composition of the lipid fraction (high degree of unsaturation) and/or the whole food (high lipid content

and/or low water activity). Oxidation of lipids is a major problem in the processing and storage of fish, crustaceans and molluscs (Maestre et al., 2011) due to the high relative proportion of polyunsaturated fatty acids (PUFAs) in their depot (triacylglycerols) and structural lipids (phospholipids) (Frega et al., 2002; Pacetti et al., 2015). Secci and Parisi (2016) analysed the factors influencing lipid oxidation of fish from farming to consumption and the measures to prevent oxidative spoilage throughout the fish supply chain. More recently, Wu et al. (2024) analysed the factors (plasma source, source parameters, fish species, lipid composition) affecting the oxidative degradation of the lipid fraction of marine and freshwater products after CP treatments. However, according to Ke et al. (2022b), the very short half-life of many reactive species generated by plasma sources and the ability of food components other than lipids to react with ROS/RNS cannot fully explain the progression of lipid oxidation in CP-treated animal tissues during storage. In fact, iron ions and other products derived from the degradation of heme in myoglobin may play a key role in the rate of lipid oxidation in fish muscle during storage.

Several biopreservatives derived from natural sources have been tested for their synergistic antimicrobial activity and their ability to counteract the oxidative pressure exerted by ROS/RNS on food components. Flavonoids with excellent antioxidant and antibacterial activities were extracted from the exocarp of coconut (*Cocos nucifera* L.) and were found to be effective in retarding microbial proliferation and lipid oxidation during storage of chilled Asian sea bass slices (Olatunde et al., 2019a) and oyster meat (Zhao et al., 2024) treated with a DBD plasma source. Olatunde et al. (2020a) suggested the use of liposomal encapsulated ethanolic coconut shell extract to limit the colour change of sea bass slices and improve the antimicrobial properties of the extract. Liu et al. (2024a) soaked tilapia fillets in a 60% ethanolic extract of mango fruit (*Mangifera indica* Linn.) and an aqueous extract of partridge tea (*Mallotus oblongifolius*) and Shiekh and Benjakul (2020) soaked Pacific white shrimp in aqueous leaf extract of Chamuang (*Garcinia cowa* Roxb.) before exposure to a DBD plasma source. Shiekh et al. (2021a, 2021b) enhanced the penetration of antioxidants (Chamuang leaf extract) into shrimp tissue by pulsed electric field (PEF) pretreatment and vacuum impregnation (VI). In Singh and Benjakul (2020) and Singh et al. (2021), chitooligosaccharide from squid pen chitosan was incorporated into Asian sea bass slices prior to plasma treatment. In the study by Wang et al. (2023), an edible film of chitosan enriched with the essential oil of wampee (*Clausena lansium* Skeels) seeds was tested in combination with CP treatment and MAP for quality preservation and shelf-life extension of golden pompano fillets during cold storage. Chaijan et al. (2022) investigated the effect of a combination of PAW soaking followed by edible coating of whey protein isolate enriched with aqueous ginger extract (*Zingiber officinale*) on the cold storage stability of Asian sea bass steaks. All natural extracts were effective in inhibiting lipid oxidation of fish products, as evidenced by lower indices of primary and secondary lipid oxidation and lower loss of unsaturated fatty acids (UFAs).

Interestingly, Gao et al. (2024) observed that the order of treatment significantly influenced the result: marinating in an aqueous solution of flavonoids from coconut exocarp followed by soaking in PAW was more effective in protecting against lipid oxidation (lower thiobarbituric acid reactive substances) than soaking in PAW followed by marinating in flavonoids.

4. Assessment of lipid oxidation

Autoxidation and photooxidation of food lipids generate a complex mixture of volatile and non-volatile substances whose relative amounts are influenced by a variety of factors, i.e. fatty acid (FA) composition, amount of free FAs, content of pro- and antioxidants (natural or added). The inherent complexity of lipid oxidation, exacerbated by the interactions of these factors and matrix effects, makes the choice of the appropriate method for monitoring the oxidative state of lipids a real challenge (Abeyrathne et al., 2021; Kanner & Rosenthal, 1992; Kerrihard et al., 2015).

Gavahian et al. (2018), Perinban et al. (2019) and Herianto et al. (2021) have recently reviewed and discussed the oxidative effects of CP technologies on food fats, but despite the large amount of experimental data on the decontamination effect of plasma, the currently available data on the oxidative degradation of food lipids are sparse and limited to a few parameters. The classical indices for measuring the oxidative degradation of food lipids (peroxide value, UV specific extinctions at 232 and 270 nm, p-anisidine value and thiobarbituric acid reactive substances) have been used for more than seven decades and are still the most popular (Table 2), as they have minimal equipment requirements, can be easily compared with literature data and have been shown to be related to sensory evaluations.

4.1. Indices of primary oxidation

Primary lipid oxidation products (FA hydroperoxides) can be quantified by iodometry, VIS and UV spectrometry, Fourier transform infrared spectroscopy (FTIR), chemiluminescence, liquid chromatography-mass spectrometry (LC-MS) (Kanner & Rosenthal, 1992; Kerrihard et al., 2015).

4.1.1. Peroxide value

Traditional methods for the determination of hydroperoxides exploit their oxidising properties. Therefore, the peroxide value (PV) should be considered as a quantitative expression of the total amount of substances that can oxidise the reagent under the test conditions and is therefore strictly dependent on them. If hydroperoxides are the main contributors to the index value, other reducing substances may also contribute depending on their nature and reactivity.

Reverse iodometric titration is the most commonly used analytical method for the quantification of lipid hydroperoxides, but several authors (Albertos et al., 2017; Chaijan et al., 2021, M. 2022; Hatab et al., 2022; Olatunde et al., 2021a; Shiekh et al., 2021a, 2021b; Shiekh & Benjakul, 2020; Singh et al., 2021; Singh & Benjakul, 2020) have used the spectrophotometric method based on the oxidation of iron(II) ions and subsequent complexation of iron(III) ions with thiocyanate. In addition, Mohamed et al. (2021) have used the ferric-xylenol orange (FOX) method, in which a different reagent, namely xylenol orange, is used to form a coloured complex with iron(III) ions that can be quantified by spectrophotometry. The spectrophotometric methods are simpler than iodometric titration, and the iron(II) ion is less sensitive to oxygen than the iodide, which reduces bias. (Abeyrathne et al., 2021). The determinations were usually carried out on the lipid extract obtained according to the method originally developed by Folch et al. (1957) or the modification proposed by Bligh and Dyer (1959). However, several authors (Chen et al., 2019; Esua et al., 2021b; Mohamed et al., 2021; Mousavi et al., 2022; Olatunde et al., 2021a; Shiekh et al., 2021b; Singh et al., 2021; Singh & Benjakul, 2020) have performed the titrimetric or spectrophotometric measurements on samples homogenised directly in the solvent mixture.

In CP-treated samples, PV ranged from < 0.1 meq O/kg in tilapia fillets (Sang et al., 2024) to 46.48 meq/kg in golden pompano fillets (Wang et al., 2023). However, the use of different units of measurement makes it difficult to compare the literature data. Ke et al. (2022a) and Sang et al. (2024) reported the result of iodometric titration in g I/100 g. Chaijan and co-workers (Chaijan et al., 2021, 2022) provided the result of PV determination by the iron(III)/thiocyanate method in absorbance unit at 500 nm, but other authors (Olatunde et al., 2021a; Shiekh et al., 2021a, 2021b; Shiekh & Benjakul, 2020; Singh et al., 2021; Singh & Benjakul, 2020) used cumene hydroperoxide to make the calibration curve and observed PV in the range of 1–15 mg cumene hydroperoxide/kg in CP-treated swimming crabs, Pacific white shrimp and Asian sea bass.

The main criticism of PV relates to the chemical instability of hydroperoxides, which can lead to an inverted U-shaped trend over time,

as observed by Chen et al. (2019) in chub mackerel fillets and by Singh and Benjakul (2020) in Asian sea bass slices treated with a DBD source and stored at 4 °C for 16 and 18 days, respectively. On the other hand, a progressive increase in PV was reported by Qiu et al. (2024) during 24 days of room temperature storage of semi-dried golden pompano and by several authors during refrigerated storage (from 8 to 30 days) of PAW-treated Asian sea bass steaks (Chaijan et al., 2021, 2022) and DBD-treated bolti fish, blue swimming crab, tilapia fillets, Pacific white shrimp, oysters, and herring fish oil (Mohamed et al., 2021; Olatunde et al., 2021a; Sang et al., 2024; Shiekh et al., 2021b; Shiekh & Benjakul, 2020; Wang et al., 2024a; Zhao et al., 2024). These are two manifestations of a process in which the formation and degradation of hydroperoxides occur simultaneously on different time scales, each with its own specific dependence on temperature (generally assumed to be of the Arrhenius type). The possibility of recording a peak in the value of PV (or any other oxidation index) at a given temperature is related to the difference between the two time scales with respect to the duration of the experiment. It follows that the simple measurement of PV cannot have a decisive analytical meaning and does not allow a correct positioning of the fat/oil on the time axis (degree of oxidative damage): a relatively low PV could indicate either an early or a late stage of oxidative degradation. This is particularly true for lipid matrices that have undergone heat treatments (e.g. frying) or other technological interventions that can greatly accelerate the degradation of hydroperoxides. The assessment of the oxidation state by PV measurement retains some relevance for lipid matrices rich in monounsaturated fatty acids (MUFAs), as other analytical determinations (Section 4.1.2.) may be less sensitive. In addition, the assays do not require expensive and sophisticated instrumentation.

Although PV does not detect volatile compounds, it is a measure of quality deterioration and could be a useful predictor of sensory evaluation and consumer acceptance. The strength of this correlation depends on the type of food matrix and the key odour substances (Kerrihard et al., 2015). A threshold of 10 meq/kg was used by Chen et al. (2019) to estimate an 8-day extension in the shelf-life of pre-packaged chub mackerel treated with DBD.

There are contradictory results in the literature on the effects of CP treatments on the primary oxidation of fish lipids. Sang et al. (2024) observed an increase in PV of tilapia fillets pre-packaged in different atmospheres (air; $O_2/N_2/CO_2$ 10:50:40 and 30:30:40) after a 3-min exposure to a DBD plasma source and during an 8-day cold storage. Similar results were reported for semi-dried golden pompano stored at room temperature for 24 days (Qiu et al., 2024) and for blue swimming crab meat pre-packaged in Ar/O_2 90:10 and stored at 4 °C for 12 days (Olatunde et al., 2021a). Primary oxidation of Atlantic mackerel fillets, tilapia fillets and dry-cured black carp was found to increase with increasing source voltage and/or application time (Albertos et al., 2017; Ke et al., 2022a; Liu et al., 2023). In addition, Wang et al. (2024a) observed a PV increase in herring fish oil subjected to plasma treatment with a DBD source at a voltage of 50 V for a duration of 3 minutes. Zhao et al. (2024) found that CP treatment significantly aggravated lipid peroxidation in oysters (higher PVs), but the PVs of the treated group were significantly lower than those of the untreated group after 4–8 days of cold storage. Similar behaviour was observed in PAW-treated Asian sea bass slices during 30 days of refrigerated storage (Chaijan et al., 2021), in chub mackerel fillets treated with a DBD source and stored at 4 °C for 16 days (Chen et al., 2019) and in DBD-treated tilapia samples during 10 days of refrigerated storage (Mohamed et al., 2021). Mousavi et al. (2022) also reported lower PVs in Pacific white shrimp treated with a gliding arc plasma source than in the untreated samples. Chaijan et al. (2021) attributed the lower PV increase in PAW-treated sea bass to the denaturation of surface protein induced by ROS and the acidity of PAW, which could hinder the diffusion of oxygen and reactive species into the fish tissue. Chen et al. (2019) and Mohamed et al. (2021) hypothesised that CP has an inhibitory effect on endogenous lipase and/or lipase-carrying microorganisms, which could limit the production of free FAs that are more susceptible to oxidation than esterified complex lipids (Frega et al., 1999). Sun et al. (2023) attributed the inhibitory effect of PAW treatments on lipid oxidation to microbial decontamination and destruction of prooxidative enzymes.

Mozzon et al. (2023, 2024) reported no significant effect of plasma treatments on sardine fillets after soaking in PAW for 10–30 minutes, Zhao et al. (2021) on mackerel fillets dipped in PAW, Choi et al. (2016) and Puligundla et al. (2018) on dried Alaska pollock shreds and gwamegi directly exposed to a corona discharge plasma jet. Hatab et al. (2022) treated myofibrillar protein isolate from hairtail with air plasma generated by a DBD source for different exposure times (30 to 300 s) and reported PVs in the narrow range of 4.20–4.23 meq/kg with no significant differences between treated and untreated samples.

4.1.2. Conjugated polyenes

Non-volatile conjugated polyenoic systems are formed by the shift of double bonds in naturally occurring methylene-interrupted hydrocarbon chains of PUFAs in the early stages of lipid oxidation. Conjugated dienes and trienes can be easily and quickly quantified with a UV–VIS spectrophotometer, as they have absorption maxima in the range of 230–232 and 268–270 nm, respectively, depending on the solvent used. Mozzon et al. (2024) found higher specific absorbances at 232, 270 and 315 nm in lipid extracts of sardine fillets immersed in PAW than in controls immersed in distilled water, especially at the longer soaking time (30 min). Albertos et al. (2017) also reported an increase in UV absorbance in the conjugated triene region (268 nm) in mackerel fillets exposed to direct contact with plasma generated in the packaging atmosphere by a DBD source, while Sang et al. (2024) observed increased absorbance at 232 nm in tilapia fillets treated with a DBD plasma source. Wang et al. (2024a) found increased dienes/trienes in herring fish oil treated with air plasma generated by a DBD source, but lower absorbance at 232 and 268 nm in treated than untreated samples after 7 days of storage.

The degradation of hydroperoxides can produce carbonyl groups conjugated to carbon-carbon double bonds, which are characterised by absorption maxima in the dienic (α,β-unsaturated ketones) and trienic range (ethylenic diketones, ketodienes). Secondary oxidation can therefore influence the level of absorption in the UV region, as can other food components that contain conjugated double bonds such as carotenoids.

According to Kerrihard et al. (2015), UV absorption often shows a good correlation with PV and sensory evaluation. Apparently good correlations between conjugated dienes/trienes and PV were observed in mackerel fillets treated with CP at different source voltages and exposure times (Albertos et al., 2017) and in tilapia fillets under different treatment conditions (Sang et al., 2024), while Mozzon et al. (2024) found no correlation in PAW-soaked sardine fillets due to high variability or replicates. Wang et al. (2024a) also described a different behaviour between PV and conjugated dienes/trienes during a 7-day storage at room temperature of herring fish oil treated with a DBD plasma source.

4.2. Indices of secondary oxidation

Various degradation products of hydroperoxides are used to assess the extent of oxidative damage of food lipids: malondialdehyde (MDA; direct determination by UV spectrophotometry or HPLC; derivatisation with thiobarbituric acid and VIS spectrophotometry or fluorimetry), carbonyl compounds (direct determination by GC–MS or HPLC; p-anisidine value), non-volatile polymers (LC-MS). Despite criticism of its reproducibility and reliability, the 2-thiobarbituric acid (TBA) test is widely used. In fact, it is the most commonly used analytical method to assess the oxidative damage of the lipid fraction of marine and freshwater products after direct and indirect CP treatments (Table 2).

4.2.1. Thiobarbituric acid reactive substances

Aldehydes coming from the degradation of hydroperoxides yield coloured products with various reagents, which can be quantified by spectrophotometry. Depending on the reagent used, the relative contribution of the various aldehydes to the colour intensity changes. TBA is considered specific for MDA and MDA-like products, even if they are less represented than other oxidation products such as alkenals and alkadienals, as well as for compounds that can develop MDA under the test conditions (unsaturated aldehydes, hydroperoxides of FAs with three or more double bonds). The acronym TBARS (thiobarbituric acid reactive substances) designates the group of chromogenic substances for the reaction with TBA.

Numerous protocols are described in the literature, but they can be traced back to three basic strategies for carrying out the reaction with TBA: (a) directly on the acidified matrix and possible subsequent extraction of the pigments; (b) on the volatile fraction collected by steam distillation; (c) on the aqueous acid extract of the matrix. Acid extraction with 5–20% trichloroacetic acid (TCA) is the most commonly used method, followed by direct reaction in TCA/TBA or HCl/TBA (Herianto et al., 2022), while the distillation method was rarely used (Choi et al., 2020; Mol et al., 2023).

For CP-treated fish and fish products, the authors reported TBARS values in a wide range, from <0.1 to 70 mg MDA/kg. Some authors reported the results of the TBA test in different units: Choi et al. (2016, 2017a) reported 1.85–57.79 mg MDA/kg on a dry matter basis in dried Alaska pollock and dried squid, while Ke et al. (2023) and Huang et al. (2023) reported 14.05–74.28 μmol MDA/kg in PAW-treated tuna and DBD-treated surimi gel, respectively. Since the qualitative and quantitative composition of the plethora of newly formed aldehydes is closely related to the FA composition of the analysed lipid substance, the comparison of data from different fish products may not be meaningful. This consideration can also be transferred to other aldehyde indices (e.g. p-anisidine value).

As discussed in Section 4.1.1, direct and indirect CP treatments can inhibit lipid oxidation and lead to lower TBARS levels after treatment and a slower increase in TBARS levels during storage than in controls. These results were reported for tilapia fillets (Mohamed et al., 2021), hairtail (Xu et al., 2022), chub mackerel fillets (Chen et al., 2019), oysters (Zhao et al., 2024), salmon fillets (Zhu et al., 2023), Asian sea bass steaks (Chaijan et al., 2021) and crayfish (Sun et al., 2023). In addition, glazing with PAW and storage in PAW ice were also effective in slowing the TBARS increase during storage of shrimp (Herianto et al., 2022; Liao et al., 2018). Ke et al. (2023) observed a decrease in TBARS of tuna muscle homogenised with increasing amounts of PAW, which could not be due to the inhibition of lipid oxidation, as UFAs (mainly oleic and arachidonic acids) were also significantly reduced in the same samples. The authors also demonstrated that nitrite in the acidic media can react with MDA during the analytical procedure, reducing the amount of MDA measured.

CP treatment was found to have no effect on lipid oxidation in mackerel fillets during a 7 days of storage at 4 and 8 °C and a 14 days of storage at -20 °C (Pérez-Andrés et al., 2020b), in mackerel fillets exposed to DBD plasma at different voltages and application times (Albertos et al., 2017), in Atlantic herring treated at 70 kV for 5 minutes (Albertos et al., 2019), in wine-pickled Korean mud snail (Lin et al., 2020), in Pacific white shrimp (Elliot et al., 2021) and in myofibrillar protein isolate from hairtail fish (Hatab et al., 2022).

In contrast to the above findings, several articles report that CP promotes lipid oxidation in fish and fish products. The same treatment conditions (80 kV, 5 min, DBD) had no effect on mackerel fillets (Albertos et al., 2019), but increased TBARS in Atlantic herring (Albertos et al., 2017). DBD plasma treatment was found to increase the secondary products of lipid oxidation, as measured by TBARS, in silverfish (Cai et al., 2022), dried blackmouth angler (Choi et al., 2020), dry-cured black carp (Ke et al., 2022a), tilapia fillets (Liu et al., 2023; Sang et al., 2024; Wang et al., 2022b), semi-dried golden pompano (Qiu et al., 2024), sushi products (nigiri and hosomaki) (Kulawik et al., 2018), Pacific white shrimp (Liu et al., 2024b), Asian sea bass slices (Olatunde et al., 2019b, 2019c, 2020a, 2020b), blue swimming crab (Olatunde et al., 2021a), snakehead surimi gel (Huang et al., 2023), silver carp fillets (Shen et al., 2023) and sea bream (Giannoglou et al., 2021; Tappi et al., 2023). A significant increase in TBARS levels was observed in dried Alaska pollock shreds (Choi et al., 2016), semi-dried squid (Choi et al., 2017a, 2017b), gwamegi (semi-dried raw Pacific saury) (Puligundla et al., 2018) and smoked salmon (Colejo et al., 2018) treated with plasma jets. Similar results were obtained in sea bass treated with a newly designed plasma source (Mol et al., 2023), in dried filefish fillets exposed to air plasma generated by high-energy UV light (Park & Ha, 2015) and in gilthead sea bream fillets treated with a novel pin-to-plate plasma generator (Spanou et al., 2024). Soaking in PAW enhanced lipid oxidation and contributed to higher TBARS levels in Yellow River carp fillets (Liu et al., 2021), sea bream fillets (Chanioti et al., 2023) and golden pompano fillets (Gao et al., 2024). Zhao et al. (2021) observed that a single PAW treatment increased the TBARS values of mackerel fillets, while no significant change was observed after the combination of ultrasound (US) and PAW. Immersion of grass carp cuboids in plasma-activated liquids (deionised water, citrate-phosphate buffer) and their combination with US showed significant increases in TBARS and p-AnV (Esua et al., 2021b). Electrochemical treatment of PAW to enhance the redness of tuna meat resulted in a significant increase in TBARS (Ke et al., 2024). Wang et al. (2024c) combined the effects of PAW soaking and direct in-package treatment with a DBD plasma source to extend the shelf-life of Asian sea bass fillets during refrigerated storage. The authors reported effective microbial decontamination but the highest TBARS for PAW-DBD samples after 15 days of refrigerated storage.

The extremely low perception thresholds make carbonyl compounds the key contributors to organoleptic properties compared to other volatile oxidation products (alcohols, hydrocarbons, furans) (see Section 4.2.4.). Indeed, a significant correlation between TBARS and sensory evaluations is frequently reported in the literature and many authors have used threshold values for TBARS to predict the shelf-life of CP-treated fish and fish products (Albertos et al., 2019; Cai et al., 2022; Chen et al., 2019; Choi et al., 2016; Esua et al., 2021b; Lin et al., 2020; Mohamed et al., 2021; Mol et al., 2023; Olatunde et al., 2019a, 2019b, 2019c; Secci & Parisi, 2016; Shen et al., 2023; Sun et al., 2023). However, the threshold at which TBARS values indicate that secondary volatile oxidation products can be detected by consumer has been reported to be in a wide range (0.5–10 mg MDA/kg), which limits the use of TBARS as a freshness index.

The main criticisms attributed to the TBA test are its inaccuracy and low sensitivity. As previously reported, MDA is only a minor compound in oxidised oils rich in oleic and linoleic acids and its formation depends on the composition of the lipid fraction. In addition, other food components can react with TBA as lipid oxidation products (e.g. proteins, carbohydrates, free amino acids) and form coloured end products, leading to an overestimation of oxidation (Abeyrathne et al., 2021).

4.2.2. p-anisidine reactive substances

The newly formed carbonyl compounds include both volatile aldehydes, which are characterised by extremely low odour thresholds and are therefore organoleptic early indicators of oxidative damage, and non-volatile aldehydes, which form on the structure of triacylglycerols during lipid oxidation. The p-anisidine value (p-AnV) is an index of total carbonyl compounds, both low and high molecular weight substances. It may therefore be a more appropriate parameter than the colourimetric measurement of the adduct with TBA, but has rarely been used in studies on lipid oxidation of fish and fish products induced by CP treatments.

Sang et al. (2024) investigated the effects of feeding gas on lipid oxidation of tilapia fillets treated with a DBD plasma source and found that CP treatment significantly increased all primary (PV, conjugated dienes) and secondary (TBARS, p-AnV) lipid oxidation indices. Esua

et al. (2021b) showed that contact of grass carp cuboids with plasma-activated liquids (deionised water, citrate-phosphate buffer) and their combinations with US increased p-AnV (and PV, TBARS, as previously reported). DBD treatment was found to increase p-AnV, PV and TBARS levels in herring fish oil (Wang et al., 2024a). In contrast, PAW and plasma-activated slightly acidic electrolysed water (PASW) were found to decrease p-AnV in Atlantic salmon fillets compared to fresh fillets (Zhu et al., 2023).

The test is particularly sensitive to the strong-smelling α- and β-unsaturated aldehydes and many studies confirm the correlation of p-AnV with sensory perceptions and volatile substances (Kerrihard et al., 2015). However, only Wang et al. (2024a) reported that the findings on the volatiles of CP-treated herring fish oil were consistent with the values of TBARS and p-AnV.

4.2.3. Total oxidation index

The TOTOX (TOTal OXidation) index is derived from the weighted linear combination of PV and p-AnV to overcome the limitations of the two parameters and allow a more effective assessment of the actual state of oxidative alteration of a fatty substance, as it can be conceptually interpreted as a combination of past (p-AnV) and current (PV) oxidative history. It was only used by Sang et al. (2024) and Wang et al. (2024a) to give an overall assessment of oxidative deterioration of tilapia fillets and herring fish oil treated with a DBD plasma source.

4.2.4. Volatile substances

The degradation of the odourless and tasteless hydroperoxides leads to the formation of various low-molecular weight compounds with a distinct odour, whose structures reflect the substrate and the chemical pathway.

Headspace sampling by SPME (solid phase micro extraction) and subsequent gas chromatography-mass spectrometry (GC–MS) analysis of oxygenated volatile compounds has proven to be a sensitive and reliable method for assessing the oxidation progress of food lipids, but little data is currently available for seafood processed with CP technologies. In the headspace of the lipid fraction extracted from sardine fillets, Mozzon et al. (2023, 2024) detected several markers of lipid oxidation originating from the β-cleavage of hydroperoxide isomers, which strongly increase after 10–30 minutes of soaking in PAW: saturated and unsaturated aldehydes (hexanal, n-octanal, n-nonanal, 2-pentenal, 2-hexenal, 4-heptenal, 2,4-heptadienal), ketones (3-penten-2-one, 3,5-octadien-2-one), alcohols (2-penten-1-ol) and cyclic compounds (2-ethylfuran). Qiu et al. (2024) extended the shelf-life of semi-dried golden pompano by 10–12 days by exposing the pre-packaged product to a DBD plasma source. CP treatment resulted in a significant increase in straight-chain alkanals (hexanal, heptanal, nonanal, undecanal) derived from the most abundant oleic and linoleic acids, as well as ketones (3-hydroxy-2-butanone, 2-undecanone and 3,5-octadien-2-one) and alcohols (2,3-butanediol and 1-octen-3-ol). However, the increase in volatiles in the CP-treated samples during storage at room temperature was slower than in the control samples, suggesting that microbial decontamination plays a role in the development of the flavour. Zhai et al. (2024) investigated the flavour profile of silver carp meat that was pretreated with a DBD plasma source and then salted and dried. In the headspace of the final product, the authors found that aldehydes (hexanal, 2-octenal, octanal and nonanal) were the most abundant and increased in the CP-treated dried samples. Wang et al. (2024a) investigated the physical and chemical properties of herring fish oil treated with air plasma generated by a DBD device. After CP treatment, the relative abundance of aldehydes decreased, while ketones and alkanes increased. The addition of antioxidants (curcumin, tea polyphenols, vitamin E and β-carotene) led to a decrease in the relative abundance of alcohols and olefins, while the proportion of aldehydes, ketones and alkanes increased.

Gas chromatography-ion mobility spectrometry (GC-IMS) is becoming increasingly popular as a novel analytical technique for food quality control. This technology combines the separation capacity of capillary GC with the fast response of ion mobility spectrometry, providing a two-dimensional data matrix that correlates well with sensory assessments by trained panels. It also requires no pre-processing of samples. Huang et al. (2023) analysed the aroma characteristics in snakehead surimi gels under the influence of different DBD treatment times. Alkanals and alkenals were the most abundant volatiles in the samples exposed to CP for 60 s, while alcohols were the most abundant in the samples treated for longer (90–120 s). Ke et al. (2022a) used CP-treated air in the final stage of processing dry-cured black carp. Ten odour-active substances (1-octen-3-ol, 3-methylbutanal, hexanal, heptanal, octanal, 2-nonenal, nonanal, 2,4-nonadienal, decanal, 2,4-decadienal, 1-octen-3-one) increased significantly the longer the fish were exposed to the sanified air. A negative correlation between the content of odour-active substances and UFAs in CP-treated fish spoke for the origin of the volatile substances from FA hydroperoxides. Wang et al. (2024d) identified 38 volatiles in the headspace of Asian sea bass fillets treated with PAW, DBD and a combination of dipping in PAW and exposure to a DBD plasma source. Higher levels of aldehydes, ketones and alcohols were found in the PAW-DBD group. Hexanal in particular showed the greatest increase, followed by nonanal and octanal.

Attempts have been made to assess the relative contribution of volatile compounds to the overall aroma profile (Fang et al., 2018; Gómez-Cortés et al., 2015; Vandamme et al., 2015; Xu et al., 2017; Zhai et al., 2024) used the odour activity value (OAV), which is calculated as the ratio of the concentration to the perception threshold in water/air, to identify the key substances in the aroma of CP-treated dried silver carp. However, several critical factors (few data on odour detection thresholds, the variety of internal standards used to quantify volatiles and the unpredictable interactions between volatiles) severely limit the reliability of the quantitative parameters proposed to weigh the contributions of volatiles to sensory perception. Although hexanal is often chosen as a typical marker to measure the degree of oxidation of food lipids, the high relative proportion of PUFAs in seafood draws attention to other strong odorants such as 2,4-heptadienal and 4-heptenal that may contribute to the unpleasant fishy aftertaste (Gómez-Cortés et al., 2015; Xu et al., 2017).

The increase in volatile oxidation products induced by CP treatments affects the sensory properties of seafood at a very early stage of oxidative degradation of tissue lipids and reduces the overall acceptability of the product (Olatunde et al., 2020b; Park & Ha, 2015). However, several authors have pointed out that mild oxidation of UFAs does not significantly affect the overall acceptability of fish and fish products (Giannoglou et al., 2021; Olatunde et al., 2019c, 2020a) or may even be beneficial for the development of better sensory properties of seafood during storage (Ke et al., 2022a; Puligundla et al., 2018). Wang et al. (2024d) pointed out that the increase in ketones and alcohols effectively mitigated the fishy odour and improved the overall flavour profile of Asian sea bass fillets after a combined treatment with PAW and DBD. The positive effects of CP treatments on fish flavour were attributed to the microbicidal activity of plasma reactive species and the resulting reduced production of trimethylamine oxide (TMO) during storage (Olatunde et al., 2019b; Wu et al., 2024; Zhou et al., 2024). Zhou et al. (2024) recently reviewed the mechanisms of off-flavour formation in farmed freshwater fish and the innovative strategies to eliminate them and concluded that CP technologies can effectively mitigate undesirable sensory characteristics.

4.2.5. Cholesterol oxidation products

The presence of a double bond in position 5,6 of the B-ring makes cholesterol, like MUFAs, susceptible to autoxidation and photooxidation reactions and a number of polar (epoxy, hydroxy and keto derivatives) and non-polar (dienes, dienones, enones) cholesterol oxidation products (COPs) have been described in the literature. Polar COPs in particular have been studied for decades, as dietary intake of exogenous polar COPs leads to their accumulation in various organs and tissues, where

they can exert toxic effects associated with various degenerative diseases such as cancer, Alzheimer's and Parkinson's disease, age-related macular degeneration, cataracts and osteoporosis (Maldonado-Pereira et al., 2018). Due to the widely varying degrees of toxicity, the identification and quantification of the chemical species produced during the oxidative degradation of cholesterol is essential for assessing the safety of CP technologies. The ability to monitor and control the levels of these substances in food is a crucial step for the successful introduction of these technologies in food processing and for their scale-up from pilot plant to industrial production.

Pérez-Andrés et al. (2020a) first reported the ability of a DBD plasma source to degrade pure cholesterol in a model system, but no data on degradation products were presented. Details of cholesterol oxidation triggered by plasma reactive species have been described by Mozzon et al. (2023, 2024): twelve COPs (7-hydroxycholesterol epimers, 6-hydroxycholesterol epimers, 4-hydroxycholesterol epimers, 5-hydroxycholesterol, 5,6-epoxycholesterol isomers, 7-ketocholesterol and cholestane-3,5,6-triol isomers) were identified or tentatively identified in sardine fillets after soaking in PAW for 10–30 min. The authors reported a total COPs content of 88.6–171.1 μg/g fish fat, corresponding to 374–736 μg/100 g fresh weight and 0.92–2.74% of total cholesterol. These values are consistent with the total COPs content found in raw sardines by Barreira et al. (2023) (39.53 ± 2.14 μg/g dry weight), de Carvalho et al. (2021) (11.5 ± 0.1 μg/g dry weight) and Saldanha et al. (2008) (19.4 ± 0.4 μg/g dry weight), but are lower than the values observed by Ferreira et al. (2017) (61.2 ± 2.8 μg/g dry weight) and higher than the values reported by Cardenia et al. (2013) (62–371 μg/100 g fresh weight).

Although Mozzon and co-workers (Mozzon et al., 2023, 2024) found no significant effect of PAW treatment on the degree of cholesterol oxidation in sardine fillets, the COPs levels detected could pose a risk to human health according to the threshold of toxicological concern (TTC) for unclassified compounds (0.15 μg/person/day) reported by Cardenia et al. (2013). The same authors observed a significant increase of COPs in sardine fillets after only 4 hours of cold storage under light exposure. Therefore, measures should be taken to avoid a further increase of COPs in cholesterol-containing foods during processing and storage.

The reaction mechanisms involved in the formation of COPs are largely understood (Iuliano, 2011). The qualitative and quantitative profile of COPs could therefore provide useful information on the preferred mechanism of oxidation and help to clarify the relationships between the causes (plasma reactive species) and the effects (COPs), allowing the optimisation of process conditions. Mozzon et al. (2023) suggested that the free radical-mediated oxidation pathway, which led to a predominance of 7-hydroxy and 7-keto derivatives (65–71% of total COPs), and epoxidation, whose products (5,6-epoxycholesterol isomers) accounted for 14–20% of total COPs, were major contributors. The formation of 5,6-epoxides can occur via both free radical and non-radical mediated pathways, depending on which chemical species (hydrogen peroxide, peroxynitrite, ozone, FA hydroperoxides and peroxyl radicals) triggers the oxidative cascade. In addition, the presence of 5- and 6-hydroxy derivatives supports the contribution of photosensitised oxidation of cholesterol by concerted ene addition of singlet oxygen, which involves the shift of Δ5-unsaturation.

4.3. Fatty acid composition

The total FA composition determined by GC of their methyl ester derivatives can serve as an indirect measure of the extent of oxidation, since a decrease in MUFAs and PUFAs can be expected.

The literature data on the FA composition of fish and fish products subjected to various direct and indirect CP treatments are contradictory. A decrease in MUFAs (oleic acid) and/or PUFAs (linoleic acid, arachidonic acid, DHA, EPA) was observed in Asian sea bass slices and mackerel fillets exposed to direct plasma treatment by a DBD source (Albertos et al., 2017; Olatunde et al., 2019a, 2019b, 2019c, 2020a; Singh & Benjakul, 2020), in dry-cured black carp after exposure (3–12 min) to CP-treated air (Ke et al., 2022a), in crab meat packaged in modified atmosphere (Ar/O2 90:10) and exposed to a DBD plasma source for 5 to 15 min (Olatunde et al., 2021a), in tilapia fillets pre-packaged with different gas mixtures and exposed to a DBD source (Sang et al., 2024), in sardine fillets after 10–30 min soaking in PAW (Mozzon et al., 2023), in Asian sea bass fillets after PAW and combined PAW-DBD treatments (Wang et al., 2024b, 2024d) and in tuna meat dipped in PAW and electrochemically treated PAW (Ke et al., 2023, 2024). Notably, no EPA was detected in Asian sea bass slices after 12 days of refrigerated storage, regardless of the exposure time (5–10 min) to argon/oxygen plasma generated by a DBD source (Olatunde et al., 2019b). Wang et al. (2024a) found a decrease in the relative content of PUFAs in herring fish oil after CP treatment, but the percentages of PUFAs changed only minimally after the addition of curcumin and vitamin E. Several authors (Shiekh et al., 2021a, 2021b; Shiekh & Benjakul, 2020; Zhao et al., 2024) showed that soaking with antioxidants in combination with PEF and VI effectively mitigated the loss of PUFAs in Pacific white shrimp and oysters, as summarised in Section 3.

A 5.86% reduction in EPA and a 2.34% reduction in DHA was found in sea bass skin after 18 days of ice storage (Sae-leaw & Benjakul, 2014). The same authors emphasised the role of lipoxygenase in the fish skin, whose activity increased significantly after nine days of ice storage. Therefore, further studies are needed to verify whether the loss of UFAs is due to a direct interaction with plasma reactive species or whether enzymatic pathways are involved.

In contrast, Mozzon et al. (2024) observed no significant differences in FA composition between controls and PAW-soaked sardine fillets, although there was evidence of plasma-induced oxidation of PUFAs (increased UV absorbances, volatile oxidation products, TBARS, PV, and p-AnV). Similar results were reported by Huang et al. (2024) in PAW-soaked tilapia fillets, by Kulawik et al. (2018) in sushi products exposed to a DBD plasma source and by Esua et al. (2021b) in grass carp exposed to a combination of plasma-functionalised liquids (deionised water, citrate-phosphate buffer) and sonication. Mackerel fillets treated directly with CP from a DBD source also showed no significant differences in the content of nutritionally valuable PUFAs (EPA, DHA) (Pérez-Andrés et al., 2020b). Tappi et al. (2023) reported that plasma treatment did not significantly affect FA composition in undigested and in vitro digested sea bream fillets. The same authors pointed out the potential of digestibility studies to provide information on the bioaccessibility of FAs, i.e. the percentage of ingested FAs that is released from the food matrix during digestion and is available for absorption.

According to Kulawik et al. (2018), the increase in TBARS without significant differences in FA composition suggests that TBARS could be formed from other non-lipid molecules such as proteins, nucleic acids or carbohydrates, confirming the unsuitability of global indices to describe the oxidative state of dietary fats and lipid fractions of foods.

4.4. Other analyses

Only a very limited number of studies focussed on analytes other than FAs and their previously described primary and secondary oxidation products, namely hydroperoxides, volatile and non-volatile aldehydes and COPs. Ke et al. (2022a) determined the content of non-volatile hydroxylated α,β-unsaturated aldehydes, which are closely related to the oxidation of n-6 and n-3 PUFAs, in black carp dried with CP-treated air and found that the content of 4-hydroxy-2-nonenal increased from 1.56 μg/kg to 6.05 μg/kg when the exposure time was extended from 0 to 12 min. Mozzon et al. (2023, 2024) reported no significant effect of PAW-soaking on the content of oxidation-sensitive substances identified in the unsaponifiable matter of lipids extracted from sardine fillets, namely squalene and α-tocopherol.

More recently, a lipidomic approach based on LC-MS has been used to investigate the changes in Asian sea bass muscle lipid profiles after treatment with PAW (Wang et al., 2024b) and after a combined

immersion in PAW and exposure to a DBD source (Wang et al., 2024d). A comparative analysis between the treated and control samples revealed the presence of more than 100 lipid molecules identified as "differentially abundant". These molecules were primarily associated with 20 metabolic pathways, predominantly involving the glycerophospholipid metabolism. Huang et al. (2024) also applied a metabolomic approach using UPLC-Q-TOF/MS to an 80% aqueous acetonitrile extract of tilapia fillets dipped in PAW and stored refrigerated. A total of 37 metabolites derived from the hydrolysis and oxidation of tissue lipids were identified and a significant down-regulation of some products of FA oxidation (4-hydroxy-octanoic acid, 4-amino-pentanoic acid) was detected in PAW-treated samples. LC-MS-based lipidomics analyses could be a valuable tool to gain new insights into the changes in cellular metabolism induced by CP treatments and thus contribute to the understanding of the chemistry and biochemistry of interactions between plasma reactive species and fish lipids. However, these studies are still very limited and have so far been restricted to PAW-treated tilapia and sea bass fillet, while no data are available for direct plasma treatments of fish and fish products.

5. Conclusions

There are conflicting results in the literature on the effects of CP technologies on lipid oxidation in marine and freshwater products. Although several studies show, as expected, a pro-oxidative effect of the plasma reactive species, others report no significant effects on lipid oxidation and even a lower rate of lipid oxidation during storage of fish products. This emphasises the complexity of the interactions between reactive species and fish components and the number of variables involved in the onset and progression of oxidative degradation of fish lipids. Most of these findings are limited to the classical assays for primary and secondary oxidation products (PV, conjugated dienes, TBARS, p-AnV) and total FA composition, the latter as an indirect measure of the degree of oxidation, while advanced analytical methods for the direct quantification of volatile and non-volatile chemical species derived from the oxidation of FAs and sterols have been performed only to a very limited extent. On the other hand, the studies carried out so far on the effects of CP in fish lipids show a remarkable fragmentation, with a large number of products (marine and freshwater fish, seafood, food preparations) tested under very different conditions. This makes it a major challenge to compare literature data and, above all, to clarify the cause-and-effect relationships in order to identify critical operating parameters and pave the way for optimising of the process conditions.

Further research is needed to take CP technologies from the experimental phase in laboratories, to which they are currently limited, to pilot plants and large-scale applications. In particular, it is crucial to increase the knowledge on the safety aspects of the technology, as only limited data on toxic oxidation products have been published so far, to investigate the oxidation products of lipids other than FAs, to minimise the loss of natural antioxidants (e.g. tocopherol, ascorbate) and the increase in oxidation products of antioxidants (e.g. tocopherolquinone or ascorbyl radical) and to establish acceptable thresholds for oxidation based on nutritional and safety criteria.

CRediT authorship contribution statement

Massimo Mozzon: Writing – review & editing, Writing – original draft, Visualization, Supervision, Investigation, Conceptualization. **Roberta Foligni:** Writing – original draft, Investigation. **Cinzia Mannozzi:** Writing – review & editing, Investigation. **Sauro Vittori:** Writing – review & editing, Supervision.

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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