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Lipid oxidation in food systems: Mechanisms, detection methods, and prevention strategies

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Abstract
The degradation of unsaturated fatty acids results in the formation of off-flavors, toxic compounds, and nutrient loss; it can occur through enzymatic or non-enzymatic pathways; factors such as oxygen, heat, light, and pro-oxidant metals play a critical role in its progression; precise detection methods, such as peroxide value, TBARS, and advanced spectroscopic techniques, are crucial for monitoring and controlling lipid oxidation; and prevention strategies, such as the use of antioxidants, packaging innovations, and controlled storage conditions, help mitigate oxidative damage, so maintaining food quality and safety. A comprehensive understanding of the mechanisms and preventive approaches is crucial for enhancing food preservation and promoting consumer health.

Keywords: Lipid oxidation, food quality, nutritional safety, shelf life, sensory properties, unsaturated fatty acids, off-flavors

1. Introduction

Because it significantly affects the nutritional value, safety, shelf life, and sensory qualities of food products, lipid oxidation is a major concern in food systems (Wang *et al*., 2023) [55]. The breakdown of unsaturated fatty acids is a complicated process that results in the production of poisonous chemicals, off flavours, and a reduction in vital nutrients (Lunn and Theobald, 2006) [32]. The presence of oxygen, light, heat, and pro-oxidant metals are some of the variables that affect the mechanisms of lipid oxidation, which can occur through enzymatic or non-enzymatic routes (Dragoev, 2024) [14]. For food quality to be guaranteed, lipid oxidation must be accurately detected and quantified using methods like peroxide value, thiobarbituric acid reactive substances (TBARS), and sophisticated spectroscopic techniques (Barriuso *et al*., 2013) [6]. A variety of preventative techniques, such as the application of synthetic and natural antioxidants, innovative packaging, and carefully monitored processing conditions, have been developed to lessen lipid oxidation (Tian *et al*., 2013) [52]. To improve food preservation and preserve consumer health, it is essential to comprehend the underlying mechanisms, detection techniques, and preventive measures.

2. Mechanisms of Lipid Oxidation

A basic chemical process called lipid oxidation has a big influence on the nutritional content, safety, and quality of food products, especially those high in unsaturated fatty acids (Wang *et al*., 2023) [55]. Lipids and oxygen interact in this intricate mechanism to produce primary oxidation products like hydroperoxides, which then break down into secondary molecules like alcohols, ketones, and aldehydes (Johnson and Decker, 2015) [27]. Unwanted alterations in flavour, taste, colour, and texture are caused by these oxidation products, which can also shorten food's shelf life and compromise its safety since harmful compounds may occur (Ogwu and Ogunsola, 2024) [39]. Autoxidation, photooxidation, and metal-catalyzed oxidation are examples of enzymatic or non-enzymatic routes by which lipid oxidation can occur (Wanjala, 2022) [56]. Gaining an understanding of these mechanisms is crucial to creating techniques that effectively stop or slow down lipid oxidation, protecting the stability and quality of food systems that contain lipids (Shahidi and Zhong, 2010) [46].

2.1. Initiation
The initial and most crucial stage of lipid oxidation is called initiation, and it sets the stage for a series of chemical events that jeopardise the nutritional value, safety, and quality of food products (Wang *et al*., 2023) [55]. Lipid radicals are created during this stage when lipid molecules, especially unsaturated fatty acids, undergo hydrogen abstraction mostly as a result of exposure to reactive oxygen species (ROS), heat, light, or metal catalysts (Jadhav *et al*., 1995) [26]. The propagation phase is accelerated by these extremely unstable radicals' quick reaction with molecular oxygen to produce lipid peroxyl radicals (Yin *et al*., 2011) [62]. Developing focused solutions to prevent lipid oxidation and prolong the shelf life of foods containing lipids requires an understanding of the mechanisms behind initiation (Shahidi and Zhong, 2010) [46].

2.2. Propagation
The quality, safety, and shelf life of food systems are all greatly impacted by the intricate chain reaction known as lipid oxidation (Wang *et al*., 2023) [55]. One of its stages, the propagation phase, is a crucial mechanism that, once started, continues the oxidative breakdown of lipids (Frankel, 1984). Lipid radicals and molecular oxygen react during propagation to produce peroxyl radicals, which then take hydrogen atoms from other lipid molecules to create new lipid radicals and hydroperoxides (Yin *et al*., 2011) [62]. As a result of this cycle's rapid continuation, oxidative products including aldehydes, ketones, and other secondary chemicals build up and cause rancidity, off flavours, and other health hazards. Developing efficient methods to regulate lipid oxidation during food processing and storage requires an understanding of the propagation mechanisms.

2.3. Termination
The last phase of lipid oxidation, termination, is essential for stopping the chain reaction that causes lipids in food systems to degrade (St. Angelo *et al*., 1996) [48]. Free radicals produced during the start and propagation stages of lipid oxidation combine with oxygen and unsaturated fatty acids to form hydroperoxides and secondary oxidation products, which lead to rancidity, off flavours, and a reduction in nutritional value (Rouzer and Marnett, 2003) [44]. Free radicals like peroxyl and alkoxyl radicals combine to create stable, non-radical end products during the termination phase, so halting the chain reaction (Abd El, 2012) [1]. This stage is essential for regulating the degree of lipid oxidation, and environmental factors like temperature and light exposure, as well as the availability of antioxidants and lipid composition, can affect how effective it is (McClelland, 2004) [36]. Gaining knowledge of the termination processes can help design solutions to improve lipid stability and extend food products' shelf lives.

2.4. Factors Influencing Lipid Oxidation
Food products' quality, safety, and shelf life are greatly impacted by the intricate chemical process of lipid oxidation, especially those high in fats and oils (Hu and Jacobsen, 2016) [24]. It involves lipids reacting with air to produce rancidity, bad flavours, and perhaps hazardous chemicals (Shahidi and Hossain, 2022) [46]. The degree of fatty acid unsaturation, the presence of pro-oxidants such metal ions, exposure to light and heat, the availability of oxygen, and the presence or lack of natural or synthetic antioxidants are some of the variables that affect the rate and magnitude of lipid oxidation (Islam *et al*., 2023) [25]. Furthermore, processing and storage conditions, as well as the physical makeup of the food matrix, are important factors. To effectively regulate lipid oxidation and guarantee food quality and safety, it is imperative to comprehend these influencing factors (Wang).

2.4.1 Fatty acid composition (degree of unsaturation)
Lipids' susceptibility to oxidation is largely determined by their fatty acid content, specifically the level of unsaturation (Shahidi and Zhong, 2010) [46]. Because polyunsaturated fatty acids (PUFAs) contain numerous double bonds that act as reactive sites for oxygen and free radicals, they are particularly vulnerable to oxidative destruction (McClelland, 2004) [36]. In addition to degrading food's nutritional value and sensory appeal, lipid oxidation produces potentially hazardous substances (Wang *et al*., 2023) [55]. The kind and location of double bonds, the length of the fatty acid chain, the presence of pro-oxidants or antioxidants, environmental factors like temperature and light, and processing techniques are some of the variables that affect the rate and degree of lipid oxidation. Understanding the relationship between fatty acid composition and oxidation mechanisms is essential for developing effective strategies to improve the stability and shelf life of lipid-containing food products (Shahidi and Zhong, 2010) [46].

2.4.2 Presence of pro-oxidants (e.g., Fe^{2+}, Cu^{2+})
Lipid oxidation is accelerated in food systems by the presence of pro-oxidants such ferrous (Fe^{2+}) and cupric (Cu^{2+}) ions (Jadhav *et al*., 1995) [26]. Through redox cycling, these metal ions catalyse the breakdown of lipid hydroperoxides into free radicals, starting and sustaining oxidative chain reactions (Abd El, 2012) [1]. These pro-oxidants' content, chemical form, binding affinity to food ingredients, pH, and the presence of chelating agents are some of the factors that affect their activity (Vertuani *et al*., 2004) [54]. Furthermore, the availability and reactivity of metal ions can be impacted by food processing methods and storage conditions (Watzke, 1998) [57]. Developing efficient antioxidant solutions to preserve the nutritional value, safety, and quality of foods containing lipids requires an understanding of the impact of pro-oxidants.

2.4.3 Oxygen availability
One of the main causes of food systems' declining quality, lipid oxidation, is initiated and progressed in large part by oxygen availability (Jadhav *et al*., 1995) [26]. Peroxides and secondary oxidation products, which cause rancidity, off flavours, and decreased nutritional value, are the result of a chain reaction known as lipid oxidation, which starts when oxygen molecules contact with unsaturated fatty acids (Dragoev, 2024) [14]. The physical makeup of food matrices, storage conditions, and packing materials are some of the variables that affect oxygen availability (Gupta, 2024) [23]. Lipids may be exposed to more oxygen due to oxygen-permeable packaging or insufficient sealing, which speeds up oxidation. Moreover, environmental factors such as temperature and light can enhance oxygen diffusion and promote oxidative reactions (Fan *et al*., 2024) [16]. Understanding the dynamics of oxygen availability is essential for developing effective strategies to mitigate lipid oxidation and extend the shelf life of lipid-containing food products.

2.4.4 Light and temperature exposure
Exposure to light and temperature has a significant impact on a number of biological and chemical processes, particularly in food systems (Bhabani *et al*., 2024) [7]. The shelf life, stability, and quality of food products can all be greatly impacted by these environmental conditions (Subramaniam and Wareing, 2016) [49]. Exposure to light, especially ultraviolet (UV) light, can cause sensitive substances like vitamins, pigments, and lipids to degrade, resulting in nutrient loss and aesthetic alterations (Farris and Valacchi, 2022) [17]. Conversely, temperature influences microbial growth, enzymatic activity, and the rate of chemical reactions, all of which can lead to food preservation or spoiling. Developing measures to prevent damage and preserve the nutritional value and sensory qualities of food products requires an understanding of the mechanisms through which temperature and light affect food quality (Amit *et al*., 2017) [3].

2.4.5 Water activity and pH
Water activity and pH are critical factors influencing lipid oxidation in food systems (McClements and Decker, 2000) [3]. Water activity, which refers to the availability of free water in a food product, plays a significant role in the rate of oxidation reactions. A higher water activity typically promotes the activity of enzymes and microorganisms, leading to accelerated oxidation, while lower water activity can slow down these processes (Tapia *et al*., 2020) [51]. pH, on the other hand, affects the stability of lipids by influencing the behavior of pro-oxidant and antioxidant compounds (Zhou and Elias, 2012) [65]. In an acidic environment, lipid oxidation is often faster due to the increased formation of reactive oxygen species, whereas alkaline conditions tend to stabilize lipids by inhibiting the production of these reactive species (Shahidi and Zhong, 2010) [46]. Understanding the interplay between water activity and pH is essential for developing strategies to control lipid oxidation and enhance the shelf life and nutritional quality of food products (Barden and Decker, 2016) [5].

3. Detection and Measurement of Lipid Oxidation
The complicated process of lipid oxidation causes lipids to break down, which can lead to unfavourable alterations in food quality such rancidity, off flavours, and decreased nutritional value (German, 1999) [21]. Lipid oxidation must be detected and measured in order to guarantee food safety and quality and to comprehend the fundamental principles driving this process (Wang *et al*., 2023) [55]. Lipid oxidation is measured using a variety of analytical techniques, from more sophisticated ones like mass spectrometry (MS), gas chromatography (GC), and high-performance liquid chromatography (HPLC) to more conventional ones like peroxide value and thiobarbituric acid reactive substances (TBARS) (Barriuso *et al*., 2013) [6]. These methods allow for the detection of primary and secondary oxidation products, enabling researchers and food industry professionals to monitor oxidative stability, optimize food preservation, and develop strategies to prevent or mitigate lipid oxidation in food systems (Barriuso *et al*., 2013) [6].

3.1. Primary Oxidation Products
- **Peroxide Value (PV):** Measures hydroperoxides; a common early indicator of lipid oxidation (Gotoh *et al*., 2011) [22].
- **Conjugated Dienes and Trienes:** UV absorbance of conjugated double bonds formed during oxidation (Takagi *et al*., 1987) [50].

3.2. Secondary Oxidation Products
- **Thiobarbituric Acid Reactive Substances (TBARS):** Measures malondialdehyde (MDA); indicative of secondary oxidation (Papastergiadis *et al*., 2012) [40].
- **Gas Chromatography (GC):** Identifies and quantifies volatile compounds like hexanal and pentanal (Romeu-Nadal *et al*., 2004) [43].

3.3. Advanced Methods
- High-Performance Liquid Chromatography (HPLC)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Electron Spin Resonance (ESR) for free radicals
- Nuclear Magnetic Resonance (NMR) for molecular structure changes

Table 1: Detection Methods for Lipid Oxidation in Food Systems

Method	Target Oxidation Products	Principle	Common Applications	Reference
Peroxide Value (PV)	Primary (Hydroperoxides)	Measures peroxide content via iodometric titration	Edible oils, fats	Zhang *et al*., 2021 [63]
Conjugated Dienes/Trienes	Primary (Conjugated double bonds)	UV absorbance at 232-270 nm due to conjugated dienes/trienes	Plant oils, meat products	Yerlikaya and Gokoglu, 2010 [61]
Thiobarbituric Acid Reactive Substances (TBARS)	Secondary (Malondialdehyde)	Spectrophotometric detection of MDA-TBA complex at 532 nm	Meat, fish, dairy	Reitznerová *et al*., 2017 [42]
p-Anisidine Value	Secondary (Aldehydes)	Reacts with aldehydes to form Schiff bases; absorbance at 350 nm	Oils, fats	Dubois *et al*., 1996 [15]
Total Oxidation Value (TOTOX)	Combined Primary & Secondary	Calculated as TOTOX = 2 × PV + p-Anisidine value	Comprehensive oil assessment	Juncos *et al*., 2024 [28]
Fluorometric Method	Secondary (Aldehydes)	Fluorescent detection of oxidation products; excitation/emission at specific wavelengths	Meat, fish, cereals	Radotićet *al*., 2023
Gas Chromatography (GC)	Secondary (Volatile compounds)	Separation and quantification of volatile oxidation products like aldehydes and ketones	Meat, oils	Bueno *et al*., 2019 [10]
High-Performance Liquid Chromatography (HPLC)	Primary & Secondary	Separation and quantification of hydroperoxides and aldehydes	Various food matrices	Zhao *et al*., 2021 [64]
Electron Spin Resonance (ESR)	Free Radicals	Detection of unpaired electrons in free radicals	Research applications	Davies, 2016 [30]
Nuclear Magnetic Resonance (NMR)	Structural Changes	Identifies molecular changes due to oxidation	Detailed structural analysis	Capitani *et al*., 2012 [11]
Rancimat Method	Oxidative Stability	Measures induction period by monitoring volatile acids under accelerated conditions	Edible oils	Xu *et al*., 2017 [60]
OXITEST	Oxidative Stability	Determines oxygen uptake under accelerated oxidation conditions	Shelf-life prediction	Tsao *et al*., 2021 [53]

4. Strategies for Prevention of Lipid Oxidation

Lipid oxidation is a major concern in food systems, leading to the deterioration of quality, flavor, and nutritional value, as well as the potential formation of harmful compounds (Amaral *et al*., 2018) [2]. Preventing lipid oxidation is critical for enhancing the shelf life and safety of food products. Strategies for the prevention of lipid oxidation include the use of antioxidants (Shahidi and Zhong, 2010) [46], both natural (such as tocopherols, polyphenols, and essential oils) and synthetic (such as BHT and BHA), to scavenge free radicals and inhibit oxidative reactions. Additionally, controlling environmental factors such as light, temperature, and oxygen exposure can significantly reduce oxidative damage (Xie *et al*., 2019) [59]. Incorporating novel packaging techniques, such as vacuum or modified atmosphere packaging, and optimizing food formulations with a balance of fatty acid composition also contribute to effective prevention (Mastromatteo *et al*., 2010) [34]. Understanding the mechanisms of lipid oxidation and employing a combination of these strategies is essential to maintaining the quality and stability of food products.

4.1. Antioxidants

Because they stabilise lipid molecules and stop oxidative breakdown, antioxidants are essential in reducing these negative consequences (Abd El, 2012) [1]. These substances, which might be synthetic or natural, function as scavengers of free radicals, preventing the chain reactions that cause lipid peroxidation (Sisein, 2014) [47]. The use of antioxidant-rich components, the addition of certain chemicals to food systems, and the improvement of storage conditions are methods for using antioxidants to avoid lipid oxidation (Wu *et al*., 2022) [58]. In addition to maintaining the product's nutritional value and sensory qualities, this method extends its shelf life, improving food safety and customer satisfaction (Lohita and Srijaya, 2024) [31].

- **Natural Antioxidants:** Tocopherols, flavonoids, rosemary extract, green tea polyphenols.
- **Synthetic Antioxidants:** BHA, BHT, TBHQ - effective but increasingly restricted due to health concerns.

4.2. Packaging Innovations

Innovations in packaging are essential for prolonging food products' shelf lives and preserving their quality because they stop lipid oxidation, which is a primary cause of rancidity and nutritional deterioration (Majid *et al*., 2018) [33]. The food industry has responded to the growing consumer demand for fresh, minimally processed foods by developing innovative packaging techniques that focus on preserving fats and oils (De Corato, 2020) [13]. Among these tactics are the use of modified atmosphere packaging (MAP) to lower oxygen exposure and active packaging materials like oxygen scavengers and films impregnated with antioxidants (Arvanitoyannis, 2012) [4]. Additionally, developments in biodegradable packaging and nanotechnology are enabling more efficient and sustainable ways to manage oxidative damage in food systems. This paper explores various packaging innovations, examining their mechanisms, benefits, and challenges in preventing lipid oxidation, ultimately offering insights into how these strategies enhance food quality and safety.

- Modified atmosphere packaging (MAP)
- Oxygen-impermeable materials
- Active packaging incorporating antioxidant compounds

4.3. Processing and Storage Controls

Controls over processing and storage are essential for reducing or stopping lipid oxidation in order to lessen this (German, 1999) [21]. Optimising storage conditions, such as controlling humidity and temperature, is one of these tactics since these factors have a big impact on oxidation rates (Mercanti *et al*., 2024) [38]. Furthermore, a number of processing methods are used to reduce oxygen exposure and maintain the integrity of lipids, including vacuum packing, freezing, and blanching (Ogwu and Ogunsola, 2024) [39]. Food quality can be preserved over time by further inhibiting oxidative processes during food processing and storage by the use of antioxidants, both natural and synthetic. By comprehending the mechanisms underlying lipid oxidation and implementing these preventive measures, food products can maintain their nutritional value, improve food safety, and extend their shelf life (Wang *et al*., 2023) [55].

- Temperature and light control
- Use of inert gases (e.g., nitrogen flushing)
- Metal chelators (e.g., EDTA, citric acid) to inhibit catalytic oxidation

4.4. Emerging Technologies

Emerging solutions for lipid oxidation prevention have drawn a lot of attention as the food industry looks to preserve product quality and increase shelf life (De Corato, 2020) [13]. To prevent oxidative rancidity in food items, new innovations including nanotechnology, encapsulating methods, and the use of unique antioxidants and preservatives are being investigated (Biswas *et al*., 2022) [9]. These technologies present viable approaches to improving food stability while preserving consumer safety and nutritional quality (Lisboa *et al*., 2024) [30]. With an emphasis on the mechanisms underlying oxidative damage and the state-of-the-art tactics intended to mitigate its consequences in diverse food systems (Bilal and Iqbal, 2020), this paper attempts to examine the most recent developments in lipid oxidation prevention.

- **Encapsulation of lipids or antioxidants** to reduce exposure to pro-oxidants
- **Use of nanomaterials** for better delivery and protection
- **Biotechnological approaches** to modify fatty acid profiles for enhanced oxidative stability

5. Applications and Implications in the Food Industry

The applications and implications of various scientific advancements in the food industry have revolutionized the way we produce, process, and consume food (Floros *et al*., 2010) [18]. With the continuous development of innovative technologies, such as probiotics, food safety practices, and preservation methods, the food industry is better equipped to address challenges related to nutrition, sustainability, and food security (Mattila-Sandholm *et al*., 2002) [35]. These advancements have also paved the way for more personalized dietary solutions, improved food quality, and enhanced shelf life (De Corato, 2020) [13]. However, the integration of these new technologies comes with a range of implications, including regulatory concerns, consumer acceptance, and potential health impacts. Understanding both the positive applications and the broader implications is essential for ensuring that these innovations contribute to a safe, sustainable, and healthy food system (Khan *et al*., 2021) [29].

6. Conclusion

To sum up, lipid oxidation is still a major problem in food systems, impacting goods' quality, safety, and shelf life, especially those high in unsaturated fats. Developing successful preventative methods requires an understanding of the many mechanisms involved, including initiation, propagation, and termination, as well as the variables impacting oxidation, such as fatty acid content, oxygen availability, and environmental circumstances. Among these tactics include the application of antioxidants, creative packaging ideas, and regulated processing methods. Additionally, improvements in detection techniques enable accurate tracking of lipid oxidation, which supports the creation of more effective preservation techniques. As emerging technologies continue to evolve, they offer promising avenues for improving food stability, ensuring better consumer health, and addressing the sustainability challenges faced by the food industry. Ultimately, a comprehensive understanding of lipid oxidation and its mitigation is key to maintaining the nutritional integrity and sensory qualities of food products.

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