





Cite this: *Sustainable Food Technol.*,
2025, 3, 1668

Non-iron oxygen scavengers in food packaging: mechanisms, applications, and the shift towards green alternatives

Prachi Jain, ^a Bhushan P. Meshram, ^a Suman Singh ^b
and Kirtiraj K. Gaikwad ^{*a}

Oxygen exposure in packaged foods accelerates oxidative spoilage, microbial growth, and sensory degradation. Although iron-based oxygen scavengers dominate current applications, concerns about safety, recyclability, and consumer acceptance have driven interest in non-iron alternatives. This review critically examines recent developments in natural and synthetic non-iron oxygen scavengers, including antioxidants (ascorbic acid and tocopherol), unsaturated hydrocarbons (polybutadiene), enzymes (glucose oxidase and catalase), microorganisms, and polyphenolic plant extracts (gallic acid and catechu). Reported oxygen scavenging capacities range from 6.44 mL O₂ g⁻¹ (α -tocopherol) to 200 mL O₂ g⁻¹ (polybutadiene), with activation often triggered by moisture, UV light, or pH. Plant-based systems, such as catechu–calcium carbonate combinations, stand out as biodegradable and food-safe alternatives, making them especially suitable for moisture-rich foods. Compared to conventional iron-based scavengers, these systems offer advantages in terms of safety, sustainability, and consumer appeal. This review further discusses activation mechanisms, incorporation into polymer matrices, regulatory issues, and barriers to commercialization. Emerging trends include biodegradable films, multifunctional packaging, and smart indicators, which highlight non-iron oxygen scavengers as promising solutions for safer and more sustainable active packaging.

Received 9th July 2025
Accepted 17th September 2025

DOI: 10.1039/d5fb00368g

rsc.li/susfoodtech

^aDepartment of Paper Technology, Indian Institute of Technology Roorkee, Roorkee-247667, Uttarakhand, India. E-mail: simanki.singh27@gmail.com; kirtiraj.gaikwad@pt.iitr.ac.in

^bDepartment of Food Engineering, Institute of Food Science & Technology, VCSG Uttarakhand University of Horticulture and Forestry, Majri grant, Dehradun, 248140, Uttarakhand, India



Prachi Jain

Prachi Jain received her BSc degree in Food Technology (2020) from the Bhaskaracharya College of Applied Sciences, Delhi University, India and her MSc degree in Food Science and Nutrition (2022) from Pondicherry University, India. She is pursuing her PhD under the joint supervision of Prof. Kirtiraj K. Gaikwad and Prof. Suman Singh, at the Indian Institute of Technology, Roorkee, India. She has received the most presti-

gious Prime Minister's Research Fellowship 2023. Her research is focused on sustainable plant-based packaging materials for enhancing food quality and shelf life and alternative materials to single use plastics.



Bhushan P. Meshram

Bhushan Meshram obtained a BTech in chemical engineering from Sant Gadge Baba Amravati University, Amravati, India, in 2022. Currently, he is enrolled in MTech in packaging technology in the Department of Paper Technology, Indian Institute of Technology Roorkee (Roorkee, Uttarakhand, India), under the supervision of Prof. Kirtiraj K. Gaikwad. His studies concentrate on edible food packaging applications and

biodegradable and sustainable food packaging. He was also awarded the "Best Innovator Award PG 2024" (Professional Development & Innovation Award) for his M.Tech Dissertation work for the year 2023–2024 by IIT Roorkee, India.



Sustainability spotlight

Oxygen scavengers play a critical role in active packaging, aiming to reduce or eliminate oxygen within food packages to mitigate oxidative deterioration. The food industry increasingly relies on this technology, traditionally dominated by iron-based scavengers. However, organic oxygen scavengers present a promising, sustainable alternative. These innovative materials include bioactive molecules, natural pigments, fatty acids, biochemical agents, biological agents, and plant-based polyphenols. Their non-toxic nature and renewable sources align with sustainability objectives, offering a viable solution for enhancing food preservation while minimizing environmental impact. By incorporating organic scavengers, the food industry can transition towards more eco-friendly practices, ultimately contributing to a more sustainable future.

1. Introduction

The Earth's entire gaseous atmosphere comprises 20.9% molecular oxygen (O_2) by volume, a highly volatile gas essential to sustain all organic living systems. Oxygen is a strong oxidizing agent and thus readily accepts electrons, causing high reactivity towards various chemical and biological substrates. Oxygen ingress poses a significant challenge in food packaging.¹ Oxygen promotes the growth of aerobic pathogens, including *Pseudomonas aeruginosa*, *Listeria monocytogenes*, *Rhizopus stolonifer*, and *Aspergillus niger*, which accelerate food spoilage. Even at oxygen levels as low as 0.4 vol% in gas mixtures, oxidative damage and aerobic pathogen growth present major challenges to maintaining food quality.²

Moreover, oxygen presence in food substrates jeopardizes food safety by accelerating insect infestation and promoting chemical and biochemical degradation reactions like lipid oxidation or rancidity, loss of vitamins, and oxygen-assisted enzymatic browning, all of which render the food product unsuitable for human consumption and contributes to food loss.³ An effective way to control molecular oxygen is by using chemical scavengers, also known as oxygen scavengers. Oxygen scavengers eliminate excess oxygen in the package headspace by chemically binding or quenching free oxygen, thereby maintaining desirable conditions. They are also compatible with permeable packaging materials since they exert active oxygen-scavenging activity.^{4,5}

Oxygen scavengers are commonly applied as sachets or integrated coatings that are placed in direct contact with food inside the product package. Metal-based oxygen scavengers, especially those based on iron powders, have been the most commercially successful so far. They do, however, present certain challenges, such as regulatory concerns, unintentional ingestion, and the potential to trigger unnecessary alarms during metal detector screening. Several studies in the past have discussed the urgency of finding an alternative solution to iron-based commercial scavengers.

While iron-based scavengers dominate commercially, most previous reviews have focused mainly on these systems and have given limited attention to non-iron alternatives. Where non-iron scavengers are discussed, the discussions are often brief and do not critically address their activation mechanisms, compatibility with polymeric matrices, or sustainability aspects. Yet, non-iron systems have recently gained significant academic and industrial interest because of their advantages in consumer perception and environmental safety. These biodegradable oxygen scavengers eliminate major drawbacks of iron-based systems, such as accidental ingestion and non-recyclability. Additionally, compared to the dispersion of inorganic metallic powders, these non-iron scavenging systems exhibit superior dispersion and compatibility with polymeric matrices, allowing the production of optically transparent active barrier polymer films⁶ and even edible films.⁷



Suman Singh

Prof. Suman Singh earned her PhD from GB Pant University, Uttarakhand, India. She worked as a post-doctoral fellow at Yonsei University, Seoul, South Korea. She is currently working as an Assistant Professor at the Veer Chandra Singh Garhwali Uttarakhand University of Horticulture & Forestry. Her area of interests includes antimicrobial packaging, food processing and preservation techniques, and waste valorization.

She was named one of the most influential women of the year – 2024 in India by PrintWeek and awarded the packaging person of the year title.



Kirtiraj K. Gaikwad

Prof. Kirtiraj K. Gaikwad earned his MS (packaging technology) from Michigan State University, USA, and his PhD (packaging technology) from Yonsei University, Seoul, South Korea. After his PhD, he worked as a post-doctoral fellow at Polytechnique Montréal, Canada. He is currently working as an Associate Professor in the Department of Paper Technology at the Indian Institute of Technology Roorkee, India. His research is

aimed at active food packaging and waste valorization. He has published more than 100 peer-reviewed papers and 2 international and 4 Indian patents. He was listed in Stanford's list of top 2% of scientists in the world – 2023.



Against this background, this review aims to present an outline discussion of the non-iron oxygen scavenging systems that have been researched so far. The paper first discusses major non-iron scavenging agents, their activation, and scavenging chemistry. Further, it presents an overview of the potential food application, sizing calculations, and regulatory requirements for the emerging non-iron oxygen scavenging systems.

2. Fundamentals of oxygen scavenging

In food packaging, the processor can limit oxidative degradation by reducing nutrient loss and the accompanying physiological changes by quickly removing trapped oxygen inside the package using oxygen scavengers. Oxygen scavengers are the most commercially important subgroup in active packaging applications, part of a much broader class of absorbers or scavenging materials for gases. The scavenging reaction usually proceeds by the reaction of dissolved oxygen with scavenging components to form stable compounds. Some common mechanisms include chemisorption of oxygen, catalytic hydrogen gas formation to form water, oxidation of non-iron and inorganic nitrogen compounds, oxidation of sulphites to sulphates, catalytic oxidation of unsaturated hydrocarbons and non-iron compounds, and oxidation of reduced transition metals to form stable oxides.⁸

The activation mechanism of an oxygen scavenger is another important property for commercial applications. Some scavengers get activated instantly during manufacture and thus pose the problem of early saturation. Scavengers that can activate themselves only upon exposure to specific external factors, like moisture in the package, UV light, and temperature, are more desirable.⁹

Oxygen scavengers must also comply with specific parameters in food packaging applications because the scavenger components may come into contact with food or be unintentionally swallowed. These parameters should ensure that they pose no risk to human health and do not alter the sensory properties of food, such as taste, odor, and appearance. In polyunsaturated hydrocarbon or fatty acid-based scavengers, self-oxidation is a well-known occurrence during the scavenging process. This reaction generates aldehydes and other volatile compounds, which impart rancid odors and are undesirable in food packaging applications.

However, to ensure effective application while minimizing such drawbacks, oxygen scavengers are typically incorporated into highly permeable sachets or packs. The materials used to create these packs or sachets include paper, polymeric films (microperforated or solid), porous nonwovens (such as spun-bound polyolefins), and their combinations.¹⁰

3. Non-iron-based oxygen scavengers

Recent research has increasingly focused on finding alternatives to metallic/inorganic oxygen scavengers. This interest is

a result of increasing negative consumer perception towards the use of synthetic chemicals in food. Moreover, growing awareness regarding food safety concerns emphasizes shifting focus towards sustainable and biodegradable packaging solutions, which include materials that are generally recognized as safe (GRAS) by the Food and Drug Administration (FDA).¹¹ As outlined in sections 3.1–3.5, non-iron oxygen scavengers can be broadly classified into five categories: antioxidants (ascorbic acid and tocopherols), hydrocarbons (polybutadiene and polyisoprene), enzymatic systems (*glucose oxidase* and *catalase*), biological (yeast), and plant-derived polyphenols (gallic acid and catechin). Additional examples of these scavengers, along with their reported oxygen-scavenging capacities, are summarized in Table 1.

3.1. Antioxidant-based scavengers

Ascorbic acid, with the chemical formula $C_6H_8O_6$, is a mild reducing agent and a common non-iron antioxidant. L-Ascorbic acid, also known as vitamin C, is the naturally occurring chemical form. Ascorbic acid is a scavenger of molecular oxygen because it quickly oxidizes under both air and aqueous conditions. Transition metal catalysts, preferably copper and light, can accelerate the redox reaction. The oxidation route for L-ascorbic acid results in the formation of dehydroascorbic acid and water, as shown in Fig. 1. In later stages of oxidation, furfural and various other compounds are formed by the removal of the diol side group. However, this reaction has a relatively low scavenging capacity, requiring larger quantities of reactant to match iron-based systems.¹² The scavenging reaction is greatly influenced by the pH of the environment. In comparison to the ascorbate monoanion ($A-H^-$), which predominates at high pH levels, the completely protonated form ($A-H_2$) is more stable and has significantly reduced vulnerability to oxygen at low pH values.²⁰

A study in 2018 employed a combination of sodium L-ascorbate and activated carbon as oxygen scavenging systems for the preservation of raw meatloaves. The results indicated reduced lipid oxidation effects in meatloaves packed with the developed oxygen scavenger.²¹ Another study²² utilized ascorbic acid solution as a direct oxygen scavenging coating on fuyan longan fruits. The postharvest quality of fruits was reported to be significantly improved with the application of a coating.

Erythorbic acid is a stereoisomer of ascorbic acid with an oxidation reaction pathway identical to that of ascorbic acid. The sodium, potassium, and calcium salts of erythorbic acid are generally recognized as safe food antioxidants. In the past, sodium erythorbate was investigated as an oxygen scavenger for the packaging of citrus juice. The headspace oxygen content (%) decreased to 0% over approximately 10 days of storage. A rate constant (k) value of 0.089 h^{-1} was determined at $25\text{ }^\circ\text{C}$, which was reported to be higher than commercial iron-based oxygen scavengers like Freshpax® R-200 (0.043 h^{-1}).^{23,24} From the available literature, it is suggested that the oxidation of erythorbic acid usually requires a transition metal catalyst.²⁵ The mechanism of the oxygen scavenging reaction is illustrated in Fig. 1.





Table 1 Overview of various oxygen scavenging systems based on different non-iron components for food packaging applications

Packaging material	Oxygen scavenging agent	Non-iron oxygen scavengers	Optimum scavenging composition ^a	Key findings	Reference
When protein isolate (WPI) films incorporating ascorbic acid (AA) and glycerol	Ascorbic acid	Antioxidant	0.2 M AA + 5% (w/w) WPI	The headspace oxygen was reduced to 17.1% ± 0.2% over 3 days of storage	12
Thermally activated polycaprolactone nanoparticles loaded with α -tocopherol	α -Tocopherol	Antioxidant	200 mg nanoparticles + 50 μ l water	The reported oxygen scavenging capacity was 6.44 cm ³ O ₂ g ⁻¹ and an oxygen scavenging rate of 0.21 cm ³ O ₂ per g per day	13
Polyvinyl alcohol (PVA) films fabricated with natural rubber latex (NRL) and a photocatalytic system (PS)	Natural rubber latex (polybutadiene)	Unsaturated hydrocarbon	10 g PVA + 19.4 g NRL + 0.6 g PC	The films demonstrated an oxygen scavenging capacity of 558 cm ³ O ₂ g ⁻¹ at 25 °C	14
Natural rubber latex (NRL) based low-density polyethylene films	Natural rubber latex (polybutadiene)	Unsaturated hydrocarbon	5% NRL (w/w)	A total scavenging capacity of 61 cm ³ g ⁻¹ was reported	11
Hydroxyl-terminated polybutadiene (HTPB) blended with polythene and poly(lactic acid)	Hydroxyl-terminated polybutadiene	Unsaturated hydrocarbon	10% HTPB (w/w)	The maximal oxygen absorption was approximately 30 cm ³ g ⁻¹ after 30 days	15
Glucose oxidase (Gox), catalase, glucose, and kaolin clay/latex coating	Glucose oxidase and catalase	Enzymatic system	0.6% Gox + 0.5% catalase + 95 pph clay	The observed scavenging rate was 600 μ mol O ₂ min ⁻¹ g ⁻¹ (substrate)	16
Alginate films entrapping microorganisms	<i>Pseudomonas putida</i> or <i>Saccharomyces cerevisiae</i>	Biological system	A higher number of cells results in greater oxygen scavenging	No reported data	17
Galic acid (GA) and sodium carbonate (NC) based multilayer packaging	Galic acid	Polyphenolic system	15% GA + NC (w/w)	Reported oxygen absorption value was 447 mg O ₂ g ⁻¹ GA	18
Galic acid (GA) and potassium chloride (PC) based polythene films	Galic acid	Polyphenolic system	20% GA + PC (w/w)	Oxygen scavenging capacity of 0.709 mL cm ⁻² at 23 °C	19

^a * expressed as reported in the source.

based scavenging reactions can propagate in dry environments.²⁸ Thus, these kinds of scavenging systems have great potential in the application of dry product packaging. The mechanism of auto-oxidation follows a 3-step reaction scheme. The first step, termed the chain initiation step, is marked by the generation of a free alkyl radical. The generated alkyl radical further reacts with molecular oxygen and a proton to form peroxy and alkoxy radicals.

This is followed by chain propagation, where peroxides are formed, driving the reaction to the last step, known as chain termination. In the last step, final oxidation products like aldehydes, ketones, *etc.*, are formed. Molecular oxygen is only consumed in the initial stage or chain initiation step. A detailed mechanism is illustrated in Fig. 2. Aldehydes and ketones are final lipid oxidation products that can impart undesirable flavour and odour to the packaged food.²⁹ Their presence is unwanted and detectable by humans even at concentrations below 1 ppm.

Unsaturated hydrocarbons like 1,4-polybutadiene, the most common hydrocarbon used for oxygen scavenging purposes, follow a similar oxidative mechanism to fatty acids. Therefore, the final reaction products are also similar, which compromises the sensory quality characteristics of the packaged food. The scavenging system requires the presence of transition metal salts like cobalt neodecanoate or manganese chloride. An investigation reported that oxygen-scavenging polyisoprene films can prolong the shelf life of beef jerky. The developed system exhibited an oxygen scavenging capacity of 16.72 mL O₂ g⁻¹.³⁰ Recently, natural rubber latex was investigated as a source for polybutadiene for its scavenging potential in the form of

polythene composite or pure natural rubber latex-based oxygen scavenging films.^{11,31}

3.3. Enzyme-based scavengers

Enzymes are non-iron catalysts that accelerate the biochemical reactions occurring in a living system. Using enzyme-based technology as an active agent for oxygen absorption is well known.³² Specific food-grade enzymes, when entrapped over a solid matrix or within polymer barriers, biofilms, and sachets, can act as oxygen scavengers, as shown in Fig. 3. The presence of an oxidizable substrate based on enzyme specificity is necessary for enzyme-based scavenging technology to act in any composition. Moreover, most of these developed enzyme systems require high relative humidity and specific pH environments to function at their highest efficiency. Recent advances in enzyme immobilization on nanofibers or hydrophobic matrices show potential to improve stability and reduce leaching, warranting deeper exploration.

In 2001, an active enzyme mixture containing *glucose oxidase*, catalase, glucose, and calcium carbonate was incorporated into an industrial laminate dedicated to milk packaging. The prepared laminates exhibited an oxygen absorption capacity of $7.6 \pm 1.0 \text{ L m}^{-2}$.³³ Glucose was externally added as a substrate for the enzyme, whereas calcium carbonate neutralized the pH drop due to the formation of gluconic acid and compensated for the decrease in pressure due to oxygen consumption through CO₂ production. Another study involved immobilizing *glucose oxidase* in electrospun nanofibrous membranes based on polyvinyl alcohol, chitosan, and green tea



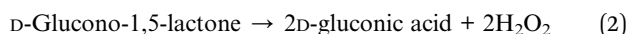
Fig. 2 The oxygen scavenging mechanism of polyunsaturated fatty acids and ethylenic hydrocarbons through the autoxidation pathway.





Fig. 3 Entrapment of enzymes, microorganisms, and spores into a polymer matrix for active oxygen scavenging in a food package.

extract.³⁴ Recently, a *glucose oxidase* coated polymer film was prepared, which could efficiently decrease the headspace oxygen level by 2% in a closed container over 8 weeks of storage.³⁵ The common reaction pathway followed by *glucose oxidase* can be represented by eqn (1)–(3).



where GOx denotes *glucose oxidase*

The reaction is initiated by hydrogen transfer from the glucose molecule (–CHOH group) to molecular oxygen in the presence of water through the enzymatic activity of *glucose oxidase*. Following this, delta-gluconolactone is formed as an intermediate product, which further quickly reacts with water and yields gluconic acid and hydrogen peroxide (H₂O₂).⁸ Since hydrogen peroxide formation is undesirable, catalase is added to initiate the breakdown of peroxide into water and oxygen. Overall, half a mole of oxygen is removed per mole of *glucose oxidase*.³⁶

Other enzyme scavenging systems explored so far include a combination of oxalate oxidase and catalase co-immobilized into a polymer latex. Oxalate oxidase catalyses the conversion reaction of oxalic acid to carbon dioxide and hydrogen peroxide while scavenging molecular oxygen. Another example is laccase, a copper-containing enzyme, which, in combination with phenolic compounds like pyrogallol and liginosulfates, has also been used as an oxygen scavenger in films and coatings.^{37,38} In the oxidation reaction catalysed by laccase, molecular oxygen is reduced to water as given in eqn (4).



where poly-OH emphasizes the phenolic hydroxyl group participating in the reaction.

3.4. Biological scavenging systems

Biological oxygen scavengers rely on the respiration of microorganisms that are entrapped in a polymer matrix or incorporated in sachet forms, as shown in Fig. 3. Among them, yeast has been the most extensively explored due to its food-grade status and well-established role in fermentation. Early patents (1985 and 1992) demonstrated two approaches for applying yeast in packaging: incorporation into beer bottle closures and development of sachet systems. In the closure-based design, viable yeast cells were immobilized within the cork or polymer insert of the cap. Residual moisture and dissolved nutrients from the beer acted as triggers, allowing the yeast to resume limited metabolic activity. The oxygen present in the bottle headspace was consumed during respiration, while small amounts of carbon dioxide and ethanol were produced as by-products. Importantly, because beer naturally contains both CO₂ and ethanol, these by-products did not alter product quality.^{39,40}

Other microorganisms besides *Saccharomyces* yeast have also been investigated for oxygen scavenging. For instance, *Pichia subpelliculosa* and *Kocuria varians*, two different microorganisms, were entrapped into a combined matrix of polyvinyl alcohol and were further investigated as oxygen scavengers. The authors reported that these microorganisms were best suited to act as oxygen scavengers when coated on high macromolecular substrates under high humidity conditions.⁴¹ A related but different approach included incorporating spores of *Bacillus amyloliquefaciens* into polyethylene terephthalate bottles, which, upon rehydration, will result in spore germination followed by oxygen consumption through respiration. Rehydration of the model system will be from high humidity conditions created by the food product. The reported oxygen scavenging

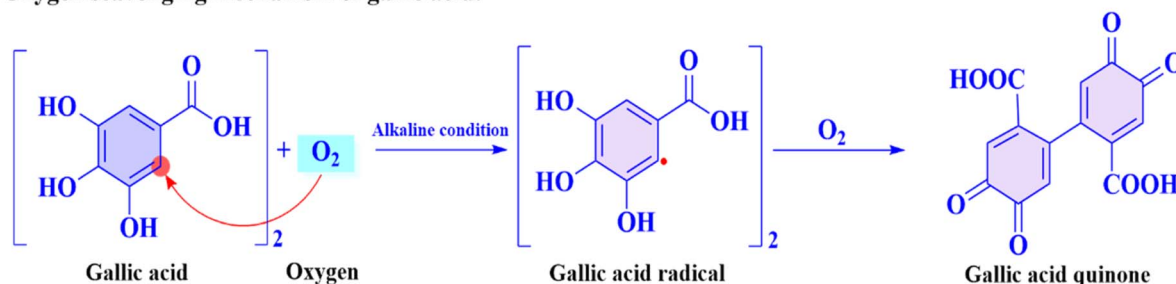


rate was 0.10 ± 0.02 mL O_2 per g day, which is comparable to those of metallic scavengers.⁴²

Despite these encouraging results, several limitations remain. The viability of microorganisms during long-term storage is difficult to maintain, and activation generally requires high moisture levels, restricting applications in dry products. Safety considerations also arise, as microbial

metabolites such as ethanol or organic acids may alter product quality if not carefully controlled. Moreover, the intentional use of live microorganisms in food packaging requires strict regulatory evaluation. Overall, only a few microbial strains have been investigated to date, and little is known about their performance in real food systems. Expanding this research to assess sensory effects, stability, and practical applications will

(A) Oxygen scavenging mechanism of gallic acid:



(B) Oxygen scavenging mechanism of pyragallol:



(C) Oxygen scavenging mechanism of resorcinol:



(D) Oxygen scavenging mechanism of catechin:

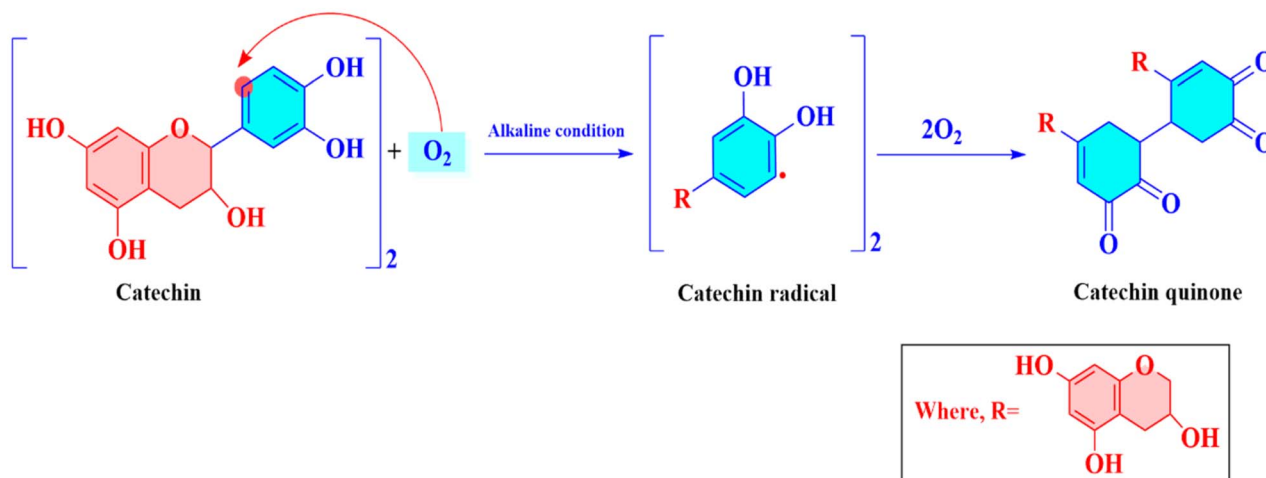


Fig. 4 Schematic illustration of the reaction pathways for various polyphenolic oxygen scavengers, along with a brief overview of the structural changes occurring from initial reactants to end products.



be important for future development. At present, the most promising use appears to be in beer packaging, where the metabolic by-products of yeast are compatible with the product, though future work may explore other high-moisture foods and beverages.

3.5. Polyphenolic and plant-based scavenging systems

The term polyphenols covers a diverse range of naturally occurring plant compounds containing one or multiple phenol group functionalities with variable hydroxyl (–OH) substituents. Naturally occurring polyphenols have long been utilized for medicinal and pharmaceutical purposes. Moreover, plant polyphenols act as strong antioxidants and reduce oxidative stress in the system.⁴³ The mechanism of free radical scavenging for all polyphenols (natural and synthetic) is broadly based on hydrogen atom transfer.⁴⁴

In the past, various polyphenolic oxygen scavenging systems have been explored. In 2012, a patent was published involving the utilization of gallic acid as a non-iron oxygen scavenger/indicator in combination with sodium hydroxide.⁴⁵ In 2016, the oxygen scavenging potential of pyrogallol, a natural polyphenol present in Amla fruit (*Emblia officinalis* Gaertn), was explored. Pyrogallol in combination with an alkali demonstrated potential oxygen scavenging capacities at room temperature, which were reported to be comparable to a few iron-based oxygen scavengers. The activation of ground-state molecular oxygen (³O₂) into reactive species involves its conversion to singlet oxygen (¹O₂), often triggered by photo-irradiation or alkaline environments. Singlet oxygen is an electronically excited form that is significantly more reactive than its ground-state counterpart.

Under these conditions, ¹O₂ can participate in electron transfer reactions, generating reactive oxygen species such as superoxide anion (O₂^{•−}), hydrogen peroxide (H₂O₂), or hydroxyl radicals (•OH). These intermediates are then neutralized by polyphenols or antioxidants through hydrogen atom donation or radical quenching pathways, as reported in ref 46 and further reduced to reactive oxygen species, which are finally eliminated by electron donation through pyrogallol.⁴² Similarly, in another attempt, the polyphenolic compound resorcinol was explored. The oxygen scavenging system comprised pure resorcinol powder along with potassium carbonate. The system exhibited a fast oxygen scavenging phenomenon, and a 0% (v/v) oxygen content was reported within 264 h at 5 °C, 68 h at 25 °C, and 48 h at 45 °C.⁴⁷

Recently, the oxygen-scavenging properties of the plant-based substance *Acacia catechu* were studied. Catechu powder, along with calcium carbonate, comprised the oxygen scavenging system, which was also reported as food-grade or edible. The results suggested that with an oxygen scavenging capacity of 10 mL O₂ g^{−1} over 20 days of storage, the developed system is suitable for foods at an intermediate risk of oxidation.⁴⁸ The oxygen-scavenging properties of catechu powder were linked to the presence of a polyphenol known as catechin. The chemical structures of initial and final reaction products for reported polyphenols so far are given in Fig. 4.

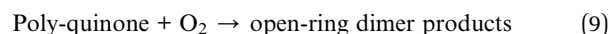
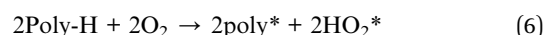
Plant-based oxygen scavengers have many desirable qualities, making them a very interesting topic in modern food technology. This approach also aligns with the current consumer demand for minimal chemical use. Among all the reported systems so far, the presence of alkaline conditions is necessary. This is due to polyphenolic chemistry, which results in increased deprotonation activity under alkaline conditions. Moreover, alkaline conditions also activate ground-state oxygen to the singlet state, resulting in the initiation of the oxygen scavenging reaction.

Further, the recurring presence of carbonate salts in the above-described systems helps increase the system's dependence on moisture. Briefly, the system will only activate after drawing moisture from the packed food product, thus eliminating the problem of early saturation of oxygen scavengers. The common scavenging reactions for polyphenolic oxygen scavenging systems are given in eqn (5)–(9).

Activation mechanism:



Scavenging mechanism:



where X = single valent metal ion (sodium – (Na), potassium – (K), etc.)

Poly = any polyphenol (gallic acid, pyrogallol, resorcinol, and catechin)

* = electron

4. Packaging applications and scavenger loading

Oxygen scavengers are generally utilized for the packaging of food products with high fat or moisture. Meat, fish, dry fruits, coffee powders, bakery products, milk products, and alcoholic and non-alcoholic beverages are some common examples where oxygen scavenging technology is utilized to maintain product quality during their anticipated shelf life. Typically, oxygen scavengers are used in sachet forms, which are placed in direct contact with food. However, unsustainable consumption of plastics in sachet formation, as well as incompatibility with liquid beverages, drove researchers to find newer package-based solutions.

Currently, there is considerable interest in directly embedding active oxygen scavenging agents into packaging materials. Many studies have experimented and produced polymer/biopolymer-based oxygen scavenging films and coatings and active scavenging polyethylene terephthalate bottles for food packaging applications.^{42,49}



Table 2 Summary of emerging non-iron oxygen scavengers, reported food applications, and effects on product stability

Category	Oxygen scavenging system	Intended food application	Effect on shelf life	Oxygen scavenging capacity ^a	Advantages	Disadvantages	References
Antioxidant-based	Sodium erythorbate impregnated matrix	Citrus juice	Maintained 0.8% headspace O ₂ for 24 days	Not reported	Food-grade, GRAS, cost-effective	Limited oxygen capacity, requires higher loading	52
	Sodium L-ascorbate + activated carbon	Fresh meatloaves	Reduced oxidative spoilage	39.1 cc g ⁻¹ sachet	Widely available, GRAS	Low capacity compared to iron-based systems	53
	Biodegradable α -tocopherol-PLA microparticles embedded in packaging	Not reported	Not reported	0.12 cm ³ g ⁻¹	Biodegradable, GRAS	Microparticle safety and regulatory concerns	54
Hydrocarbon-based	α -Tocopherol + transition metal	Liquid and dry food products	Not reported	6.72 mL O ₂ g ⁻¹	Natural antioxidant, suitable for dry products	Low scavenging capacity, safety concerns from metal catalysts	26
	Natural rubber latex-based polyethylene films	Khoa	Shelf life extended by 3 days	61 cc g ⁻¹	High oxygen uptake, suitable for dry foods	Off-flavour risk	55
	Rubber-based scavenger with a food-grade catalyst	Fresh cheese curd	Shelf life extended from 4 to 9 days	98.7 \pm 6.1 cm ³ g ⁻¹	Food-safe catalysts, high oxygen uptake	Off-flavour risk	56
Enzyme-based	<i>Trans</i> -polyisoprene active films	Roasted peanuts	Oxidation was inhibited for up to 90 days	16.72 mL O ₂ g ⁻¹	Effective for lipid-rich foods	Scalability challenges	57
	LDPE + polyisoprene films	Beef jerky	Maintained oxidative stability for 90 days	16.72 mL O ₂ g ⁻¹	High oxygen scavenging capacity, suitable for dry foods	Requires UV-activation, limited industrial validation	30
	Glucose oxidase + catalase in laminates	Tetra Brik-type food products	Reduced oxygen and improved stability	7.6 \pm 1.0 L m ⁻²	Efficient and biodegradable	Sensitive to pH and humidity, high-cost	58
Biological	Yeast/microbial spore entrapped films (<i>e.g.</i> , <i>Saccharomyces</i> , <i>Kocuria</i> , and <i>Pichia</i>)	Beer and other beverages	Preservation through microbial respiration	0.10 \pm 0.02 mL O ₂ per g day	Natural, compatible with beverages	Difficult long-term stability, regulatory concerns	59
	Polymer films with pyrogalllic acid	Peeled garlic	Prevented oxidative discoloration (20–30 days)	Not reported	Effective natural compound	Limits long-term performance	60
Polyphenol-based	Pyrogalllic acid + sodium carbonate	Fish cake	Maintained quality for 30 days	Not reported	Effective natural compound	Requires high pH for activation	61
	Catechu + CaCO ₃ system	Dairy, moist foods	Suitable for moderate oxidation-risk foods	10 mL O ₂ g ⁻¹ (20 days)	Natural, biodegradable, food-safe	Slow scavenging and not suitable for dry foods	62
	Gallic acid-based multilayers/films	Oils, nuts	Maintained oxidative stability during storage	447 mg O ₂ g ⁻¹ GA; 0.709 mL cm ⁻²	Strong uptake, bio-based, consumer-friendly	Regulatory approval challenges	63

^a Expressed as reported in the source.

4.1. Food and beverage applications

Headspace and dissolved oxygen are major contributors to food spoilage in packaged food. Oxygen-related food spoilage has already been discussed in section 1. Oxygen scavengers can be used in a variety of food products for extending shelf life and maintaining specific quality characteristics. The findings of previous studies using non-iron or natural oxygen scavengers to increase food product shelf life are summarised in Table 2. It was reported that with the application of pyrogallol acid-blended linear low-density polyethylene oxygen scavenging films, the storage quality of peeled garlic could be maintained till 20 days at room temperature.⁵² Further, another study utilized oxygen scavenging films as a replacement for artificial antioxidant preservatives added for oil preservation. Soybean oil packed in pyrogallol-coated scavenging films maintained oxidative stability over 30 days, whereas oxidative degradation was observed in control oil samples.^{50,51}

Another scavenging system utilizing a non-iron oxygen scavenger formulation could maintain the quality characteristics of meatloaves over 4 days of storage,⁶⁴ whereas control meatloaves over the same storage time exhibited signs of oxidative degradation and microbial spoilage.²¹ Similarly, many oxygen scavenging systems have been researched and applied to a variety of food products, including alcoholic beverages, beef products,^{32,65} fish,⁶⁶ dry products like walnuts,⁶⁷ dairy products like khoa,¹¹ etc.

4.2. Sizing calculation for efficient scavenging

For an efficient oxygen scavenger application, two distinct design goals are quick headspace oxygen removal and limiting oxygen ingress through the packaging material from the outside environment.⁸ Sizing calculations aim to measure the real volume of oxygen that must be scavenged over time, including headspace and oxygen ingress into packaging material for low- to high-oxygen barrier packaging material. The amount of oxygen that must be scavenged is determined by calculating the percentage of oxygen in the initial headspace gas mixture, considering the package and headspace volume. Eliminating initial oxygen may be sufficient for a product with a short shelf life. But for a lot of packages, throughout the course of their distribution life, more oxygen seeps through than was initially in the headspace.

If so, the oxygen transmission rate (OTR) of the barrier in use and the surface area of the package should be multiplied by the estimated shelf life of the product to determine the expected oxygen ingress into the package over shelf storage. The total capacity required for the oxygen scavenger for that application is then calculated by adding the initial oxygen concentration and the oxygen ingress during the shelf life. For high barrier packaging materials like polyvinyl alcohol and aluminium foil, only the elimination of headspace oxygen is of primary concern. Thus, a lower mass of scavengers is needed to exhibit the necessary scavenging powers. Therefore, the formula for the total amount of oxygen to be removed from a package along its shelf life can be formulated as

$$O_{2(\text{ingress})} = \text{OTR} \times \text{SA} \times \text{SL} \quad (10)$$

$$\text{TO}_2 = O_{2(\text{headspace})} \times O_{2(\text{ingress})} \quad (11)$$

where $O_{2(\text{ingress})}$ = total oxygen ingress (mL) through the package over time (t)

OTR = oxygen transmission rate (mL O_2 per m^2 per day)

SA = surface area (m^2)

SL = shelf life (days)

TO_2 = total volume of oxygen to be scavenged (mL)

$O_{2(\text{headspace})}$ = volume (mL) of oxygen in headspace.

4.3. Regulatory aspects

Directive 89/109/EEC, the European Union framework regulation that applies to all materials with direct food contact, states that such materials must not pose a risk to human health and must not adversely alter the sensory qualities of packaged meals. Oxygen scavengers are usually in direct or close contact with food products.⁶⁸ Therefore, strict regulations must be followed to avoid any compromise on the food safety of the packaged food. Using oxygen scavenging films, coatings, labels, or direct entrapment over a matrix limits the risk of accidental ingestion, unlike sachets. Moreover, using a non-iron composition further depletes the risk of food contamination as compared to iron-based scavengers. However, several possible oxidation by-products, their toxicity, and their migratory characteristics inside the packing structures need to be considered while developing a scavenging system.

Furthermore, it should be ensured that all detected extractables are within their authorised limitations to obtain a valid licence for commercial usage. The maximum mass of non-volatile compounds that can transfer from packing material into food is expressed as the overall migration limit (OML). The European Union in Regulation 10/2011 states that for food contact packaging materials, the overall migration limit is 10 mg dm^{-2} and 60 mg kg^{-1} (infant food).⁶⁹

4.4. Challenges and future perspectives

Over the years, the development of non-iron oxygen scavenging systems has accelerated for active and sustainable food packaging applications. Non-iron scavenging systems/films in food packaging are anticipated to have a prosperous future because they align with the food safety plan, which calls for increased food safety and customer transparency.

However, several challenges restrict the industrial adoption of non-iron scavengers. These include material availability, economic feasibility, regulatory approval, sensitivity towards moisture and pH, and potential by-product toxicity. Addressing these issues is essential to ensure both safety and compliance with food packaging standards. A comparative evaluation of cost-effectiveness is critical for the industrial adoption of non-iron oxygen scavengers.^{39,70}

While enzyme- and nanoparticle-based systems (e.g., glucose oxidase and α -tocopherol) offer high specificity and efficiency, they are relatively expensive due to complex production and stabilization requirements. In contrast, plant-derived polyphenols



such as gallic acid, catechu, and pyrogallol are more economically viable, especially when sourced from agro-waste or abundant natural materials. These systems also require fewer processing steps and can be activated under ambient conditions, further reducing costs. Thus, while advanced scavengers offer superior performance, plant-based alternatives strike a better balance between efficacy and affordability, making them promising candidates for large-scale food packaging applications.

To bridge the gap between laboratory development and commercial application, additional research and real-world food studies are necessary. Future work should also examine the integration of oxygen-scavenging packaging with complementary preservation technologies. The development of biodegradable films for packaging is becoming more and more important to save the environment and reduce the pollution that packaging materials produce. The strict regulations for food packaging will continue to keep the application of multi-layer oxygen scavenging films in focus.

5. Conclusion

Non-iron oxygen scavengers represent a crucial step toward safer, more sustainable, and consumer-acceptable active packaging. This review contributes by systematically categorizing them into antioxidant, hydrocarbon, enzyme, biological, and polyphenol-based systems and by connecting their chemistry to real food applications. The novelty lies in presenting a unified framework that makes it easier to compare their potential and limitations across classes. Looking forward, the main challenges are scaling up and incorporating into packaging materials, ensuring stability under real storage conditions, and generating comprehensive data on sensory impact, migration, and safety to meet regulatory requirements. Cost-effectiveness and lifecycle sustainability must also be demonstrated to compete with established iron-based systems. Hybrid approaches that combine complementary mechanisms and improved stabilization strategies are especially promising. Overall, the pathway to commercialization will depend on bridging laboratory results with pilot-scale validation and industry trials, so that non-iron systems will become feasible and viable solutions to future food packaging.

Author contributions

Prachi Jain – experimenting, formal analysis, data curation, validation, figures, writing, and editing of the draft manuscript. Bhushan Meshram – figure editing. Suman Singh – supervision, methodology, editing, and reviewing of the manuscript to be published. Kirtiraj K. Gaikwad – investigation, project administration, supervision, conceptualization, methodology, resources, editing, and reviewing of the final manuscript.

Conflicts of 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

All data generated or analysed during this study are included in this published article.

Supplementary information is available. See DOI: <https://doi.org/10.1039/d5fb00368g>.

Acknowledgements

Prachi Jain acknowledges the Indian Institute of Technology Roorkee and the Prime Minister's Research Fellowship for providing financial assistance.

References

- 1 J. Zhao, Z. Qu, A. Li, X. Chen, Y. Zhang and X. Chen, *J. Food Sci.*, 2020, **85**, 143–149.
- 2 N. S. Zaidi, J. Sohaili, K. Muda, M. Sillanpää and N. Hussein, *Appl. Water Sci.*, 2021, **11**, 1–12.
- 3 J. Promsorn and N. Harnkarnsujarit, *Ind. Crops Prod.*, 2022, **186**, 115226.
- 4 E. Kütahneçi and Z. Ayhan, *J. Consum. Prot. Food Saf.*, 2021, **16**, 247–259.
- 5 R. S. Cruz, G. P. Camilloto and A. C. dos Santos Pires, *Struct. Funct. Food Eng.*, 2012, **2**, 21–42.
- 6 K. K. Gaikwad, S. Singh and Y. S. Lee, *Environ. Chem. Lett.*, 2018, **16**, 523–538.
- 7 A. S. Modaresi and R. Niazmand, *Food Bioprocess Technol.*, 2021, **14**, 1184–1193.
- 8 S. E. Solovyov, *Kirk-Othmer Encyclopedia of Chemical Technology*, 2000, pp. 1–31.
- 9 Z. Kordjazi and A. Ajji, *Can. J. Chem. Eng.*, 2022, **100**, 3444–3449.
- 10 P. Gupta, *J. Food Sci. Technol.*, 2024, **61**, 242–252.
- 11 S. Pawde, S. R. Chaudhari, P. Prabhasankar and R. S. Matche, *ACS Appl. Mater. Interfaces*, 2023, **15**, 38729–38740.
- 12 T. Janjarasskul, K. Tananuwong and J. M. Krochta, *J. Food Sci.*, 2011, **76**, E561–E568.
- 13 Y. Byun, S. Whiteside, K. Cooksey, D. Darby and P. L. Dawson, *J. Agric. Food Chem.*, 2011, **59**, 1428–1431.
- 14 D. Ramakanth, K. Akhila, B. P. Kumar, K. K. Gaikwad and P. K. Maji, *Green Chem.*, 2024, DOI: [10.1039/D3GC03264G](https://doi.org/10.1039/D3GC03264G).
- 15 Z. Kordjazi and A. Ajji, *Food Control*, 2021, **121**, 107639.
- 16 K. Johansson, L. J. Jönsson and L. Järnström, *Nord. Pulp Pap. Res. J.*, 2011, **26**, 197–204.
- 17 B. Gosmann and H.-J. Rehm, *Appl. Microbiol. Biotechnol.*, 1988, **29**, 554–559.
- 18 A. F. Pant, S. Sänglerlaub and K. Müller, *Materials*, 2017, **10**, 489.
- 19 B. J. Ahn, K. K. Gaikwad and Y. S. Lee, *J. Appl. Polym. Sci.*, 2016, DOI: [10.1002/app.44138](https://doi.org/10.1002/app.44138).
- 20 T. Janjarasskul, S. C. Min and J. M. Krochta, *J. Sci. Food Agric.*, 2013, **93**, 2939–2944.
- 21 J. Lee, Y. Chang, E. Lee, H. Song, P. Chang and J. Han, *J. Food Sci.*, 2018, **83**, 682–688.



- 22 J. Liu, Y. Lin, H. Lin, M. Lin and Z. Fan, *Food Chem. X*, 2021, **12**, 100167.
- 23 E. D. Cardona, M. del Pilar Noriega and J. D. Sierra, *J. Plast. Film Sheeting*, 2012, **28**, 63–78.
- 24 M. Fernández, *Food Sci. Technol. Int.*, 2000, **6**, 97–108.
- 25 A. Al Helal, S. Ajjaoui, M. M. Mohammed, A. Barificani and H. Znad, *Process Saf. Environ. Prot.*, 2023, **175**, 516–523.
- 26 Y. Byun, D. Darby, K. Cooksey, P. Dawson and S. Whiteside, *Food Chem.*, 2011, **124**, 615–619.
- 27 P. Scarfato, E. Avallone, M. R. Galdi, L. Di Maio and L. Incarnato, *Polym. Compos.*, 2017, **38**, 981–986.
- 28 B. Röcker, G. Mäder, F. W. Monnard, M. Jancikova, M. Welker, J. Schoelkopf and S. Yildirim, *Materials*, 2021, **14**, 5000.
- 29 E. D. Othón-Díaz, J. O. Fimbres-García, M. Flores-Sauceda, B. A. Silva-Espinoza, L. X. López-Martínez and A. T. Bernal-Mercado, 2023, preprint.
- 30 K. K. Gaikwad, S. Singh, J. Shin and Y. S. Lee, *LWT-Food Sci. Technol.*, 2020, **117**, 108643.
- 31 D. Ramakanth, K. Akhila, K. K. Gaikwad and P. K. Maji, *Ind. Crops Prod.*, 2022, **178**, 114658.
- 32 A. M. Roberta, in *Biopolymer Membranes and Films*, Elsevier, 2020, pp. 535–551.
- 33 M. Andersson, T. Andersson, P. Adlercreutz, T. Nielsen and E. G. Hörnsten, *Biotechnol. Bioeng.*, 2002, **79**, 37–42.
- 34 L. Ge, Y. S. Zhao, T. Mo, J. R. Li and P. Li, *Food Control*, 2012, **26**, 188–193.
- 35 D. E. Wong, S. M. Andler, C. Lincoln, J. M. Goddard and J. N. Talbert, *J. Coat. Technol. Res.*, 2017, **14**, 489–495.
- 36 J. A. Bauer, M. Zámocká, J. Majtán and V. Bauerová-Hlinková, *Biomolecules*, 2022, **12**, 472.
- 37 R. Chatterjee, K. Johansson, L. Järnström and L. J. Jönsson, *J. Agric. Food Chem.*, 2011, **59**, 5390–5395.
- 38 K. Johansson, S. Winstrand, C. Johansson, L. Järnström and L. J. Jönsson, *J. Biotechnol.*, 2012, **161**, 14–18.
- 39 A. Dey and S. Neogi, *Trends Food Sci. Technol.*, 2019, **90**, 26–34.
- 40 H. Ahrens, J. Schröpfer, L. Stumpf, R. Pahl, J. M. Brauer and S. Schildbach, *BrewingSci.-Monatsschr. Brauwiss.*, 2018, **71**, 24–30.
- 41 C. Altieri, M. Sinigaglia, M. R. Corbo, G. G. Buonocore, P. Falcone and M. A. Del Nobile, *LWT-Food Sci. Technol.*, 2004, **37**, 9–15.
- 42 T. Anthierens, P. Ragaert, S. Verbrugghe, A. Ouchchen, B. G. De Geest, B. Nosedá, J. Mertens, L. Beladjal, D. De Cuyper and W. Dierickx, *Innov. Food Sci. Emerg. Technol.*, 2011, **12**, 594–599.
- 43 M. Krawczyk, I. Burzynska-Pedziwiatr, L. A. Wozniak and M. Bukowiecka-Matusiak, *Biomolecules*, 2023, **13**, 1402.
- 44 U. Bhuyan and J. G. Handique, *Stud. Nat. Prod. Chem.*, 2022, **75**, 243–266.
- 45 N. d F. F. Soares, A. C. S. Pires, G. P. Camilloto, P. Santiago-Silva, P. J. P. Espitia and W. A. Silva, *Recent Pat. Food Nutr. Agric.*, 2009, **1**, 171–178.
- 46 M. G. Barúa, J. P. Escalada, M. Bregliani, A. Pajares and S. Criado, *Redox Rep.*, 2017, **22**, 282–289.
- 47 B. P. Kumar, D. Ramakanth, K. Akhila and K. K. Gaikwad, *Food Packag. Shelf Life*, 2023, **38**, 101141.
- 48 P. Jain, L. Kumar, S. Singh and K. K. Gaikwad, *Sustainable Chem. Pharm.*, 2024, **37**, 101350.
- 49 S. Sänglerlaub and K. Müller, *Packag. Technol. Sci.*, 2017, **30**, 45–58.
- 50 S. Singh, K. K. Gaikwad and Y. S. Lee, *Sci. Hortic.*, 2019, **256**, 108548.
- 51 K. K. Gaikwad, S. Singh and Y. S. Lee, *Food Sci. Biotechnol.*, 2017, **26**, 1535–1543.
- 52 E. D. Cardona, M. del Pilar Noriega and J. D. Sierra, *J. Plast. Film Sheeting*, 2012, **28**, 63–78.
- 53 J.-S. Lee, Y. Chang, E.-S. Lee, H.-G. Song, P.-S. Chang and J. Han, *J. Food Sci.*, 2018, **83**, 682–688.
- 54 P. Scarfato, E. Avallone, M. R. Galdi, L. Di Maio and L. Incarnato, *Polym. Compos.*, 2017, **38**, 981–986.
- 55 S. Pawde, S. R. Chaudhari, P. Prabhasankar and R. S. Matche, *ACS Appl. Mater. Interfaces*, 2023, **15**, 38729–38740.
- 56 S. Pawde, S. R. Chaudhari, P. Prabhasankar and R. S. Matche, *ACS Sustain. Chem. Eng.*, 2011, 10.1016/j.jifset.2011.06.008.
- 57 K. K. Gaikwad, S. Singh, Y. S. Negi and Y. S. Lee, *J. Food Meas. Char.*, 2020, **14**, 1857–1864.
- 58 M. Andersson, T. Andersson, P. Adlercreutz, T. Nielsen and E. G. Hörnsten, *Biotechnol. Bioeng.*, 2002, **79**, 37–42.
- 59 T. Anthierens, P. Ragaert, S. Verbrugghe, A. Ouchchen, B. G. De Geest, B. Nosedá, J. Mertens, L. Beladjal, D. De Cuyper and W. Dierickx, *Innov. Food Sci. Emerg. Technol.*, 2011, **12**, 594–599.
- 60 S. Singh, K. K. Gaikwad and Y. S. Lee, *Sci. Hortic.*, 2019, **256**, 108548.
- 61 K. K. Gaikwad, R. K. Deshmukh and Y. S. Lee, *Biomass Convers. Biorefin.*, 2024, **14**, 5627–5636.
- 62 P. Jain, L. Kumar, S. Singh and K. K. Gaikwad, *Sustainable Chem. Pharm.*, 2024, **37**, 101350.
- 63 A. F. Pant, S. Sänglerlaub and K. Müller, *Materials*, 2017, **10**, 489.
- 64 K. K. Gaikwad, S. Singh, J. Shin and Y. S. Lee, *LWT-Food Sci. Technol.*, 2020, **117**, 108643.
- 65 S. Limbo, E. Uboldi, A. Adobati, S. Iametti, F. Bonomi, E. Mascheroni, S. Santagostino, T. H. Powers, L. Franzetti and L. Piergiovanni, *Meat Sci.*, 2013, **93**, 477–484.
- 66 S. Remya, C. O. Mohan, G. Venkateshwarlu, G. K. Sivaraman and C. N. Ravishankar, *Food Control*, 2017, **71**, 71–78.
- 67 H. Mu, H. Gao, H. Chen, F. Tao, X. Fang and L. Ge, *Food Chem.*, 2013, **136**, 245–250.
- 68 N. De Kruijf, M. Van Beest, R. Rijk, T. Sipiläinen-Malm, P. P. Losada and B. De Meulenaer, *Food Addit. Contam.*, 2002, **19**, 144–162.
- 69 B. Muhamedbegović, N. Ahmetović, J. Suljagić and B. Bajrić, *RIM 2021 – Development and Modernization of the Manufacturing*, 2021, vol. 7, p. 12.
- 70 P. Jain, K. Akhila, B. Meshram, S. Singh and K. K. Gaikwad, *Food Packag. Shelf Life*, 2025, **49**, 101478.

