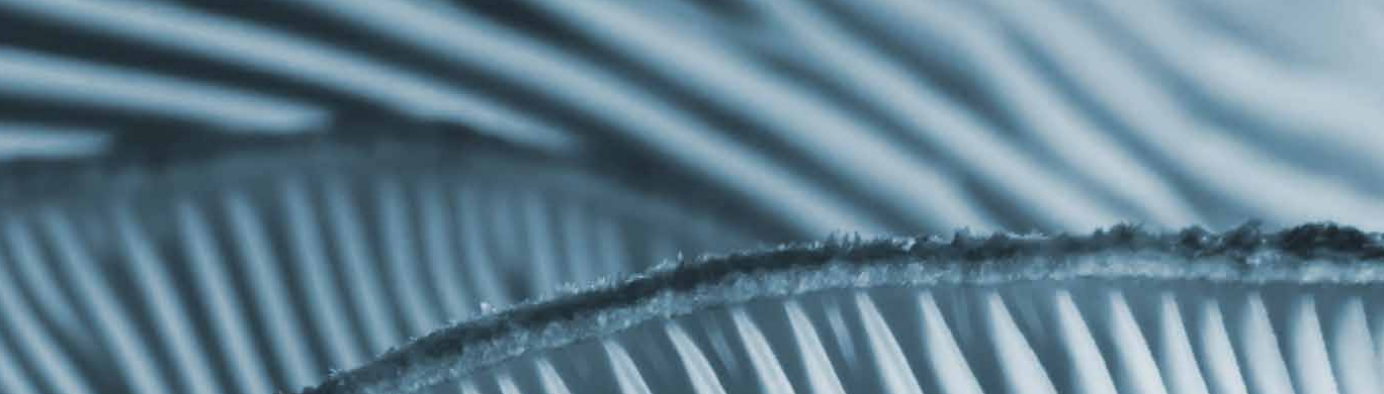




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Food Processing

Novel Technologies and Practices

*Edited by Roxana Nicoleta Ratu,
Romina Alina Marc and Andruța Elena Mureșan*



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Food Science and Nutrition

Volume 21

Aims and Scope of the Series

The significance of food is undeniable, especially in light of the impending challenge facing humanity: ensuring there will be enough food to meet the basic needs of a population expected to reach approximately 10 billion by 2050. These food-related challenges align with some of the United Nations' sustainable development goals, with a target to achieve them by 2030. One thing is certain: food should be not only nourishing and safe but also tailored to the diverse needs of individuals throughout their lifetimes, all while meeting consumers' sensory expectations. Understanding the diverse chemical composition of food, often referred to as biodiversity, and how these components can contribute to human health by considering factors like bioaccessibility, bioavailability, and bioactivity at the organ level, is crucial for grasping and promoting a healthy diet. Thanks to the continuous evolution of analytical methods and interdisciplinary research, significant strides have been made in the field of food science and nutrition.

Meet the Series Editor



Maria Rosário Bronze has been working in Analytical Chemistry since 1986. Her Ph.D. in 1999 contributed to the study of food products using capillary electrophoresis. The main goal of her research since 1999 has been focused on Analytical Chemistry applied mainly to the analysis of foods and by-products of food industry. She conducted research in collaboration with national and international research groups, at iBET and ITQB Technology Division. From 2017 until 2021 she was head of Food & Health Division at iBET and head of the Food Functionality and Bioactives Laboratory. MR Bronze has been an Associate Professor at the Pharmacy Faculty of Lisbon University and head of the Structural Analysis Laboratory since 2012. As a researcher, MR Bronze is a Senior Scientific Advisor at Food & Health Division at iBET and Head of Food Functionality and Bioactives Laboratory at the same Institute, Collaborator at iMED and Researcher at ITQB NOVA. Her current research is focused on quality and beneficial health effects of food components. Gas and liquid chromatography associated with mass spectrometry are used by MR Bronze in the characterization of samples. Sensory evaluation is also an important area of her research. The main food products studied by her are olive tree products (olive, olive oil, leaves), cereals such as maize, legumes (faba bean, pea, chickpea, lentils) fruits (apple, grapes, opuntia ficus), fruit juices and wine, among others. More recently her interests have also involved biodiversity, bioaccessibility, and bioavailability studies on food products and their components, mainly phytochemicals as phenolic compounds, using different analytical tools such as mass spectrometry. As a senior scientific advisor at Food & Health Division at iBET she is involved in different areas: (i) isolation, characterization and formulation of bioactive and functional compounds or extracts from natural sources and wastes from food and other related industries; (ii) pre-clinical assays to provide support to understand health claims related with the beneficial effects of food nutrients/bioactive components; (iii) establishment of analytical methodologies including mass spectrometry state-of-the-art to fully characterize different matrices, from food products, natural extracts or biological fluids (Food Functionality and Bioactives Laboratory).

Meet the Volume Editor



Roxana Nicoleta Rațu is an Associate Professor of Food Technologies at the "Ion Ionescu de la Brad" Iasi University of Life Sciences (IULS) in Iasi (Romania). Her research focuses on the quality, safety, and authentication of foods, particularly dairy, using advanced analytical methods such as UV-Vis spectrophotometry and enzymatic assays. A significant part of her work addresses circular-economy solutions for the agri-food sector, focusing on the valorisation of agro-industrial by-products and the ultrasound-assisted extraction of bioactive compounds for incorporation into functional ingredients and innovative foods. She has authored five scholarly books and more than 140 scientific papers, and her findings have informed process optimisation and product development in collaboration with industry partners. She serves on editorial boards and regularly reviews for international journals, contributing to the integrity and visibility of the field. She leads and participates in nationally funded, industry-linked projects, supervises early-career researchers, and promotes technology transfer to practice. ORCID: <https://orcid.org/0000-0001-5637-4376>.



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Preface

It is confirmed that in recent years, the global food sector has undergone visible and profound changes, transformations that did not occur in isolation but are the result of converging processes: accelerated technological innovation, increasing environmental pressures, changes in the regulatory landscape, and the evolution of consumer expectations. All these transformations have fundamentally changed the way food is processed, preserved, distributed, and ultimately consumed. As the agri-food sector adapts, new processing technologies and practices are no longer an option but are becoming a central element in building sustainable and resilient food systems.

The volume “*Food Processing – Novel Technologies and Practices*” was designed as a relevant contribution to this constantly evolving field. Instead of offering fragmented perspectives, this work brings together knowledge from multiple disciplines and applied research contexts. It integrates contributions from food science, engineering, and technology, reflecting the complex and interconnected nature of modern food processing. Particular emphasis is placed on approaches that aim not only to improve food safety and quality but also to reduce environmental impact and resource consumption.

In both research and industrial practice, non-thermal technologies, intelligent processing systems, digitalization, and circular economy models are playing an increasingly important role. However, their implementation depends on factors such as regulations, economic feasibility, environmental performance, and consumer acceptance. By creating this volume, the aim was to offer an integrated perspective on these aspects, facilitating an efficient transfer of knowledge between research, industry, and decision-makers.

The editors express their deep gratitude to all the authors who contributed to the creation of this book. Our sincere thanks also go to the technical editorial team for their valuable support throughout the volume’s preparation process.

We hope this work will serve as both a reliable reference source and a stimulus for future research and innovation. By offering a critical perspective on emerging

technologies and processing practices, the volume aims to inform and inspire researchers, industry specialists, and policymakers working to build a more sustainable, efficient, and technologically advanced global food system.

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Valorisation of Fruit and Vegetable By-Products in Dairy Product Technologies: A Sustainable Approach to Functional Food Development

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Abstract

The valorisation of fruit and vegetable by-products in dairy technologies is an innovative and sustainable approach to the development of functional foods. The integration of bioactive-rich by-products into dairy products offers a potential solution aligned with circular economy principles as the agri-food sector confronts escalating environmental, economic, and health challenges. This chapter emphasises the nutritional and functional potential of various fruit and vegetable residues—such as pomace, peels, and seeds—through their contributions to antioxidant capacity, dietary fibre content, probiotic viability, and sensory attributes in diverse dairy products, including cheese, yoghurt, and ice cream. The focus is on current technological advancements that facilitate the incorporation of these materials, such as encapsulation methods, and their impact on customer perception and commercial feasibility. The evaluation addresses critical concerns regarding regulatory compliance, microbiological safety, and sensory acceptance, along with proposed solutions to these challenges. This study highlights the transformative potential of by-product valorisation in advancing sustainable, health-enhancing dairy technologies through current research and industry practices.

Keywords: agri-food by-products, dairy technology, functional foods, sustainability, circular economy, bioactive compounds, food valorisation

1. Introduction

As environmental problems and the use of natural resources rise, the food industry around the world is becoming more aware of how important it is to make

food processing systems more sustainable and waste-free. Once thought of as trash, agri-food by-products are now seen as important resources with a lot of untapped potential. This shift reflects a broader commitment to developing sustainable food systems through the recovery and reuse of these materials [1].

The European Union (EU) has taken a strategic approach to this challenge by implementing a comprehensive action plan aimed at minimising food waste, guided by principles of the circular economy [2]. This way of thinking focuses on reducing, reusing, returning, and recovering resources to make them last longer and be worth more in food systems. The UN's Food and Agriculture Organisation (FAO) has said that reducing agriculture's carbon footprint is a key part of making food production more sustainable. People agree that organic farming, precision farming, and better manure management are important ways to fight climate change [3].

In addition to environmental benefits, research indicates that low-value agri-food wastes, co-products, and by-products can significantly contribute to improving soil health and nutrient cycling, thus playing a crucial role in closing the agricultural nutrient loop. These by-products, generated across various stages of agricultural and food processing operations, are typically rich in bioactive compounds, dietary fibre, proteins, vitamins, lipids, and other functional constituents [4, 5]. As such, they present promising opportunities for the development of novel, functional, and value-added food products, while simultaneously addressing the global issue of food waste.

Recent studies have demonstrated the diverse applications of these by-products, including their use in extracting health-promoting compounds, formulating alternative livestock feeds, and incorporating them into innovative food product development [6, 7]. Their nutritional richness and functional properties make them particularly suitable for integration into food systems, further enhancing the environmental and economic viability of the food industry [8].

The effective valorisation of agri-food by-products has emerged as a major area of interest among researchers, industry stakeholders, and policymakers alike. This has led to a notable increase in both scientific investigations and technological innovations aimed at reducing waste, promoting sustainability, and generating high-value products [9]. Adoption of circular economy strategies by the food sector offers significant potential to transform underutilised residues into functional ingredients, additives, and feedstocks, thereby fostering more sustainable and resource-efficient processing models [10].

Despite the evident promise, challenges remain in relation to the technological implementation, regulatory frameworks, market acceptance, and consumer perception of such by-product-derived food innovations [11]. Addressing these limitations is vital for unlocking the full potential of these materials and achieving a more resilient and sustainable food system. The potential applications of high-value compounds sourced from agri-food by-products span across the food and healthcare sectors. Nonetheless, their practical utilisation requires careful consideration of technical constraints and process optimisation [12].

This chapter aims to provide an overview of the integration of fruit and vegetable by-products into dairy processing technologies, outlining the current knowledge on their nutritional and functional properties, as well as their potential to contribute to sustainable food production. By exploring innovative practices in dairy product development, this chapter also highlights the broader implications of upcycling by-products for environmental protection, resource conservation, and health-oriented food design.

2. Functional potential of fruit and vegetable by-products

Fruits and vegetable by-products (FVB) are secondary products often discarded or neglected during manufacturing or other stages of food preparation. Vegetable by-products, such as pomace, hulls, peels, husks, and seeds, are primarily discarded during production. For some vegetable varieties, such as broccoli, cauliflower, and pumpkin, the stem and leaves are eliminated and not consumed. Fruit by-products include the peels, pomaces, and seeds. Fruit pomace is the residual solid material following the extraction of juice from fruits, which may encompass seeds, skins, pulps, and stems of specific fruits. For instance, apple pomace constitutes approximately 25% of apples, with by-products from the apple juice and cider business capable of producing substantial quantities of pomace [13].

Fruits and vegetables are the most extensively employed commodities within horticultural crops. The processing of fruits and vegetables generates a substantial amount of waste by-products, accounting for approximately 25–30% of the total commodity group [14]. Approximately 50% of by-products produced by fruits and vegetables consist of peels, cores, pomaces, seeds and unripe or damaged specimens [14].

The predominant bioactive compound in FVB is dietary fibre (DF), although phytochemicals, including carotenoids, minerals, vitamins, and phenolic compounds like anthocyanins and flavonoids, are also commonly assessed in these by-products [15].

DF comprises a diverse array of non-starch polysaccharides. DF (cellulose, hemicellulose, pectin, hydrocolloids, and lignin) has numerous recognised health advantages. Sufficient dietary fibre consumption diminishes the likelihood of acquiring chronic conditions, including coronary heart disease, stroke, obesity, hypertension, diabetes, and gastrointestinal disorders. Furthermore, DF consumption increases serum lipid profiles, regulates blood pressure and glucose levels in diabetes, facilitates weight reduction, and bolsters immune function [16].

By-products rich in dietary fibres contain several colourants, antioxidant chemicals, and other components that confer notable health benefits, with some being high in proteins (**Figure 1**).

Phytochemicals are bioactive, non-nutritional substances that confer the beneficial characteristics of fruits and vegetables. Phenolic chemicals are present in food as free, soluble conjugated forms (glycosides) and insoluble forms known as bound phenolics (cellulose, hemicellulose, lignin, pectin), primarily associated with fibre. This class of chemicals offers numerous health advantages, including antioxidant, antibacterial, antiviral, and anti-inflammatory characteristics and enhances plasma lipids and vascular function, potentially reducing the risk of cardiovascular disease [17]. For example, during the extraction of tomato juice, around 3–7% of the raw material is lost. The pomace comprises skins, seeds, and a minimal quantity of flesh. The tomato skin has far higher levels of lycopene, potentially five times more than the flesh. Hernández-Fuentes et al. [18] found that tomato peel contains lycopene and β -carotene approximately 20 times more than the entire tomato. In the food business, the pomace is predominantly utilised in powdered form as a dietary supplement for various food products, owing to its composition of phenols, dietary fibre, unsaturated fatty acids, and important amino acids.

Tocopherols (vitamin E isomers) are antioxidants found FVB, recognised for their health benefits, including the prevention of chronic diseases. Urquiaga et al. [19] confirmed the existence of α -, γ -, and δ -tocopherols in grape pomace, accounting for roughly 0.16 g/100 g of the total polyphenols. Phytosterols have not been comprehensively examined in FVB. Some studies suggest that dried and crushed

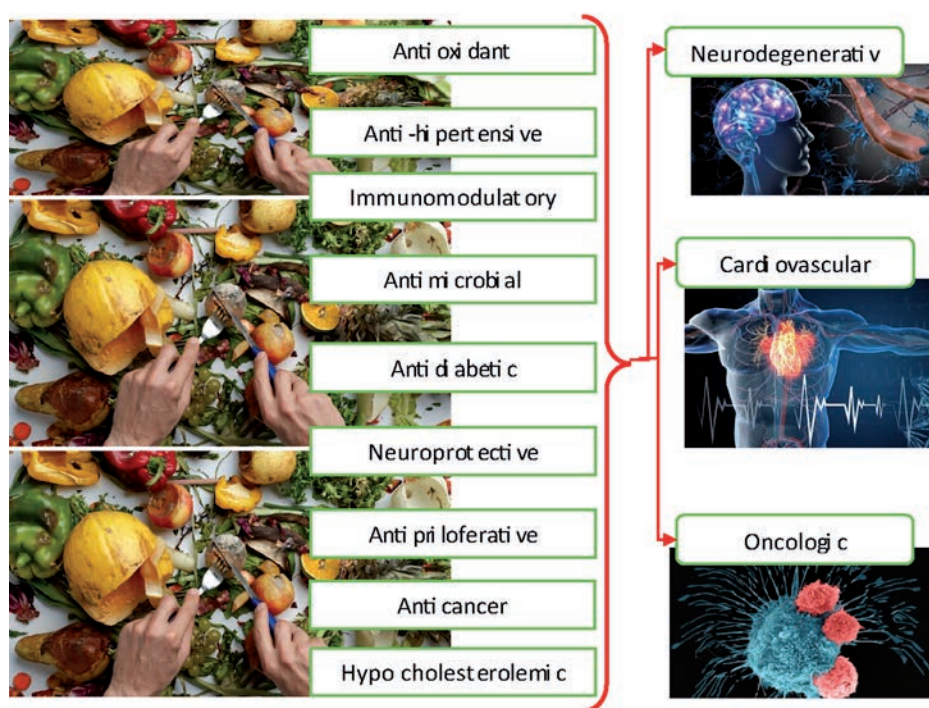


Figure 1.
Biological properties of bioactive compounds recovered from fruits and vegetable by-products.

fruit by-products contain around 4.5 mg of free phytosterols per grame of raw material [20]. The predominant phytosterols identified in the by-products of peach, mango (peels and pulp remnants) were β -sitosterol, avenasterol, β -campesterol, and stigmasterol [21].

Diverse fruit peels and pomace are abundant in phenolic compounds, demonstrating considerable radical scavenging activity. Specific fruit peels, such as mango, bambangan, rambutan, and mangosteen, are recognised for their substantial anti-oxidant properties and are suitable for incorporation as natural antioxidants in the development of functional meals [13]. They may also serve as a source of antioxidants in the food sector to inhibit lipid oxidation, antibacterial agents, or as constituents of functional foods. The characteristics of by-products possess advantageous health benefits and can enhance the shelf life of food goods. FVB are also identified as abundant in antioxidants, as well as antibacterial and antifungal agents. Polyphenols extracted from apple pomace shown enhanced radical scavenging activity relative to vitamins C and E, indicating that apple pomace could be a valuable natural source of antioxidants. Tomato pomace is an abundant source of phenolic compounds and tocopherols, which contribute to considerable antioxidant activity. Grape pomace has been included as a functional ingredient in several food products (yoghurt and cheese) owing to its significant antioxidant activity [22].

Furthermore, lemon, papaya, and sapodilla peels exhibited significant anti-bacterial activity, particularly against Gram-negative bacteria, while papaya peels showed substantial suppression of fungus. Pomegranate peels exhibit significant antioxidant and antibacterial properties against foodborne pathogens, including

Listeria monocytogenes, *Escherichia coli*, *Yersinia enterocolitica*, and *Staphylococcus aureus* [23, 24]. The findings of Feng et al. [25] demonstrated the inhibitory impact of pomegranate peel extract on *S. aureus*, together with its antioxidant capabilities. Total polyphenols, total tannins, and punicalagin showed a favourable correlation with antibacterial efficacy against *S. aureus*. FVB may serve as a potential prebiotic food element to enhance gut microbiota homeostasis, promoting the proliferation of beneficial microbes, boosting α -diversity, and/or inhibiting the growth of pathobionts, hence preventing dysbiosis. The gut microbiota metabolises fermentable fibres and polyphenols, producing new compounds that have health consequences [26].

Diverse citrus fruit by-products, such as pomegranates, are widely preferred and commonly utilised. The user can also gain from the prebiotic, anti-inflammatory, and antiproliferative properties of the bioactive phytochemicals included in these fruits. Research has demonstrated the advantages of plant phenols and their metabolites, which regulate endogenous antioxidant and immune systems and influence lipid and glucose metabolism [27].

Table 1 summarises recent applications of agri-food by-products incorporated into various dairy products, highlighting their contributions to enhanced nutritional and functional properties.

Industry	Product	Incorporated agri-food by-product	Nutritional value	References
Dairy	Dairy beverage	Olive vegetable water	Increased antioxidant activity, source of phenolic compounds	[28]
	Fermented milk	Apple pomace, wine pomace extract, grape marc flour, wine pomace extract and flour	Source of protein, probiotic protection, texturising agent, source of dietary fibre, source of phenolic compounds, increased antioxidant capacity, colourant agent	[29, 30]
	Yoghurt	Grape seed extract, grape skin flour	Texturising agent; increased phenolic content, colourant agent, reduced syneresis, maintained textural and gel formation	[31, 32]
	Cheese	Pear/apple stones, orange by-products, pomegranate peel, tomato peel, grape seed, grape pomace, wine pomace, skin and seed extract	Increased phenolic content, probiotic protection, texturising agent, increased antioxidant capacity, increased antimicrobial capacity	[33, 34]
	Butter	Tomato peel	Increased antioxidant capacity	[35]
	Ice cream	Pomegranate peel	Texturising agent, increased phenolic content, increased antioxidant capacity, colourant agent	[36]

Table 1.
Nutritional improvement in products with the addition of agri-food by-products.

3. Dairy products as vehicles for by-product valorisation

Milk represents a fundamental component of the diet for over 6 billion people worldwide [37]. In addition to milk itself, a wide range of dairy products—including cheese, yoghurt, ice cream, and butter—are produced and consumed on a large scale. As such, milk and dairy products offer a strategic and practical avenue for the valorisation of agri-food waste and by-products, enhancing their nutritional and techno-functional properties and providing new ingredients for the development of innovative dairy products [38]. However, it is essential that the fortification of dairy products does not adversely affect their sensory or physical characteristics, in order to maintain consumer acceptance and the palatability of the final products. Accordingly, the integration of agri-food waste and by-products into milk and dairy matrices, and their subsequent impact on nutritional quality, as well as physical and sensory properties, has been the focus of considerable research over the past decade.

Cheese production, which dates back to 5200 BC [39], is a longstanding practice involving the coagulation of milk from various species, such as cows, sheep, goats, buffalo, and camels. This process typically includes fermentation with lactic acid bacteria and the addition of rennet, resulting in the separation of curds and whey and significant modifications to milk proteins, carbohydrates, and lipids [40]. Key production steps—such as acidification, coagulation, whey removal, salting, and ripening—critically determine the final cheese's sensory attributes, including texture and flavour.

In recent years, there has been growing interest in enhancing the functional and nutritional properties of cheese through the incorporation of bioactive compounds derived from agri-food waste and by-products [41]. Various materials, such as powdered mango peel, grape pomace, tomato peel, artichoke leaves, and asparagus powder, have been explored as natural sources of fibre, antioxidants, and phenolic compounds [42]. These ingredients have been shown to improve the nutritional profile of cheeses, increasing antioxidant activity and phenolic content while, in many cases, preserving or even enhancing sensory qualities. Lipşa et al. [43] incorporated red onion peel (ROP) extract as an enrichment in ricotta cheese and demonstrated that it is a valuable source of bioactive compounds with high antioxidant activity. Their study showed that the addition of 1% ROP powder did not interfere with the fermentation process conducted by the commercial starter lactic acid bacteria. Moreover, the enrichment enabled the production of bovine whey cheese with distinct functional, physicochemical, and sensory properties, characterised by higher protein and polyphenol content and reduced fat levels compared to the control.

Furthermore, extracts from food by-products, such as pomegranate rind and olive oil residues, have demonstrated potential in extending cheese shelf life by reducing lipid oxidation and microbial spoilage [44]. However, successful application depends not only on the health benefits conferred but also on maintaining the traditional characteristics of cheese—especially its texture, flavour, and consumer appeal [45]. Challenges remain regarding the stability, bioavailability, and safety of incorporated bioactives during storage, as well as the economic feasibility and determination of optimal concentrations to achieve the desired functional benefits [1].

Following the advances in cheese fortification, growing attention has also been directed towards the valorisation of by-products in other dairy sectors, notably in yoghurt and ice cream production. These industries offer promising avenues for the incorporation of bioactive compounds and functional ingredients derived from agri-food waste, aiming to enhance nutritional profiles, extend shelf life, and improve

sustainability, all while maintaining desirable sensory characteristics. Yoghurt is a dairy product obtained through the acid coagulation of milk, a process primarily facilitated by lactic acid bacteria such as *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus*. During fermentation, lactose is converted into lactic acid, reducing electrostatic repulsion among casein micelles and diminishing their calcium phosphate content. These interactions result in micelle aggregation and the formation of a gel matrix, which imparts yoghurt with its characteristic texture and taste [46]. Yoghurt products are typically categorised into set, stirred, and sipping varieties.

Consumption of yoghurt has been increasing globally, attributed to its nutritional richness, functional properties, and health-promoting effects. Yoghurt naturally provides key nutrients such as vitamins, calcium, riboflavin, and zinc [47]. Although conventional production methods are widely used, innovations in processing technologies have facilitated the incorporation of additional ingredients aimed at enhancing yoghurt's nutritional, physicochemical, and sensory qualities, thereby improving market appeal [48].

In this context, researchers have investigated the fortification of yoghurt with waste materials, by-products, and their extracts to valorise agri-food residues. For instance, the addition of hazelnut powder significantly increased radical scavenging capacity, total phenolic content, and dietary fibre levels in fortified yoghurt [49]. Similarly, the incorporation of apple pomace powder not only reinforced casein gel structure but also improved yoghurt firmness, cohesiveness, and reduced syneresis over storage periods [50].

Other studies have explored the use of various plant-based by-products. Fortification with papaya peel powder enhanced antioxidant properties and nutritional content, although it negatively impacted probiotic viability and shelf life. Banana peel fibre extract improved the growth of probiotics and yoghurt viscosity, though higher concentrations adversely affected sensory attributes. Stoica et al. [51] demonstrated that black carrot pomace (BCP) powder is a significant source of bioactive compounds with high antioxidant activity. Their investigation further revealed that the incorporation of BCP powder into yoghurt enhances its bioactive content and antioxidant capacity, thereby improving the nutritional profile of the final product. Barley and rice bran have also been incorporated to enhance probiotic viability and phenolic compound content, with the timing of addition (pre- or post-fermentation) influencing syneresis and structural properties [52].

Additional valorisation approaches have included the enrichment of yoghurt with spent coffee grounds, quince seed mucilage, fermented durian seed powders, and date fibre extracts, each demonstrating improvements in antioxidant capacity, rheological properties, or shelf-life stability without markedly compromising consumer acceptance [53].

Encapsulation techniques have emerged as an effective strategy to stabilise sensitive bioactive compounds during yoghurt production and storage. For example, carrot waste extracts encapsulated via freeze-drying have been shown to enhance antioxidant activity and maintain microbiological stability in fortified yoghurts. Encapsulation methods such as spray-drying, freeze-drying, extrusion, chemical crosslinking, and liposome formation have been employed to improve the stability, bioavailability, and controlled release of bioactives in dairy matrices [54, 55].

Nevertheless, the valorisation of agri-food by-products through yoghurt fortification must address several challenges, including sustainability, safety, regulatory compliance, and competition with traditional products. These obstacles can be mitigated through continued innovation, regulatory frameworks, and collaborative

efforts among researchers, industry stakeholders, consumers, and policymakers [56]. Building on the success of yoghurt fortification with agri-food by-products, similar strategies have been explored in the development of functional ice cream. As with yoghurt, incorporating natural bioactive compounds into ice cream formulations offers an opportunity to enhance nutritional quality, improve functional properties, and align with growing consumer demands for healthier and more sustainable food products.

Ice cream, which has its origins in Europe before its introduction to the United States, is traditionally produced from a mixture of milk derivatives, eggs, sweeteners, stabilisers, colourants, and flavourings [57]. Today, ice cream enjoys widespread popularity globally, consumed both after meals and as a snack, with global sales projected to reach 75 billion US dollars by 2024 [57]. Despite its popularity, conventional ice cream formulations are often high in sugars and fats, contributing to excessive calorie intake and increasing the risk of obesity and metabolic disorders [58]. These health concerns, coupled with environmental considerations, have accelerated the demand for low-calorie, high-fibre, and functional ice cream alternatives.

The valorisation of food waste and by-products in ice cream production has attracted significant research interest. For example, Mohammed et al. [59] demonstrated that incorporating lycopene crystals extracted from tomato pomace into ice cream improved antioxidant activity and extended shelf life without adversely affecting sensory qualities. Similarly, Çam et al. [60] replaced a portion of milk fat with pomegranate seed oil, rich in punicic acid, and added pomegranate peel powder as a source of phenolics, thereby enhancing the antioxidant and antidiabetic properties of ice cream. Fortification with 0.4% pomegranate peel and 2.0% seed oil was identified as the optimal formulation for achieving functional benefits while maintaining acceptable sensory attributes.

Crizel et al. [61] also reported promising results by incorporating orange by-products, such as peel, bagasse, and seeds, into ice cream, leading to a 70% reduction in fat content alongside increased phenolic and carotenoid compounds. Trombino et al. [62] utilised carotenoids from tomato peels, improving antioxidant capacity and enhancing colour and sensory appeal.

Textural and structural properties of ice cream have also been improved through by-product incorporation. Kurt and Atalar [63] found that quince seed powder enhanced texture and reduced crystallisation and melting time. da Silva et al. [64] proposed the development of prebiotic ice cream using water-soluble rice by-product extracts combined with inulins, resulting in products with enhanced antioxidant, antihypertensive, and antidiabetic properties. Meanwhile, Yu et al. [65] incorporated nano-fibrillated cellulose derived from grapefruit peel, successfully reducing caloric content and improving melting behaviour, texture, and sensory properties, particularly at a 0.4% concentration.

The addition of dietary fibres from coconut residue was explored by Hanafi et al. [66] in probiotic ice cream formulations, where 0.03 g/mL fibre concentration notably enhanced protein content, reduced fat, and maintained probiotic viability and sensory acceptance over a 60-day storage period.

While fortification offers substantial benefits, it is essential to consider the sensory impacts on consumer acceptance. The introduction of bioactive compounds can alter taste, aroma, and texture, either positively or negatively. Moreover, cultural perceptions and preferences, as well as the alignment of ingredients with clean-label and sustainability trends, significantly influence consumer willingness to adopt these fortified products [67].

4. Nutritional and functional benefits

Lakshmanan et al. [68] report that adequate consumption of fruits and vegetables contributes positively to overall health and physiological functions, with such dietary patterns exerting a notable influence on the gut microbiota. In this context, fruit-derived by-products are receiving increasing attention for their prebiotic potential, attributed to their substantial content of dietary fibre and polyphenolic compounds. These bioactive constituents exhibit anti-inflammatory properties and may help to mitigate dysbiosis—characterised by alterations in the composition and functionality of the gut microbiota—thereby potentially decreasing the risk or progression of certain disorders [26].

Empirical evidence further suggests that the incorporation of various additional ingredients into yoghurt formulations can improve product quality, enhancing both sensory characteristics and the associated microbiota [69]. Post-fermentation supplementation of yoghurt with exotic fruits has been shown to elevate total phenolic content, while the addition of strawberry pulp increases anthocyanin concentration and antioxidant capacity [70, 71]. Likewise, yoghurts enriched with rose hips present higher phenolic levels and improved antioxidant potential in comparison with control samples lacking these fortifying agents [72].

A study by Lee et al. [73] demonstrated that the incorporation of blueberry powder enhances both the antioxidant potential of yoghurt and the overall levels of phenols and flavonoids. Two more research studies indicated that including cranberry pulp or extract enhanced yoghurt by increasing antioxidant capacity and overall phenolic content, hence exhibiting increased functional qualities [74, 75].

The modulation of gut microbiota is closely associated with the preservation of overall health and the prevention of numerous chronic illnesses, particularly via microorganisms which impact digestion, nutritional absorption, intestinal barrier integrity, and immunological functionality. Consequently, by-products from fruit and vegetable processing (such as peels, seeds, insoluble fibre, or pomace) are abundant in fibre and bioactive components, including polyphenols and indigestible oligosaccharides, which may exhibit prebiotic qualities [76, 77]. These by-products promote the development of beneficial bacteria, including *Bifidobacterium*, *Lactobacillus*, and *Faecalibacterium prausnitzii*, enhancing digestive system functionality and mitigating metabolic disorders such as type 2 diabetes or obesity [78].

A series of research has examined the impact of incorporating grape marc into yoghurt on the intestinal tract and more. Grape marc is a significant source of bioactive compounds (flavonoids, tannins, and phenolic chemicals) that function as antioxidants, anti-inflammatory agents, and antimicrobials for both humans and animals [79]. A study on grape marc from southwestern Sardinia revealed its richness in catechin, quercetin, fisetin, and gallic acid, compounds recognised for their antioxidant properties [80].

Research indicates the prospective utilisation of grape marc in the food industry, particularly due to its polyphenols, which demonstrate a diverse array of biological activities (prebiotic, antioxidant, antimicrobial, anti-lipidemic, and anti-proliferative) that may aid in the management of various conditions, such as hypertension and diabetes, obesity, ageing, cancer, and neurodegenerative conditions [81].

Apple pomace, a by-product predominantly generated during the manufacture of apple juice and cider, has been extensively investigated for its incorporation into yoghurts and other fermented dairy matrices [82]. Studies indicate that apple pomace powder exhibits favourable functional properties, including high water retention

capacity, good solubility, and notable swelling ability, in addition to improving the overall consistency of milk-based products [83]. Yoghurt formulations enriched with this ingredient have been reported to display increased antioxidant capacity, higher dietary fibre levels, and reduced syneresis, alongside enhanced textural characteristics that contribute to a firmer and more cohesive structure [84].

The inclusion of apple pomace flour in yoghurt has also been shown to elevate total phenolic content and antioxidant activity, with yoghurt extracts demonstrating inhibitory effects on the viability of colon tumour cells [85]. Ahmad et al. [86] further reported that apple peel polyphenol extracts improve both the antioxidant profile and the probiotic functionality of yoghurt products. Similarly, research by Dimitrellou et al. [87] revealed that supplementation with apple fibre substantially increased probiotic survivability beyond that afforded by the yoghurt matrix alone. Improvements were observed under simulated gastric conditions as well as in intestinal environments containing bile salts, providing a basis for the formulation of innovative functional foods capable of maintaining probiotic integrity throughout gastrointestinal passage.

5. Sensory acceptance and consumer perception

The incorporation of fruit and vegetable by-products into dairy products enhances their nutritional and functional value. The acceptance of these products among customers largely relies on their perceptions of attributes such as texture, colour, and taste. Compositional and qualitative characteristics, including protein source, texture, fat content, sugar level, and the shape of the yoghurt, influence sensory acceptance [88]. Consumer preference generally has a favourable correlation with the product's thickness and softness [89]. A decrease in sugar content in strawberry-flavoured yoghurt significantly influenced consumers' purchasing intentions in a positive way [90]. Textural variables significantly influence consumer acceptability; therefore, it is essential to correlate these parameters with sensory acceptance in yoghurt. Nevertheless, research investigating the relationship between consumer acceptability of texture, structure, and composition within the category of plant-based yoghurts is still limited [88].

Jeong et al. [91] conducted a study examining the influence of fruit and vegetable by-products on the sensory characteristics of dairy products, specifically focusing on the incorporation of tomato extracts in Queso Blanco cheese. Consequently, it was seen that acceptability and texture ratings improved with higher concentrations of tomato extract, peaking at 2%, indicating a gradual consumer acceptance of the product's enhanced functional attributes without detriment to sensory quality.

Çam et al. [36] examined the acceptability of ice cream including small quantities of citrus fibres (0.4–0.8%). An enhancement in flavour and consistency was seen relative to the control group (0%); however, a higher concentration of citrus fibres (1.2%) resulted in a marginal decline in these ratings, suggesting a threshold of sensory acceptability among respondents. Subsequent investigations into ice cream with orange fibre revealed a gradual decline in colour, flavour, and texture ratings as fibre concentration increased (up to 1.5%). The overall acceptability declined from 8.1 to 6.4, indicating that elevated concentrations of orange fibre may impair the sensory attributes of the ice cream [61].

The research by Kurt and Atalar [63] focused on producing ice cream with quince seed powder demonstrated that at concentrations up to 0.75%, the ratings for flavour,

consistency, and overall acceptability improved (≥ 7), suggesting that quince seeds can be effectively utilised in reasonable quantities without adversely impacting the sensory attributes of the final product.

Many studies indicate that factors such as health, safety, sustainability, and animal welfare are the primary determinants in the selection of food products that have the addition of natural, fruit, and vegetable by-products or even clean label claims. Studies conducted by food companies indicate that a “*clean label*” product meets the consumer’s expectations when it says it is *natural*, *organic*, or *additive/preservative free*. Therefore, a clean label product includes a basic, limited number of ingredients that buyers can understand. It also does not contain any artificial or chemical ingredients and is made up of things that you can find in your kitchen cupboard [92].

Aertsens et al. [93] showed that purchase decisions are significantly associated with specific human values, including security, compassionate behaviour, and conformity. Also, Petrescu et al. [94] have demonstrated that ethical considerations, including environmental responsibility, or because they are in fashion, enhance customers’ willingness to pay for organic products. A study published by Chauhan et al. [95] on clean-label options for food preservation shows that even though technology has improved over the last few decades, food preservation is still an important concern around the world, mostly because most of the products used are artificially created and do not break down naturally. Because of this, the food industry is putting more value on microbiota and other natural sources for bio-preservation. To get a “clean label,” natural options are being used instead of traditional processing and chemical preservatives. In this way, using fruit and vegetable by-products in this industry is a good way to make functional products that can help keep food fresh, improve its physical, chemical, and sensory properties, and keep its “clean label” status.

6. Sustainability and market potential

According to Mahongnao et al. [96], the world is currently dumping billions of tons of trash into the atmosphere. The task of managing this garbage is quite difficult. The circular economy, which upcycles trash from one process into goods with added value, is a modern, logical approach to waste management. Campos et al. [97] relate that industrial fruit by-products must be managed in order to reduce the amount of food waste that ends up in landfills and to create strategies for reuse that will increase their economic value. Food waste disposal causes a number of worldwide problems in a variety of domains, including social, environmental, and economic. For potential industrial uses in the future, these by-products offer a wealth of useful chemicals (polyphenols) with strong antioxidant activity that can be isolated using biotechnological techniques. Moving from a linear economy to a circular economy presents challenges for the management of fruit by-products in this setting.

An integrated strategy that takes into account social and environmental issues in addition to economic development is necessary for food sustainability and, more generally, sustainable development. By lowering greenhouse gas emissions, improving ecosystem services, and upholding sustainable resource management laws, minimising food waste not only helps the environment but also advances a number of social goals. Food waste is the third-largest producer of greenhouse gases worldwide, contributing 8–10% of total emissions [98].

As an underutilised resource that can be put to use, food waste and by-products are a crucial component of the circular economy. Sustainable consumption and

production, or SDG 12 of the UN 2030 Agenda for Sustainable Development, are closely linked to the circular economy, which generates more jobs with fewer resources. The circular economy model and the bioeconomy policy offer excellent prospects for addressing the problem of food waste and by-products, particularly in medium-high income nations where the majority of the issue is linked to reprehensible consumption practices at the end of the food supply chain [99].

According to Roy et al. [100], finding the proper technique for valorising food waste is critical for cost-effective management and resource conservation. Food waste's economic impact is directly related to the methods of valorisation that are employed, and the resulting end products determine the economic advantages.

Research has looked at a range of economic metrics to evaluate the viability of food waste recovery plans, emphasising the impact of economies of scale and market prices. Economic sustainability can be improved and production costs can be greatly decreased by incorporating food waste biorefineries into already-existing plants. Overall, waste stream availability and proximity to biorefinery locations must be taken into account for a thorough economic assessment of food waste valorisation. For food waste management techniques to remain economically viable, several factors are crucial [101, 102].

Several studies have focused on the application of the circular economy concept to food waste materials, recognising its potential as a paradigm for future research. One prominent area in which the linear economic model can be replaced by a sustainable circular approach is the valorisation of agri-food waste and by-products through environmentally friendly methods. Celery peel contains many essential components comparable to those found in the celery root itself, rendering it a valuable raw material. In this context, the present work proposes a novel framework for investigating celery root peel waste, emphasising its high nutritional value and potential health benefits. Furthermore, its application in the reformulation of ayran, a traditional Turkish fermented dairy beverage, is explored. Sustainable green extraction and distillation techniques were employed to obtain water-soluble extracts from celery root peel for incorporation into ayran. According to Uzel [103], the inclusion of celery root peel extract in the development of a new functional fermented beverage, inspired by traditional ayran, not only imparted favourable physicochemical, microbiological, and sensory characteristics but also extended the product's shelf life by at least 50% compared with the conventional formulation.

Consumer acceptance should be taken into account in research investigations that concentrate on the inclusion of fruits and vegetables by-product extracts, both from a sensory perspective and with regard to overcoming cultural barriers. Giving customers straightforward yet thorough information about the process that creates a particular product and how it might help preserve the environment on Earth could boost acceptance [104–106].

7. Key challenges and future outlook

FAO and the United Nations Environment Programme are now assessing the Food Loss Index and Food Waste Index to assess the progress towards SDG Target 12.3, given the significance of decreasing food losses and waste [107].

Reducing food losses and wastes in a circular economy plan meets the UN Sustainable Development Goals and has important environmental (reducing pollution) and economic (valuing by-products) ramifications. A practical and affordable

way to value and incorporate fruit and vegetable by-products into different food items is to turn them into powders. In reality, multiple studies have shown that these flours can be successfully used in bakery, dairy, meat, and extruded goods [16, 108].

To augment customer acceptance of these items, it is imperative to invest in consumer education and focused marketing methods, particularly as many of these products may be new to specific demographics. Confronting these obstacles can enable the food sector to fully use the potential of fruit and vegetable by-products, significantly impacting food security, environmental sustainability, and economic viability throughout the business [109].

In line with the European Bioeconomy Strategy and the EU Circular Economy Action Plan, there is a lot of interest these days in recycling and upgrading food waste and by-products. As was previously noted, this entails using valorised by-products in a wide range of applications across various industries, which promotes the growth of the food sector, boosts commercial outputs, and prevents issues with improper waste management and its detrimental impacts on the environment. Considering the apparent benefits of this strategy, reintroducing such items into the food chain necessitates a careful assessment of the best manufacturing and recycling techniques that ensure both their appropriateness and the safety of consumers [110].

Modified or newly created foodstuffs based on valorised by-products should also adhere to the existing EU laws governing food safety for human consumption. They are based on the production of products that are safe for human consumption and do not harm health, which also applies to items meant for animal feed [111].

Based on simple analytical techniques, a number of physicochemical characteristics have been identified to describe the novel compounds derived from food waste. Generally speaking, measurements are made of moisture, acidity, ash content, colour, and other nutritional analyses such as the amount of fibre, carbs, lipids, or proteins. Ensuring microbiological safety remains a critical issue in the food sector, while the valorisation of food by-products continues to receive increasing scholarly and industrial attention. Inadequate post-harvest handling can lead to the contamination of plant-derived by-products—such as fruits, nuts, grains, seeds, and other non-perishable commodities—with undesirable microorganisms, thereby compromising their compliance with quality requirements. Within the broader agri-food chain, contamination may occur at multiple stages, including primary agricultural production, livestock rearing, food processing, and storage, and constitutes a matter of considerable concern. Even in trace amounts, hazardous substances—both organic and inorganic in nature—present in foods can pose substantial health risks to consumers [112].

Although the recovery and reuse of food waste and by-products are gaining momentum, systematic inclusion of microbiological safety assessments in related studies remains limited. This is particularly noteworthy given that by-products from both plant and animal origins are susceptible to microbial contamination during post-harvest handling, storage, and processing [113]. Research has been conducted on a range of by-products, including coffee residues, vegetables, meat, and seafood. Most of these investigations reported no detectable levels of major pathogens such as *Salmonella* spp., *Listeria monocytogenes*, or *Escherichia coli*, suggesting that current processing technologies can effectively mitigate microbiological hazards.

Nevertheless, a persistent challenge is the absence of established reference values for many by-products. In the absence of specific regulatory benchmarks, researchers often resort to applying microbiological limits intended for analogous food groups or raw materials, such as cereal-based additives or dried products. To facilitate safer and broader utilisation of recovered by-products in both food and feed applications,

existing literature underscores the necessity for more rigorous, standardised microbiological testing protocols specifically designed for such materials, alongside the development of clearer regulatory frameworks for their safety assessment [110].

The domain of food by-products valuation is at high risk of contamination. Concerns about the environment and food safety may arise from the use of food waste, the creation of new goods, and the employment of various techniques to accomplish this. Thus, it is important to carefully consider how they may affect the end goods' quality and safety. The transfer of pollutants from the raw material to the valorised product, as well as the creation of new hazardous compounds or their enrichment during the processing of food by-products, must be assessed in this regard.

While food by-products hold considerable promise for advancing sustainable development goals, they may also harbour hazardous chemical contaminants—both organic and inorganic—introduced at various stages, including agricultural production, processing, storage, and even during value-adding operations. A substantial body of research has examined the occurrence of contaminants such as mycotoxins, pesticide residues, heavy metals, persistent organic pollutants, and processing-induced chemicals, including furfural derivatives and acrylamide. The contamination profile of a by-product is strongly influenced by its origin and intended end use. For instance, marine- and animal-derived by-products are frequently analysed for heavy metals and persistent organic pollutants due to their environmental exposure, whereas plant-based by-products are more commonly screened for pesticide residues and mycotoxins [114–116].

Variations are also observed in the extent to which the introduction or concentration of contaminants is assessed during extraction and processing steps. In some cases, conventional extraction techniques may inadvertently increase the levels of certain hazardous compounds. Although awareness of potential contamination issues has grown, the systematic assessment of pollutants is not yet an established standard practice. Furthermore, current regulatory frameworks occasionally provide insufficient guidance for these emerging compounds. In this context, the literature highlights the need to develop harmonised regulatory standards that define acceptable safety thresholds for valorised by-products, coupled with more comprehensive and frequent contamination monitoring using validated analytical methods [117, 118].

According to Pearson et al. [119], the components and administration of each nation's national food control system are influenced by a number of factors, including institutional infrastructure, economic standing, and social standing. To create an efficient food control system for functional food products, it is necessary to analyse the current state of consumer perception and attitude towards functional foods that contain by-products of fruits and vegetables, conduct a thorough investigation into the opportunities and challenges facing the food industry, and evaluate the governance capabilities of the current national food control systems.

8. Conclusions

The valorisation of fruit and vegetable by-products within dairy product technologies presents a significant opportunity to advance the development of functional foods while addressing critical environmental and economic challenges. Throughout this review, it has been clearly demonstrated that secondary side streams from agri-food industries offer a rich source of bioactive compounds, including phenolic

compounds, fibres, proteins, vitamins, and complex carbohydrates, which can be effectively incorporated into dairy matrices such as cheese, yoghurt, and ice cream. This approach not only enhances the nutritional and functional qualities of dairy products but also contributes meaningfully to waste reduction and the promotion of sustainability within the food sector.

The use of food industry by-products as functional ingredients aligns well with the principles of the circular bioeconomy, supporting a zero-waste strategy and adding value to materials that would otherwise contribute to environmental pollution. Incorporation of by-products has demonstrated the potential to improve antioxidant activity, dietary fibre content, microbial quality, and texture in dairy products, thereby meeting the growing consumer demand for healthier, more sustainable food choices. Moreover, the recovery and utilisation of secondary side streams, such as fruit and vegetable peels, cereal residues, and dairy by-products, provide tangible economic benefits and foster innovation in functional food markets.

However, the successful integration of by-products into dairy products is not without challenges. Issues such as sensory modifications, stability, bioavailability, and potential consumer acceptance must be addressed through careful formulation, processing optimisation, and comprehensive risk assessments. Of particular concern is the potential for food safety hazards associated with by-product use, including contamination by mycotoxins, pesticide residues, heavy metals, and toxic compounds formed during processing. As highlighted, compounds such as ochratoxin A, persistent pesticide residues, and toxic furans underscore the necessity for rigorous safety evaluation, compliance with regulatory standards, and transparent communication with consumers regarding the origins and benefits of fortified dairy products.

Emerging technological innovations offer promising avenues to overcome some of these challenges. Encapsulation technologies, for instance, can significantly enhance the stability, controlled release, and functional efficacy of bioactive compounds in dairy systems. Furthermore, the integration of Industry 4.0 technologies—such as robotics, artificial intelligence, big data analytics, blockchain, and the Internet of Things—is set to revolutionise dairy production processes, making them more efficient, traceable, and aligned with sustainability goals.

Future trends also point towards the exploration of novel biomolecules, including plant-derived enzymes from agri-food waste, to replace traditional animal-based rennet in cheese production. Such innovations not only cater to the growing demand for plant-based and animal-friendly alternatives but also broaden the scope for diversification within the dairy sector.

The dairy industry stands at the threshold of numerous untapped opportunities. By fully harnessing the potential of agri-food waste and by-products, dairy products can be transformed into highly nutritious, functional, and environmentally sustainable foods that resonate with the evolving preferences of health-conscious and eco-aware consumers. Nevertheless, a multidisciplinary approach involving food scientists, technologists, regulatory bodies, and industry stakeholders will be essential to address the technical, regulatory, and perceptual barriers to broader adoption.

In conclusion, the valorisation of fruit and vegetable by-products in dairy technologies offers a compelling pathway towards the development of innovative functional foods, contributing not only to human health but also to environmental protection and economic sustainability. Continued research, technological advancements, and collaborative efforts are paramount to realising the full potential of this sustainable approach, ultimately fostering a resilient and future-proof food system.

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References

- [1] Rațu RN, Veleşcu ID, Stoica F, Usturoi A, Arsenoiaia VN, Crivei IC, et al. Application of agri-food by-products in the food industry. *Agriculture*. 2023;**13**(8):1559. DOI: 10.3390/agriculture13081559
- [2] European Environment Agency. Europe's Circular Economy in Facts and Figures. EEA Report 12/2024. Luxembourg: Publications Office of the European Union; 2024. Available from: <https://www.eea.europa.eu/publications/europes-circular-economy-in-facts> [Accessed: 11 April 2025]
- [3] Food and Agriculture Organization of the United Nations. The State of Food and Agriculture 2019: Moving Forward on Food Loss and Waste Reduction. FAO: Rome, Italy; 2019. Available from: <https://www.fao.org/3/ca6030en/ca6030en.pdf> [Accessed: 15 April 2025]
- [4] Aït-Kaddour A, Hassoun A, Tarchi I, Loudiyi M, Boukria O, Cahyana Y, et al. Transforming plant-based waste and by-products into valuable products using various “Food Industry 4.0” enabling technologies: A literature review. *Science of the Total Environment*. 2024;**955**(176872):176872. DOI: 10.1016/j.scitotenv.2024.176872
- [5] Routray W, Orsat V. Agricultural and food industry by-products: Source of bioactive components for functional beverages. In: *Nutrients in Beverages*. Amsterdam, Netherlands: Elsevier; 2019. pp. 543-589
- [6] Alvi T, Asif Z, Iqbal Khan MK. Clean label extraction of bioactive compounds from food waste through microwave-assisted extraction technique—A review. *Food Bioscience*. 2022;**46**(101580):101580. DOI: 10.1016/j.fbio.2022.101580
- [7] Nabi BG, Mukhtar K, Ansar S, Hassan SA, Hafeez MA, Bhat ZF, et al. Application of ultrasound technology for the effective management of waste from fruit and vegetable. *Ultrasonics Sonochemistry*. 2024;**102**(106744):106744. DOI: 10.1016/j.ultsonch.2023.106744
- [8] Anaya-Esparza LM, la Mora ZV, Vázquez-Paulino O, Ascencio F, Villarruel-López A. Bell peppers (*Capsicum annum* L.) losses and wastes: Source for food and pharmaceutical applications. *Molecules*. 2021;**26**(17):5341. DOI: 10.3390/molecules26175341
- [9] Ezeorba TPC, Okeke ES, Mayel MH, Nwuche CO, Ezike TC. Recent advances in biotechnological valorization of agro-food wastes (AFW): Optimizing integrated approaches for sustainable biorefinery and circular bioeconomy. *Bioresource Technology Reports*. 2024;**26**(101823):101823. DOI: 10.1016/j.biteb.2024.101823
- [10] European Environment Agency. The European Environment—State and Outlook 2020: Knowledge for Transition to a Sustainable Europe. Luxembourg: Publications Office of the European Union; 2019. Available from: <https://www.eea.europa.eu/soer/publications/soer-2020> [Accessed: 15 April 2025]
- [11] Thomson L, Chatthong C, Lennerfors T.T. Navigating the business model design space: A case of insects as food and feed in Sweden. *Technological Forecasting and Social Change*. 2025;**216**(124148):124148. DOI: 10.1016/j.techfore.2025.124148
- [12] Usman I, Sana S, Afzaal M, Imran A, Jaffar HM, Sukhera S, et al.

Phytochemicals in plant food waste: Innovative insight and implications. *Journal of Agriculture and Food Research*. 2025;**20**(101779):101779. DOI: 10.1016/j.jafr.2025.101779

[13] Lau KQ, Sabran MR, Shafie SR. Utilization of vegetable and fruit by-products as functional ingredient and food. *Frontiers in Nutrition*. 2021;**8**:661693. DOI: 10.3389/fnut.2021.661693

[14] Pathania S, Kaur N. Utilization of fruits and vegetable by-products for isolation of dietary fibres and its potential application as functional ingredients. *Bioactive Carbohydrates and Dietary Fibre*. 2022;**27**(100295):100295. DOI: 10.1016/j.bcdf.2021.100295

[15] Trigo JP, Alexandre EMC, Saraiva JA, Pintado ME. High value-added compounds from fruit and vegetable by-products—Characterization, bioactivities, and application in the development of novel food products. *Critical Reviews in Food Science and Nutrition*. 2020;**60**(8):1388-1416. DOI: 10.1080/10408398.2019.1572588

[16] Santos D, Lopes da Silva JA, Pintado M. Fruit and vegetable by-products' flours as ingredients: A review on production process, health benefits and technological functionalities. *Lebensmittel Wissenschaft und Technologie*. 2022;**154**(112707):112707. DOI: 10.1016/j.lwt.2021.112707

[17] Acosta-Estrada BA, Gutiérrez-Uribe JA, Serna-Saldívar SO. Bound phenolics in foods, a review. *Food Chemistry*. 2014;**152**:46-55. DOI: 10.1016/j.foodchem.2013.11.093

[18] Hernández-Fuentes AD, López-Vargas ER, Pinedo-Espinoza JM, Campos-Montiel RG, Valdés-Reyna J,

Juárez-Maldonado A. Postharvest behavior of bioactive compounds in tomato fruits treated with Cu nanoparticles and NaCl stress. *Applied Sciences*. 2017;**7**(10):980. DOI: 10.3390/app7100980

[19] Urquiaga I, D'Acuña S, Pérez D, Dicenta S, Echeverría G, Rigotti A, et al. Wine grape pomace flour improves blood pressure, fasting glucose and protein damage in humans: A randomized controlled trial. *Biological Research*. 2015;**48**(1):49. DOI: 10.1186/s40659-015-0040-9

[20] Suárez B, Álvarez ÁL, García YD, del Barrio G, Lobo AP, Parra F. Phenolic profiles, antioxidant activity and in vitro antiviral properties of apple pomace. *Food Chemistry*. 2010;**120**(1):339-342. DOI: 10.1016/j.foodchem.2009.09.073

[21] Amaya-Cruz DM, Rodríguez-González S, Pérez-Ramírez IF, Loarca-Piña G, Amaya-Llano S, Gallegos-Corona MA, et al. Juice by-products as a source of dietary fibre and antioxidants and their effect on hepatic steatosis. *Journal of Functional Foods*. 2015;**17**:93-102. DOI: 10.1016/j.jff.2015.04.051

[22] Bruna L, Draye M, Lyautey E, Fourreaux C, Grillo G, Cravotto G, et al. Extraction of polyphenols and anthocyanins from apple pomace with natural deep eutectic solvents: Evaluation of their antioxidant and antibacterial activities. *Journal of Food Biochemistry*. 2025;**1**:8483951. DOI: 10.1155/jfbc/8483951

[23] Rakholiya K, Kaneria M, Chanda S. Inhibition of microbial pathogens using fruit and vegetable peel extracts. *International Journal of Food Sciences and Nutrition*. 2014;**65**(6):733-739. DOI: 10.3109/09637486.2014.908167

- [24] Shiban MS, Al-Otaibi MM, Al-zoreky NS. Antioxidant activity of pomegranate (*Punica granatum* L.) fruit peels. Food and Nutrition Sciences. 2012;**03**(07):991-996. DOI: 10.4236/fns.2012.37131
- [25] Feng Y, Lin J, He G, Liang L, Liu Q, Yan J, et al. Compositions and biological activities of pomegranate peel polyphenols extracted by different solvents. Molecules. 2022;**27**(15):4796. DOI: 10.3390/molecules27154796
- [26] de Oliveira FL, Arruda TYP, Morzelle MC, Pereira APA, Casarotti SN. Fruit by-products as potential prebiotics and promising functional ingredients to produce fermented milk. Food Research International. 2022;**161**(111841):111841. DOI: 10.1016/j.foodres.2022.111841
- [27] Saini RK, Ranjit A, Sharma K, Prasad P, Shang X, Gowda KGM, et al. Bioactive compounds of citrus fruits: A review of composition and health benefits of carotenoids, flavonoids, limonoids, and terpenes. Antioxidants (Basel). 2022;**11**(2):239. DOI: 10.3390/antiox11020239
- [28] Fahmi R, Blewett H, Stebbing J-A, Olson N, Ryland D, Aliani M. Acute effects of split pea-enriched white pan bread on postprandial glycemic and satiety responses in healthy volunteers—A randomized crossover trial. Foods (Basel, Switzerland). 2022;**11**(7):1002. DOI: 10.3390/foods11071002
- [29] Issar K, Sharma PC, Gupta A. Utilization of apple pomace in the preparation of fiber-enriched acidophilus yoghurt. Journal of Food Processing and Preservation. 2017;**41**(4):e13098. DOI: 10.1111/jfpp.13098
- [30] Aliakbarian B, Casale M, Paini M, Casazza AA, Lanteri S, Perego P. Production of a novel fermented milk fortified with natural antioxidants and its analysis by NIR spectroscopy. Lebensmittel Wissenschaft und Technologie. 2015;**62**(1):376-383. DOI: 10.1016/j.lwt.2014.07.037. 2
- [31] Chouchouli V, Kalogeropoulos N, Konteles SJ, Karvela E, Makris DP, Karathanos VT. Fortification of yoghurts with grape (*Vitis vinifera*) seed extracts. Lebensmittel Wissenschaft und Technologie. 2013;**53**(2):522-529. DOI: 10.1016/j.lwt.2013.03.008
- [32] Marchiani R, Bertolino M, Belviso S, Giordano M, Ghirardello D, Torri L, et al. Yogurt enrichment with grape pomace: Effect of grape cultivar on physicochemical, microbiological and sensory properties: Grape skin flour and yogurt quality. Journal of Food Quality. 2016;**39**(2):77-89. DOI: 10.1111/jfq.12181
- [33] Lucera A, Costa C, Marinelli V, Saccotelli MA, Del Nobile MA, Conte A. Fruit and vegetable by-products to fortify spreadable cheese. Antioxidants (Basel). 2018;**7**(5):61. DOI: 10.3390/antiox7050061
- [34] Sharan S, Zanghelini G, Zotzel J, Bonerz D, Aschoff J, Saint-Eve A, et al. Fava bean (*Vicia faba* L.) for food applications: From seed to ingredient processing and its effect on functional properties, antinutritional factors, flavor, and color. Comprehensive Reviews in Food Science and Food Safety. 2021;**20**(1):401-428. DOI: 10.1111/1541-4337.12687
- [35] Abid Y, Azabou S, Jridi M, Khemakhem I, Bouaziz M, Attia H. Storage stability of traditional Tunisian butter enriched with antioxidant extract from tomato processing by-products. Food Chemistry. 2017;**233**:476-482. DOI: 10.1016/j.foodchem.2017.04.125

- [36] Çam M, Erdoğan F, Aslan D, Dinç M. Enrichment of functional properties of ice cream with pomegranate by-products: Enrichment of ice cream. *Journal of Food Science*. 2013;**78**:C1543-C1550
- [37] OECD/FAO. Dairy and dairy products. In: OECD-FAO Agricultural Outlook 2023-2032. Paris: OECD Publishing; 2023. DOI: 10.1787/37c7b798-en
- [38] El-Messery TM, Aly E, López-Nicolas R, Sánchez-Moya T, Ros G. Bioaccessibility and antioxidant activity of PCL-microencapsulated olive leaves polyphenols and its application in yogurt. *Journal of Food Science*. 2021;**86**(10):4303-4315. DOI: 10.1111/1750-3841.15893
- [39] Salque M, Bogucki PI, Pyzel J, Sobkowiak-Tabaka I, Grygiel R, Szymt M, et al. Earliest evidence for cheese making in the sixth millennium BC in northern Europe. *Nature*. 2013;**493**(7433):522-525. DOI: 10.1038/nature11698
- [40] Ferreira SM, Santos L. Incorporation of phenolic extracts from different by-products in yoghurts to create fortified and sustainable foods. *Food Bioscience*. 2023;**51**(102293):102293. DOI: 10.1016/j.fbio.2022.102293
- [41] Christaki S, Moschakis T, Kyriakoudi A, Biliaderis CG, Mourtzinis I. Recent advances in plant essential oils and extracts: Delivery systems and potential uses as preservatives and antioxidants in cheese. *Trends in Food Science and Technology*. 2021;**116**:264-278. DOI: 10.1016/j.tifs.2021.07.029
- [42] Gaglio R, Barbaccia P, Barbera M, Restivo I, Attanzio A, Maniaci G, et al. The use of winery by-products to enhance the functional aspects of the fresh Ovine “primosale” cheese. *Food*. 2021;**10**(2):461. DOI: 10.3390/foods10020461
- [43] Lipşa FD, Stoica F, Raţu RN, Veleşcu ID, Cârlescu PM, Motrescu I, et al. Red onion peel powder as a functional ingredient for manufacturing ricotta cheese. *Food*. 2024;**13**(2):182. DOI: 10.3390/foods13020182
- [44] Roila R, Valiani A, Ranucci D, Ortenzi R, Servili M, Veneziani G, et al. Antimicrobial efficacy of a polyphenolic extract from olive oil by-product against “Fior di latte” cheese spoilage bacteria. *International Journal of Food Microbiology*. 2019;**295**:49-53. DOI: 10.1016/j.ijfoodmicro.2019.02.013
- [45] Picciotti U, Massaro A, Galiano A, Garganese F. Cheese fortification: Review and possible improvements. *Food Review International*. 2022;**38**(sup1):474-500. DOI: 10.1080/87559129.2021.1874411
- [46] Boukria O, El Hadrami EM, Sameen A, Sahar A, Khan S, Safarov J, et al. Biochemical, physicochemical and sensory properties of yoghurts made from mixing milks of different mammalian species. *Food*. 2020;**9**(11):1722. DOI: 10.3390/foods9111722
- [47] Hadjimbei E, Botsaris G, Chrysostomou S. Beneficial effects of yoghurts and probiotic fermented milks and their functional food potential. *Food*. 2022;**11**(17):2691. DOI: 10.3390/foods11172691
- [48] Gavril (Raţu) RN, Cârlescu PM, Veleşcu ID, Arsenoaia VN, Stoica F, Stănciuc N, et al. The development of value-added yogurt based on pumpkin peel powder as a bioactive powder. *Journal of Agriculture and Food Research*. 2024;**16**(101098):101098. DOI: 10.1016/j.jafr.2024.101098

- [49] Bertolino M, Belviso S, Dal Bello B, Ghirardello D, Giordano M, Rolle L, et al. Influence of the addition of different hazelnut skins on the physicochemical, antioxidant, polyphenol and sensory properties of yogurt. *Lebensmittel Wissenschaft und Technologie*. 2015;**63**(2):1145-1154. DOI: 10.1016/j.lwt.2015.03.113
- [50] Wang X, Kristo E, LaPointe G. Adding apple pomace as a functional ingredient in stirred-type yogurt and yogurt drinks. *Food Hydrocolloids*. 2020;**100**(105453):105453. DOI: 10.1016/j.foodhyd.2019.105453
- [51] Stoica F, Rațu RN, Motrescu I, Cara IG, Filip M, Țopa D, et al. Application of pomace powder of black carrot as a natural food ingredient in yoghurt. *Foods*. 2024;**13**(7):1130. DOI: 10.3390/foods13071130
- [52] Wu T, Deng C, Luo S, Liu C, Hu X. Effect of rice bran on properties of yogurt: Comparison between addition of bran before fermentation and after fermentation. *Food Hydrocolloids*. 2023;**135**(108122):108122. DOI: 10.1016/j.foodhyd.2022.108122
- [53] Srianta I, Kuswardani I, Ristiarini S, Kusumawati N, Godelive L, Nugerahani I. Utilization of durian seed for *Monascus* fermentation and its application as a functional ingredient in yogurt. *Bioresources and Bioprocessing*. 2022;**9**(1):128. DOI: 10.1186/s40643-022-00619-y
- [54] Martins VFR, Pintado ME, MoraisRMSC, MoraisAMMB. Valorisation of micro/nanoencapsulated bioactive compounds from plant sources for food applications towards sustainability. *Food*. 2022;**12**(1):32. DOI: 10.3390/foods12010032
- [55] Řepka D, Kurillová A, Murtaja Y, Lapčík L. Application of physical-chemical approaches for encapsulation of active substances in pharmaceutical and food industries. *Food*. 2023;**12**(11):2189. DOI: 10.3390/foods12112189
- [56] Rao M, Bast A, de Boer A. Valorized food processing by-products in the EU: Finding the balance between safety, nutrition, and sustainability. *Sustainability*. 2021;**13**(8):4428. DOI: 10.3390/su13084428
- [57] Genovese A, Balivo A, Salvati A, Sacchi R. Functional ice cream: Health benefits and sensory implications. *Food Research International*. 2022;**161**:111858. DOI: 10.1016/j.foodres.2022.111858
- [58] Krystyjan M, Gumul D, Ziobro R, Sikora M. The effect of inulin as a fat replacement on dough and biscuit properties: Dough, biscuits, inulin. *Journal of Food Quality*. 2015;**38**(5):305-315. DOI: 10.1111/jfq.12148
- [59] Mohammed NK, Badrul Khair MF, Ahmad NH, Meor Hussin AS. Ice cream as functional food: A review of health-promoting ingredients in the frozen dairy products. *Journal of Food Process Engineering*. 2022;**45**(12):e14171. DOI: 10.1111/jfpe.14171
- [60] Çam M, Erdoğan F, Aslan D, Dinç M. Enrichment of functional properties of ice cream with pomegranate by-products. *Journal of Food Science*. 2013;**78**(10):C1543-C1550. DOI: 10.1111/1750-3841.12258
- [61] de Moraes Crizel T, de Araujo RR, de Oliveira Rios A, Flôres SH. Orange fiber as a novel fat replacer in lemon ice cream. *Food Science and Technology*. 2014;**34**(2):332-340. DOI: 10.1590/fst.2014.0057
- [62] Trombino S, Cassano R, Procopio D, Di Gioia ML, Barone E. Valorization of

tomato waste as a source of carotenoids. *Molecules*. 2021;**26**(16):5062. DOI: 10.3390/molecules26165062

[63] Kurt A, Atalar I. Effects of quince seed on the rheological, structural and sensory characteristics of ice cream. *Food Hydrocolloids*. 2018;**82**:186-195. DOI: 10.1016/j.foodhyd.2018.04.011

[64] da Silva JM, Klososki SJ, Silva R, Raices RSL, Silva MC, Freitas MQ, et al. Passion fruit-flavored ice cream processed with water-soluble extract of rice by-product: What is the impact of the addition of different prebiotic components? *Lebensmittel Wissenschaft und Technologie*. 2020;**128**(109472):109472. DOI: 10.1016/j.lwt.2020.109472

[65] Yu B, Zeng X, Wang L, Regenstein JM. Preparation of nanofibrillated cellulose from grapefruit peel and its application as fat substitute in ice cream. *Carbohydrate Polymers*. 2021;**254**(117415):117415. DOI: 10.1016/j.carbpol.2020.117415

[66] Hanafi FNA, Kamaruding NA, Shaharuddin S. Influence of coconut residue dietary fiber on physicochemical, probiotic (*Lactobacillus plantarum* ATCC 8014) survivability and sensory attributes of probiotic ice cream. *Lebensmittel Wissenschaft und Technologie*. 2022;**154**(112725):112725. DOI: 10.1016/j.lwt.2021.112725

[67] Abdul, Hakim BN, Xuan NJ, Oslan SNH. A comprehensive review of bioactive compounds from lactic acid bacteria: Potential functions as functional food in dietetics and the food industry. *Food*. 2023;**12**(15):2850. DOI: 10.3390/foods12152850

[68] Lakshmanan AP, Mingione A, Pivari F, Dogliotti E, Brasacchio C, Murugesan S, et al. Modulation of gut

microbiota: The effects of a fruits and vegetables supplement. *Frontiers in Nutrition*. 2022;**9**:930883. DOI: 10.3389/fnut.2022.930883

[69] Kamber U, Harmankaya S. The effect of fruits to the characteristics of fruit yogurt. *Pakistan Journal of Agricultural Sciences*. 2019;**56**(02):495-502. DOI: 10.21162/pakjas/19.5706

[70] Pereira EPR, Ferreira BM, Freire L, Neri-Numa IA, Guimarães JT, Rocha RS, et al. Enhancing the functionality of yogurt: Impact of exotic fruit pulps addition on probiotic viability and metabolites during processing and storage. *Food Research International*. 2024;**196**:115057. DOI: 10.1016/j.foodres.2024.115057

[71] Jaster H, Arend GD, Rezzadori K, Chaves VC, Reginatto FH, Petrus JCC. Enhancement of antioxidant activity and physicochemical properties of yogurt enriched with concentrated strawberry pulp obtained by block freeze concentration. *Food Research International*. 2018;**104**:119-125. DOI: 10.1016/j.foodres.2017.10.006

[72] Sahingil D, Hayaloglu AA. Enrichment of antioxidant activity, phenolic compounds, volatile composition and sensory properties of yogurt with rosehip (*Rosa canina* L.) fortification. *International Journal of Gastronomy and Food Science*. 2022;**28**(100514):100514. DOI: 10.1016/j.ijgfs.2022.100514

[73] Lee J-A, Kim H-Y, Park C-Y, Seo I-D, Lee K-W, Seol K-H. Antioxidant activity and quality characteristics of yogurt added with blueberry powder. *Resources Science Research*. 2020;**2**(2):76-85. DOI: 10.52346/rsr.2020.2.2.76

[74] Kim DH, Yune JH, Han JH, Kim YJ, Han SG. Quality characteristics and

antioxidant activity of yogurt added with corni fructus (*Cornus officinalis*) extracts. Current Topics in Lactic Acid Bacteria and Probiotics. 2021;7(2):45-52. DOI: 10.35732/ctlabp.2021.7.2.45

[75] Varnaitė L, Keršienė M, Šipailienė A, Kazernavičiūtė R, Venskutonis PR, Leskauskaitė D. Fiber-rich cranberry pomace as food ingredient with functional activity for yogurt production. Food. 2022;11(5):758. DOI: 10.3390/foods11050758

[76] Ferenc K, Sokal-Dembowska A, Helma K, Motyka E, Jarmakiewicz-Czaja S, Filip R. Modulation of the gut microbiota by nutrition and its relationship to epigenetics. International Journal of Molecular Sciences. 2024;25(2):1228. DOI: 10.3390/ijms25021228

[77] Victoria Obayomi O, Folakemi Olaniran A, Olugbemiga Owa S. Unveiling the role of functional foods with emphasis on prebiotics and probiotics in human health: A review. Journal of Functional Foods. 2024;119(106337):106337. DOI: 10.1016/j.jff.2024.106337

[78] Lalowski P, Zielińska D. The most promising next-generation probiotic candidates—Impact on human health and potential application in food technology. Fermentation. 2024;10(9):444. DOI: 10.3390/fermentation10090444

[79] Castangia I, Fulgheri F, Leyva-Jimenez FJ, Alañón ME, de la Luz Cádiz-Gurrea M, Marongiu F, et al. From grape by-products to enriched yogurt containing pomace extract loaded in nanotechnological nutriosomes tailored for promoting gastro-intestinal wellness. Antioxidants. 2023;12(6):1285. DOI: 10.3390/antiox12061285

[80] Tuberoso CIG, Serrelli G, Congiu F, Montoro P, Fenu MA. Characterization,

phenolic profile, nitrogen compounds and antioxidant activity of Carignano wines. Journal of Food Composition and Analysis. 2017;58:60-68. DOI: 10.1016/j.jfca.2017.01.017

[81] Almanza-Oliveros A, Bautista-Hernández I, Castro-López C, Aguilar-Zárate P, Meza-Carranco Z, Rojas R, et al. Grape pomace-advances in its bioactivity, health benefits, and food applications. Food. 2024;13(4):580. DOI: 10.3390/foods13040580

[82] Asif M, Javaid T, Razzaq ZU, Khan MKI, Maan AA, Yousaf S, et al. Sustainable utilization of apple pomace and its emerging potential for development of functional foods. Environmental Science and Pollution Research International. 2024;31(12):17932-17950. DOI: 10.1007/s11356-023-28479-9

[83] Sidira M, Galanis A, Ypsilantis P, Karapetsas A, Progaki Z, Simopoulos C, et al. Effect of probiotic-fermented milk administration on gastrointestinal survival of *Lactobacillus casei* ATCC 393 and modulation of intestinal microbial flora. Journal of Molecular Microbiology and Biotechnology. 2010;19(4):224-230. DOI: 10.1159/000321115

[84] Popescu L, Ceşco T, Gurev A, Ghendov-Mosanu A, Sturza R, Tarna R. Impact of apple pomace powder on the bioactivity, and the sensory and textural characteristics of yogurt. Food. 2022;11(22):3565. DOI: 10.3390/foods11223565

[85] Jovanović M, Petrović M, Miočinović J, Zlatanović S, Lalić Petronijević J, Mitić-Ćulafić D, et al. Bioactivity and sensory properties of probiotic yogurt fortified with apple pomace flour. Food. 2020;9(6):763. DOI: 10.3390/foods9060763

- [86] Ahmad I, Khalique A, Shahid MQ, Ahid Rashid A, Faiz F, Ikram MA, et al. Studying the influence of apple peel polyphenol extract fortification on the characteristics of probiotic yoghurt. *Plants*. 2020;**9**(1):77. DOI: 10.3390/plants9010077
- [87] Dimitrellou D, Sakadani E, Kandyli P. Enhancing probiotic viability in yogurt: The role of apple fibers in supporting *Lactocaseibacillus casei* ATCC 393 during storage and gastrointestinal transit. *Food*. 2025;**14**(3):376. DOI: 10.3390/foods14030376
- [88] Gupta MK, Torrico DD, Ong L, Gras SL, Dunshea FR, Cottrell JJ. Plant and dairy-based yogurts: A comparison of consumer sensory acceptability linked to textural analysis. *Food*. 2022;**11**(3):463. DOI: 10.3390/foods11030463
- [89] Janiascki DR, Pimentel TC, Cruz AG, Prudencio SH. Strawberry-flavored yogurts and whey beverages: What is the sensory profile of the ideal product? *Journal of Dairy Science*. 2016;**99**(7):5273-5283. DOI: 10.3168/jds.2015-10097
- [90] Torrico DD, Tam J, Fuentes S, Gonzalez Viejo C, Dunshea FR. D-tagatose as a sucrose substitute and its effect on the physico-chemical properties and acceptability of strawberry-flavored yogurt. *Food*. 2019;**8**(7):256. DOI: 10.3390/foods8070256
- [91] Jeong H-J, Lee Y-K, Ganesan P, Kwak H-S, Chang YH. Physicochemical, microbial, and sensory properties of Queso Blanco cheese supplemented with powdered microcapsules of tomato extracts. *Korean Journal for Food Science of Animal Resources*. 2017;**37**(3):342-350. DOI: 10.5851/kosfa.2017.37.3.342
- [92] Asioli D, Jaeger SR. Online consumer research: More attention needs to be given to data quality. *Current Opinion in Food Science*. 2025;**63**(101307):101307. DOI: 10.1016/j.cofs.2025.101307
- [93] Aertsens J, Verbeke W, Mondelaers K, Van Huylenbroeck G. Personal determinants of organic food consumption: A review. *British Food Journal*. 2009;**111**(10):1140-1167. DOI: 10.1108/00070700910992961
- [94] Petrescu D, Petrescu-Mag R. Organic food perception: Fad, or healthy and environmentally friendly? A case on Romanian consumers. *Sustainability*. 2015;**7**(9):12017-12031. DOI: 10.3390/su70912017
- [95] Chauhan K, Rao A. Clean-label alternatives for food preservation: An emerging trend. *Heliyon*. 2024;**10**(16):e35815. DOI: 10.1016/j.heliyon.2024.e35815
- [96] Mahongnao S, Sharma P, Nanda S. Conversion of waste materials into different by-products of economic value. In: *Waste Management and Resource Recycling in the Developing World*. Amsterdam, Netherlands: Elsevier; 2023. pp. 665-699
- [97] Campos DA, Gómez-García R, Vilas-Boas AA, Madureira AR, Pintado MM. Management of fruit industrial by-products—A case study on circular economy approach. *Molecules*. 2020;**25**(2):320. DOI: 10.3390/molecules25020320
- [98] You S, Sonne C, Park Y-K, Kumar S, Lin K-YA, Ok YS, et al. Food loss and waste: A carbon footprint too big to be ignored. *Sustainable Environment*. 2022;**8**(1):2115685. DOI: 10.1080/27658511.2022.2115685
- [99] Minervini F, Comitini F, De Boni A, Fiorino GM, Rodrigues F, Tlais AZA, et al. Sustainable and health-protecting

food ingredients from bioprocessed food by-products and wastes. *Sustainability*. 2022;**14**(22):15283. DOI: 10.3390/su142215283

[100] Roy P, Mohanty AK, Dick P, Misra M. A review on the challenges and choices for food waste valorization: Environmental and economic impacts. *ACS Environmental Au*. 2023;**3**(2):58-75. DOI: 10.1021/acsenvironau.2c00050

[101] Cristóbal J, Caldeira C, Corrado S, Sala S. Techno-economic and profitability analysis of food waste biorefineries at European level. *Bioresource Technology*. 2018;**259**:244-252. DOI: 10.1016/j.biortech.2018.03.016

[102] Caldeira C, Vlysidis A, Fiore G, De Laurentiis V, Vignali G, Sala S. Sustainability of food waste biorefinery: A review on valorisation pathways, techno-economic constraints, and environmental assessment. *Bioresource Technology*. 2020;**312**(123575):123575. DOI: 10.1016/j.biortech.2020.123575

[103] Aşkın UR. Sustainable green technology for adaptation of circular economy to valorize Agri-food waste: Celery root peel as a case study. *Management of Environmental Quality*. 2022;**34**(4):1018-1034. DOI: 10.1108/meq-03-2022-0087

[104] Dilucia F, Lacivita V, Conte A, Del Nobile MA. Sustainable use of fruit and vegetable by-products to enhance food packaging performance. *Food*. 2020;**9**(7):857. DOI: 10.3390/foods9070857

[105] Hassoun A, Garcia-Garcia G, Trollman H, Jagtap S, Parra-López C, Cropotova J, et al. Birth of dairy 4.0: Opportunities and challenges in adoption of fourth industrial revolution technologies in the production of milk

and its derivatives. *Current Research in Food Science*. 2023;**7**(100535):100535. DOI: 10.1016/j.crfs.2023.100535

[106] Tarchi I, Boudalia S, Ozogul F, Câmara JS, Bhat ZF, Hassoun A, et al. Valorization of agri-food waste and by-products in cheese and other dairy foods: An updated review. *Food Bioscience*. 2024;**58**(103751):103751. DOI: 10.1016/j.fbio.2024.103751

[107] Food and Agriculture Organization of the United Nations. *The State of Food and Agriculture 2019 (Arabic Edition): Moving Forward on Food Loss and Waste Reduction*. Rome, Italy: Food & Agriculture Organization of the United Nations (FAO); 2020

[108] Föste M, Verheyen C, Jekle M, Becker T. Fibres of milling and fruit processing by-products in gluten-free bread making: A review of hydration properties, dough formation and quality-improving strategies. *Food Chemistry*. 2020;**306**(125451):125451. DOI: 10.1016/j.foodchem.2019.125451

[109] Salas-Millán JÁ, Aguayo E. Fermentation for revalorisation of fruit and vegetable by-products: A sustainable approach towards minimising food loss and waste. *Food*. 2024;**13**(22):3680. DOI: 10.3390/foods13223680

[110] Socas-Rodríguez B, Álvarez-Rivera G, Valdés A, Ibáñez E, Cifuentes A. Food by-products and food wastes: Are they safe enough for their valorization? *Trends in Food Science and Technology*. 2021;**114**:133-147. DOI: 10.1016/j.tifs.2021.05.002

[111] Union E. Directive 2002/32/EC of the European Parliament and of the council of 7 may 2002 on undesirable substances in animal feed (consolidated version 2019). *Official Journal of the European Communities*.

- 2002;**L140**:10-22. Available from: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02002L0032-20191220> [Accessed: 10 April 2025]
- [112] Karus A, Karus V. Food research opportunities and challenges: methods in food safety and functional food development: a review. In: Research for Rural Development 2018. Vol. 1. Jelgava, Latvia: Latvia University of Life Sciences and Technologies; 2018. pp. 211-214. DOI: 10.22616/rrd.24.2018.033
- [113] Taverne-Veldhuizen W, Hoogenboom R, Dam GT, Herbes R, Luning P. Understanding possible causes of exceeding dioxin levels in palm oil by-products: An explorative study. *Food Control*. 2020;**108**(106777):106777. DOI: 10.1016/j.foodcont.2019.106777
- [114] Ballesteros-VivasD, Álvarez-RiveraG, Morantes SJ, Sánchez-Camargo ADP, Ibáñez E, Parada-Alfonso F, et al. An integrated approach for the valorization of mango seed kernel: Efficient extraction solvent selection, phytochemical profiling and antiproliferative activity assessment. *Food Research International*. 2019;**126**(108616):108616. DOI: 10.1016/j.foodres.2019.108616
- [115] Xin J, Wang X, Li N, Liu L, Lian Y, Wang M, et al. Recent applications of covalent organic frameworks and their multifunctional composites for food contaminant analysis. *Food Chemistry*. 2020;**330**(127255):127255. DOI: 10.1016/j.foodchem.2020.127255
- [116] Intrasoook J, Tsusaka TW, Anal AK. Trends and current food safety regulations and policies for functional foods and beverages containing botanicals. *Journal of Food and Drug Analysis*. 2024;**32**(2):112-139. DOI: 10.38212/2224-6614.3499
- [117] Caldeira C, De Laurentiis V, Corrado S, van Holsteijn F, Sala S. Quantification of food waste per product group along the food supply chain in the European Union: A mass flow analysis. *Resources, Conservation and Recycling*. 2019;**149**:479-488. DOI: 10.1016/j.resconrec.2019.06.011
- [118] Wang SS, Canida TA, Ihrle JD, Chirtel SJ. Sample size determination for food sampling. *Journal of Food Protection*. 2023;**86**(9):100134. DOI: 10.1016/j.jfp.2023.100134
- [119] Pearson AJ, Mukherjee K, Fattori V, Lipp M. Opportunities and challenges for global food safety in advancing circular policies and practices in agrifood systems. *npj Science of Food*. 2024;**8**(1):60. DOI: 10.1038/s41538-024-00286-7

Post-Harvest Valorization Technologies for Natural Substitutes for Fruit Sugar

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Abstract

Fruit sugars, mainly fructose, glucose, and sucrose, are key carbohydrates found in various fruits. These sugars are essential for energy production, but their excessive consumption can contribute to health problems such as obesity and diabetes. Recent valorization technologies focus on the efficient extraction and conversion of fruit sugars into valuable products. These technologies aim to exploit the potential of fruit sugars for biofuels, bioplastics, food additives, and pharmaceuticals. Techniques such as enzymatic hydrolysis, fermentation, and chemical conversion are increasingly being used to improve sugar recovery and maximize their applications. One promising area is the development of bio-based chemicals from fruit sugars, which are more sustainable than petroleum-derived alternatives. Advances in microbial fermentation and metabolic engineering have also enabled the production of high-value compounds such as organic acids and amino acids from fruit sugars. In addition, some fruits with high sugar contents can be processed to obtain powders as a natural sugar substitute rich in aromas and other nutrients which can also be used for the purposes of enrichment or flavoring of food products such as pastry products. As the demand for sustainable solutions increases, these valorization technologies offer innovative avenues to utilize fruit sugars in various industries.

Keywords: sugar, fruit, application, technologies, health benefits

1. Introduction

The need for healthier food options is rising as lifestyle diseases like diabetes, obesity, and metabolic disorders become more common. Since refined sugar consumption in excess is associated with various health problems, food manufacturers and consumers are looking for natural sugar substitutes that offer sweetness along with extra nutritional value. Fruits such as date (*Phoenix dactylifera*), grape (*Vitis vinifera*), and apricot (*Prunus armeniaca*) contain natural sugars, including glucose, fructose, and sucrose, making them viable alternatives to conventional sweeteners [1–4]. These fruits also have a lot of dietary fiber, flavonoids, carotenoids, and polyphenols, which are bioactive substances that add to their health-promoting qualities [5].

The valorization of fruit-derived sugars involves multiple post-harvest processes, including extraction, concentration, purification, and stabilization, to ensure

efficient utilization while preserving nutritional and sensory attributes. The optimization of sugar yield, preservation of the integrity of bioactive compounds, and extension of shelf life all depend on the choice of suitable post-harvest technologies.

Fruit syrups have long been produced using conventional processing techniques like thermal extraction and evaporation, but more recently, environmentally friendly and sustainable technologies have made significant strides in extraction efficiency and product quality. Examples of these technologies include membrane filtration, ultrasonic-assisted extraction, and nanoencapsulation [6].

Fruit-derived sugars are becoming more and more popular in functional food applications because of their low glycemic response and other health advantages, in addition to their use as sweeteners [7]. The development of fruit-based sweeteners aligns with consumer preferences for clean-label products that are free from artificial additives. Furthermore, using fruit by-products—like peels and seeds—for other purposes or the extraction of bioactive compounds supports waste reduction and sustainable agriculture [8].

This chapter examines the most recent developments in post-harvest technologies for the extraction and processing of sugars derived from fruit, as well as their uses in the food industry and their contribution to sustainable and health-conscious eating habits. It offers a thorough examination of pre-treatment methods, extraction techniques, concentration and purification strategies, and encapsulation technologies that improve the functionality and market potential of fruit-based sweeteners.

Furthermore, the economic and environmental consequences of fruit sugar production are discussed, emphasizing the advantages of incorporating valorization processes into the larger food supply chain. Fruit-derived sugars can be a viable alternative to refined sugar by utilizing innovative processing techniques, promoting healthier consumption patterns while ensuring food production system sustainability.

2. Post-harvest processing techniques for sugar extraction

Post-harvest processing plays a crucial role in optimizing sugar yield, maintaining nutritional quality, and improving the functionality of fruit-derived sweeteners. In order to guarantee high-quality sugar recovery while maintaining bioactive components, these procedures include pre-treatment, extraction, and separation approaches.

2.1 Pre-treatment methods

Pre-treatment is an essential step in sugar extraction, as it prepares raw fruit materials for efficient processing while minimizing losses [9]. Typical pre-treatment methods include:

- **Washing and sorting:** Fruits are thoroughly washed to remove dirt, pesticides, and microbial contaminants. The sorting process removes damaged or unripe fruit that can affect the quality of the final product.
- **Peeling and pitting:** Depending on the type of fruit, mechanical or enzymatic methods are used to remove the peels and seeds. This step improves the sugar extraction process by isolating the pulp that contains the highest concentration of sugar.

- **Enzyme treatment:** The use of enzymes such as pectinase, cellulase, and hemicellulase helps break down the plant cell walls, thereby releasing intracellular sugars and improving juice production. Enzymatic hydrolysis also reduces viscosity, thus improving subsequent extraction steps.
- **Bleaching:** A mild heat treatment that inactivates the enzymes responsible for oxidation and degradation. This process is particularly useful for preserving the color and flavor of extracted fruit juices.
- **Grinding and homogenization:** Fruits are mechanically ground into a fine pulp to increase surface area for more efficient sugar extraction. Homogenization ensures a uniform mixture for optimized processing.

2.2 Extraction techniques

Extraction methods play a crucial role in isolating sugars from fruit matrices while preserving their nutritional and sensory properties. Several techniques are used, including both traditional and cutting-edge technologies [10]:

- **Thermal extraction:** Traditional heat-based methods involve boiling or heating the fruit pulp in water to release the sugars.
- **Ultrasound-assisted extraction:** High-frequency sound waves generate cavitation bubbles that disrupt cellular structures, enhancing sugar release while preserving bioactive compounds.
- **Microwave-assisted extraction:** This technique uses microwave energy to rapidly heat the fruit, improving mass transfer and reducing extraction time. Microwave-assisted extraction is particularly effective at preserving heat-sensitive bioactive compounds.
- **Supercritical fluid extraction:** Supercritical carbon dioxide is used as a solvent to extract sugars and other valuable components under controlled pressure and temperature.
- **Pressure and diffusion extraction:** Mechanical pressure techniques, such as hydraulic press or screw press, are commonly used to extract date syrup and pomegranate juice.
- **Membrane-assisted extraction:** Involves ultrafiltration or reverse osmosis to selectively extract sugars from fruit juices while removing unwanted compounds, thereby improving purity and concentration.

2.3 Optimization strategies for sugar extraction

To improve extraction efficiency and optimize sugar recovery, various parameters need to be carefully controlled [11], including:

- **pH control:** Maintaining the optimal pH level during extraction prevents sugar degradation and maintains enzyme activity.

- Temperature control: Using moderate temperatures avoids thermal degradation while ensuring maximum sugar dissolution.
- Selection of solvents: Water is the most commonly used solvent, but ethanol-water mixtures are sometimes used to improve sugar selectivity and retain bioactive compounds.
- Extraction times: Long extraction times can lead to degradation of sensitive compounds, so optimizing the duration is essential to achieve high yields.

3. Concentration and purification technologies

Various thermal and non-thermal technologies for sugar concentration and purification have been developed and studied [12–14].

3.1 Evaporation and vacuum concentration

- Rotary evaporation: Uses controlled heating under vacuum to remove excess water, preserving flavor, aroma, and nutritional quality.
- Vacuum-assisted drying: A low-temperature drying method that prevents caramelization and degradation of heat-sensitive bioactive compounds.
- Freeze concentration: Involves freezing the sugar solution and separating the ice crystals, ensuring minimal loss of nutrients and flavor compounds.
- Multi-effect evaporation (MEE): A highly efficient process that uses multiple evaporation chambers to concentrate sugars while minimizing energy consumption.

3.2 Membrane technologies

- Ultrafiltration (UF) and reverse osmosis (RO): Allows for selective separation of sugars from undesirable compounds, improving clarity and purity.
- Nanofiltration (NF): Facilitates molecular fractionation to obtain specific sugar profiles, commonly used in the production of date and pomegranate syrups.
- Electrolysis: Uses voltage to separate the ionic components of sugar solutions, improving purity and reducing unwanted mineral content.
- Forward osmosis (FO): Uses a semi-permeable membrane to efficiently extract water, reducing energy consumption in sugar concentration.

3.3 Chromatographic purification

- Ion exchange chromatography: Removes metals, organic acids, and other impurities, improving the purity of the sugar.

- Size exclusion chromatography: Separates sugar molecules based on molecular weight, commonly used in the purification of high fructose fruit syrups.
- Adsorption chromatography: Selective resins are used to remove unwanted colors and bitter compounds, ensuring a cleaner final product.

By implementing these advanced concentration and purification techniques, fruit-derived sugars can be efficiently processed and converted into high-quality sweeteners suitable for food and beverage applications while retaining their health-promoting properties.

4. Drying and encapsulation technologies

Drying and packaging techniques play a major role in enhancing the value of natural sugars from fruits by improving their storage stability and ease of handling. They allow for dry and protected forms, making them easier to incorporate into various food and nutritional products. Various sugar drying and encapsulation technologies have been developed and studied [15–18].

4.1 Spray drying (atomization drying)

Spray drying is a commonly used process for converting fruit syrup into powder. It involves atomizing the liquid in a drying chamber where a stream of hot air rapidly evaporates the water, leaving behind solid, powdery particles.

Advantages:

- Fast and economical process.
- Preserves and improves the sweetness of a product with low water content.
- Easy to integrate into food formulations and instant fish.

Encapsulation support:

- Maltodextrin: improves the solubility and reduces the hygroscopicity of fine sugar.
- Gum arabic: protects biologically active compounds and improves oxidative stability.

4.2 Freeze drying (Lyophilization)

Freeze drying is a cold drying process that preserves heat-sensitive components by removing water through vacuum sublimation. This technique is particularly suitable for high-value-added natural sweeteners, such as pomegranate sugar extracts.

Advantages:

- Optimal preservation of the integrity of sugars and biologically active compounds (polyphenols and vitamins).

- Better solubility and rehydration capacity.
- Improved sensory and taste quality compared to other drying methods.

4.3 Encapsulation technologies

The encapsulation process of sugars aims to improve their stability, controlled release, and bioaccessibility in food and nutraceutical formulations.

Microencapsulation:

- Protects sugars from moisture and oxidation.
- Prolongs the shelf life of sweet powders.
- Facilitates integration into food products sensitive to texture and taste variations.

Nanoencapsulation:

- Improves the bioavailability of sugars in therapeutic food applications.
- Allows controlled release, which is beneficial for extended-release products.
- Improves integration into complex food matrices, such as functional beverages.

5. Applications in food and beverage industry

The integration of natural fruit sugars into the food industry provides healthier alternatives to synthetic sweeteners and refined sugar. Various applications of sugars in food and the food industry have been developed and studied [7, 8, 19, 20].

5.1 Functional sweeteners for healthier alternatives

Fruit-derived sugars have nutritional and sensory benefits that suit many applications:

- Apricot-derived sugars: Used in baby foods and confectionery, providing natural sweetness with a moderate glycemic load.
- Date syrup: Used as a natural sweetener in bakery and dairy products, providing a caramel flavor and interesting functional properties (natural humectant).
- Grape sugar extracts: Incorporated into functional beverages and food preparations for their antioxidant properties and balanced sweetening power.

5.2 Enhancing texture and stability in processed foods

Fruit-derived sugars contribute to texture, moisture retention, and shelf life:

- Apple-derived pectin and sugars: Improve gelling and thickening in jams, sauces, and fruit-based spreads while providing a natural source of sweetness.

- **Mango syrup:** Acts as a natural stabilizer in frozen desserts and smoothies, preventing ice crystallization and maintaining smooth texture.
- **Fig-based sugars:** Used in snack bars and energy gels to enhance chewiness and moisture retention without artificial additives.

5.3 Sugar alternatives in fermentation

Fruit sugars are ideal substrates for fermentation processes. Fruit-derived sugars are used in the manufacture of bioactive vinegar and polyphenol-rich kombucha, enhancing natural fermentation while increasing health benefits.

6. Sustainability and economic considerations

The spread of natural sweeteners also depends on aspects of sustainability and economic feasibility, which help reduce food waste and meet the growing demand from consumers for healthier and more environmentally friendly products [21, 22].

6.1 Waste valorization

By-products from fruit processing are a valuable source of bioactive compounds and sustainable applications:

- **Valuing of peels and seeds:** These residues are rich in fiber, polyphenols, and antioxidants, which can be used in functional foods, cosmetics, or as texture agents in food formulations [23].
- **Bioconversion of waste:** Fruit waste can be fermented to produce bioethanol or organic acids (e.g. lactic acid and citric acid), thus reducing the carbon footprint and generating secondary revenues.

6.2 Emerging trends

The natural sweeteners market is witnessing growth driven by several key trends:

- **Increasing preference for natural and clean sweeteners:** Consumers are looking for alternatives that are perceived as healthier and less processed than refined white sugar or artificial sweeteners.
- **Regulatory developments:** Several legislations support the incorporation of fructose into food formulations, thus encouraging its adoption by the food industry.

6.3 Benefits to the economy and the food chain

There are considerable financial advantages to the production and use of fruit-derived sugars at several stages in the food supply chain. Fruit growers benefit from extra revenue streams created by the market demand for natural sweeteners, which allows them to use excess or imperfectly shaped fruits that would otherwise go to

waste. Using fruit-based sweeteners can help food processors and manufacturers stand out in a crowded market by appealing to premium consumers who value sustainability and health.

Small and medium-sized businesses (SMEs) in developing nations also profit from the expanding fruit sugar market. These companies can improve regional economic stability and generate jobs locally by investing in natural sweetener processing facilities. In general, decreasing the dependence on artificial sweeteners and refined sugar contributes to a more robust food chain through the diversification of sweetener sources, reduction of supply chain risks, and encouragement of fair trade applications.

7. Conclusion and future perspectives

The extraction of natural post-harvest sugars from apricots, dates, and pomegranates represents a sustainable and health-promoting alternative to refined sugar. Thanks to technological advances in extraction, concentration, drying, and packaging, these natural sweeteners gain quality, stability, and commercial appeal.

Future research should focus on several areas for improvement:

- Improving processing methods to maximize profitability and minimize environmental impact.
- Improving sensory attributes to obtain sweeteners with a taste closer to conventional sugar.
- Expanding functional applications, especially in the sectors of clinical nutrition, fermented beverages, and high-value-added products.

By combining technological innovation with sustainable approaches, natural sugars from fruits can play a key role in the transition to healthier and more environmentally friendly diets.

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References

- [1] Ayour J, Benichou M, Alahyane A, Harrak H. Relationships between biochemical criteria, volatile compounds, and sensory profiles of ten apricot clones at commercial and consumption ripening stages. *Journal of Food Quality*. 2020;**2020**:8873835. DOI: 10.1155/2020/8873835
- [2] Ayour J, Alahyane A, Harrak H, Neffa M, Taourirte M, Benichou M. Assessment of nutritional, technological, and commercial apricot quality criteria of the Moroccan cultivar “Maoui” compared to introduced Spanish cultivars “Canino” and “Delpatriarca” towards suitable valorization. *Journal of Food Quality*. 2021;**2021**:6679128. DOI: 10.1155/2021/6679128
- [3] Cornehl L, Krause J, Zheng X, Gauweiler P, Schwander F, Töpfer R, et al. Determination of sugars and acids in grape must using miniaturized near-infrared spectroscopy. *Sensors*. 2023;**23**(11):5287. DOI: 10.3390/s23115287
- [4] Harrak H. Revue des principaux acquis de la recherche dans l'amélioration et le développement de la valorisation post-récolte des dattes marocaines. *African and Mediterranean Agricultural Journal-Al Awamia*. 2022;**134**:1-29
- [5] Stanhope KL. Sugar consumption, metabolic disease and obesity: The state of the controversy. *Critical Reviews in Clinical Laboratory Sciences*. 2016;**53**(1):52-67. DOI: 10.3109/10408363.2015.1084990. Epub 2015 Sep 17
- [6] Julai K, Sridonpai P, Ngampeerapong C, Tongdonpo K, Suttisansanee U, Kriengsinys W, et al. Effects of extraction and evaporation methods on physico-chemical, functional, and nutritional properties of syrups from Barhi dates (*Phoenix dactylifera* L.). *Food*. 2023;**12**(6):1268. DOI: 10.3390/foods12061268
- [7] Kumar CS, Ali A, Manickavasagan A. Health benefits of substituting added sugars with fruits in developing value-added food products: A review. *International Journal of Nutrition, Pharmacology, Neurological Diseases*. 2020;**10**(3):75-90. DOI: 10.4103/ijnpnd.ijnpnd_34_20
- [8] Sayas-Barberá E, Paredes C, Salgado-Ramos M, Pallarés N, Ferrer E, Navarro-Rodríguez de Vera C, et al. Approaches to enhance sugar content in foods: Is the date palm fruit a natural alternative to sweeteners? *Food*. 2023;**13**(1):129. DOI: 10.3390/foods13010129
- [9] Wani AK, Rahayu F, Fauziah L, Suhara C. Advances in safe processing of sugarcane and bagasse for the generation of biofuels and bioactive compounds, 100549. *Journal of Agriculture and Food Research*. 2023;**12**:100549. DOI: 10.1016/j.jafr.2023.100549. ISSN 2666-1543
- [10] Mohanta B, Sen DJ, Mahanti B, Nayak AK. Recent advances in the extraction, purification, and antioxidant activities of fruit polysaccharides: A review. *Food Hydrocolloids for Health*. 2023;**4**:100163. DOI: 10.1016/j.fhfh.2023.100163. ISSN 2667-0259
- [11] Sayah I, Njehi M, Cicero N, Nava V, M'hadheb MB, Majdoub H, et al. Optimization of sugar extraction process from date waste using full factorial design toward its use for new biotechnological applications. *Biotech*. 2024;**13**(4):39. DOI: 10.3390/biotech13040039

- [12] Babu AS, Adeyeye SAO. Chapter seven - extraction of sugar from sugar beets and cane sugar. In: Jafari SM, Akhavan-Mahdavi S, editors. *Unit Operation and Processing Equipment in the Food Industry, Extraction Processes in the Food Industry*. Cambridge, United Kingdom: Woodhead Publishing; 2024. pp. 177-196. DOI: 10.1016/B978-0-12-819516-1.00007-7. ISBN 9780128195161
- [13] Mouadili H et al. New grafted polymer membrane for extraction, separation and recovery processes of sucrose, glucose and fructose from the sugar industry discharges. *Separation and Purification Technology*. 2018;**200**:230-241
- [14] Oriez V, Pham NT-T, Peydecastaing J, Behra P, Pontalier P-Y. Membrane filtration applied to the purification of sugarcane bagasse mild alkaline extracts. *Clean Technologies*. 2023;**5**(2):518-530. DOI: 10.3390/cleantechnol5020027
- [15] Du L, Huang X, Li Z, Qin Z, Zhang N, Zhai X, et al. Application of smart packaging in fruit and vegetable preservation: A review. *Food*. 2025;**14**(3):447. DOI: 10.3390/foods14030447
- [16] Dhayalan RD, Shankar VS. Comparative analysis on the sugar content of vacuum packed fig fruit (*Ficus Carica*) stored under different packaging materials with varying moisture content. In: *AIP Conference Proceedings*. Vol. 3193. No. 1. Melville, New York, USA: AIP Publishing; 2024
- [17] Radojčin M, Pavkov I, Bursać Kovačević D, Putnik P, Wiktor A, Stamenković Z, et al. Effect of selected drying methods and emerging drying intensification technologies on the quality of dried fruit: A review. *PRO*. 2021a;**9**(1):132. DOI: 10.3390/pr9010132
- [18] Radojčin M, Pavkov I, Bursać Kovačević D, Putnik P, Wiktor A, Stamenković Z, et al. Effect of selected drying methods and emerging drying intensification technologies on the quality of dried fruit: A review. *PRO*. 2021b;**9**(1):132. DOI: 10.3390/pr9010132
- [19] Ashurst PR. *Chemistry and Technology of Soft Drinks and Fruit Juices*. ISO: John Wiley & Sons; 2016. p. 690
- [20] Valliath AS, Johar V, Mondal R, Tejaswi S, Das P, Saha I. Application of natural preservatives and sweeteners in fruit products to reduce health risks-a review. *Environment Conservation Journal*. 2023;**24**(4):344-354
- [21] Li J, Li H, Liu H, Luo Y. Recent advances in the biosynthesis of natural sugar substitutes in yeast. *Journal of Fungi*. 2023;**9**(9):907. DOI: 10.3390/jof9090907
- [22] Saraiva A, Carrascosa C, Raheem D, Ramos F, Raposo A. Natural sweeteners: The relevance of food naturalness for consumers, food security aspects, sustainability and health impacts. *International Journal of Environmental Research and Public Health*. 2020;**17**(17):6285. DOI: 10.3390/ijerph17176285
- [23] Scordino M et al. Highly purified sugar concentrate from a residue of citrus pigments recovery process. *LWT-Food Science and Technology*. 2007;**40**(4):713-721

A Review on Sustainable Sources of Edible Biocoating Solutions for Extended Postharvest Shelf Life and Quality of Fruits and Vegetables

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Abstract

Edible biocoatings have been proposed as sustainable solutions to extend the postharvest shelf life of fresh fruits and vegetables, by minimising decay and senescence. They also help to suppress the emergence of postharvest diseases. One major advantage of using edible films and coatings is that several bioactives can be adsorbed into the polymer matrix and consumed with the food, thus possibly enhancing the safety, nutritional and sensory attributes of the food. This review looks into the existing and potential sources of edible biocoating agents. It is intended for researchers, industry professionals and policymakers who are interested in sustainable preservation alternatives and their implications for food security and environmental sustainability. By the end of this review, the audience will gain a thorough understanding of the existing and potential sources of biocoating agents and their prospects in the food preservation industry.

Keywords: biocoating, edible coating, shelf life, packaging, biodegradable, circular bioeconomy

1. Introduction

Fruits and vegetables are very perishable with a very limited shelf life. This has resulted in significant postharvest losses (PHL) along their value chain, with approximately 14% of the food produced globally being lost during postharvest stages before reaching retail stage [1]. Food losses in Sub-Saharan Africa occur across a wide spectrum, including up to 50% of fruits and vegetables [1]. Several studies have been conducted to investigate possible interventions to mitigate postharvest losses (PHL) [2–6]; however, there is still a huge gap, as most of the proposed interventions usually require high

investment and are not always cost-effective in developing countries [6, 7]. This has called for more research into better cost-effective interventions to reduce PHL.

Edible coatings have been proposed as one of the possible cost-effective and environmentally friendly ways of reducing the decay of fruits and vegetables. This is mainly because of their biodegradability properties, which ensure that they do not place a strain on the environment. Edible coatings/films on the other hand, in addition to prolonging the shelf life of fruits and vegetables, help to improve the appearance of horticultural commodities by improving the shine appearance, masking scars and blemishes, suppressing decay and physiological disorder developments [8]. Moreover, the modern-day consumer has become more health-conscious and tends to prefer safer, natural and stable food products over their synthetic alternatives [9]. The rise in biodegradable films and coatings turns into a vital segment in the packaging sector. This has changed the consumer preferences over the years and has seen consumers preferring natural and biodegradable coating as a better alternative solution to synthetic forms such as plastic packaging. In this book chapter, we review various sustainable sources of edible biocoating agents and their applications as edible coating of fruits and vegetables. Various sources of edible coating have been used as ingredients. The role of an ingredient in the coating's functionality is influenced by the ingredient's concentration and stability [10]. It is also influenced by how it disperses within the coat and also how it interacts with the matrix of the polymer [10].

The term “*edible coating*” may have different definitions depending on context and geographic location, hence there may not be one specific definition. Some authors refer to edible coatings as coatings that are legal and safe to use on food products, while other authors define edible coatings as those that are acceptable to consumers [11]. Edible coatings are a thin coating applied on the surface of fruits and vegetables, to create a physical and chemical barrier between the fruit or vegetable surface and its outer environment [12]. They are made from either natural or synthetic compounds. The technical definition of edible coating though is that these are coatings that have a coat thickness below 0.025 mm [9]. All “coatings” with a thickness above 0.050 mm technically become named as films or sheets [9]. Edible coatings are novel packaging techniques that have the potential to extend the shelf life of fruits and vegetables. They help restrict the microbial growth, help retain some volatile compounds and also help to keep the fruits fresh. One major advantage of using edible films and coatings is that the coating enables the incorporation into the coating polymer matrix of more than one ingredient, which helps to give the fruit or vegetable some superior nutritional and sensory attributes [13]. Some of these ingredients include bioactive compounds, which have additional health benefits. Edible biocoating agents have the potential to significantly contribute towards the Circular Bioeconomy, as their usage may help reduce the use of non-biodegradable plastic packaging [10]. Nevertheless, the development of novel edible coatings with better functionality and performance for fruits and vegetables is still one of the prime challenges of the postharvest industry [14].

2. Mechanism of edible biocoating agents

Edible biocoating agents have a history dating back to the twelfth century in China, where they were used on citrus fruits [11]. The natural waxy cuticle barrier on the surface of fruits often gets washed off during fruit processing, leading to excessive transpiration and thus water loss [11]. Edible coatings have been developed with the idea of forming a barrier to control water loss and thus extend the shelf life of

minimally processed fruits and vegetables. The major functionalities of edible films and coatings include [15]:

- Physical protection from handling, mechanical damages and ultraviolet (UV) radiation
- Barrier properties:
 - Moisture barrier
 - Gas exchange regulation
 - Volatile organic compounds (VOC) barrier
- Bioactivity: antioxidant, antimicrobial and antifungal properties
 - Biodegradability
 - Structural integrity
 - Maintenance of food quality: minimal influence on texture, flavour or colour
- Aesthetics and sensory properties (**Figure 1**)

2.1 Physical protection from handling, mechanical damages and UV radiation

Edible coatings typically consist of thin layers (less than 0.025 mm) [9] of biopolymer edible materials capable of forming a continuous film on the food/fruit

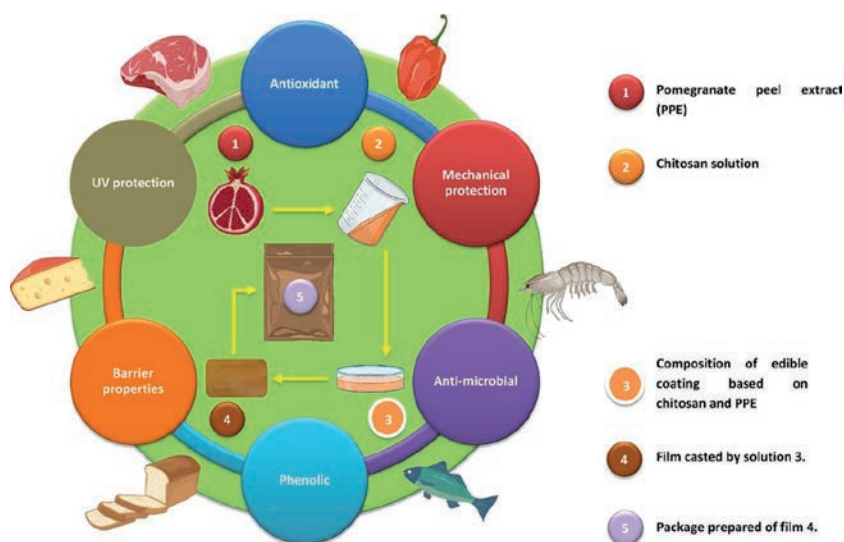


Figure 1.
 Mechanisms of edible coating agents [16].

surface. The thin layer of biopolymer material is capable of providing an additional layer of protection to the natural waxy cuticle on the fruit surface. The edible coating layer offers physical protection to the fruit by preventing or reducing bruising, tear, shear, pressure and impact. From mechanical tests to study the resistance of packaging material against tearing, the maximum forces sustainable by natural hydrated fruit cuticles across all species averaged 0.82 N (range 0.15–1.63 N), while the maximum stresses averaged 13.2 MPa (range 2.0–29.0 MPa) [17]. Adding an additional layer of edible coating increases the maximum resistance to stresses and tear [18]. Packaging material is often tested for elasticity modulus (EM), elongation at break (E) and tensile strength (TS) [19], according to the ASTM D 882-18 standard [18]. Packaging material should have an increased ductility (increased elongation at break and decreased Young's modulus), which is essential for a food packaging material [18]. Impregnation of the cuticle and fruit surface with edible coating such as waxes increases the stiffness and strength of the layer but decreases extensibility, while impregnating the fruit surface with polysaccharides enhances the elasticity of the cutin matrix [17]. In addition, edible coating fills up the minute cracks on the pericarp of fruit, which results in closing of stomata and lenticels leading to delay in development of physiological disorders such as reduction in weight [20].

Edible coatings provide mechanical barrier, physical and biological properties for food products, and also protect against ultraviolet rays (280–315 nm) [21]. Edible coating often provides barriers to both UV and visible light [22]. Composite edible coatings are formulated from various ingredients. Some of these ingredients may offer significant UV protection by absorbing the harmful UV rays. Curcumin, for example, is a naturally occurring colourant and hydrophobic polyphenol compound extracted from turmeric roots, which has UV absorption properties in addition to its other benefits [22].

2.2 Barrier properties

Edible coating or films create a semi-permeable barrier around the surface of the fruit. This creates a modified atmosphere (MA) restricting the transfer of oxygen (O₂) and carbon dioxide (CO₂) and also becoming a barrier for the transfer of aromatic compounds [23]. By reducing gaseous exchange, edible coating retards respiration rate, thereby minimising senescence and weight loss. Depending on the formulations of the coatings, the effect on the barrier environment can act as either controlled atmosphere chambers or modified atmosphere packaging [11]. However, if oxygen levels fall too low, this may activate the anaerobic pathway, which produces ethanol, leading to off-flavours. Edible coating also acts as a moisture barrier preventing excessive loss of moisture through transpiration, which leads to dehydration, desiccation and weight loss of fruits. The coating barrier also locks in volatile aromatic compounds, which may be responsible for aroma and sensory properties.

2.3 Bioactivity

Bioactive compounds are compounds that are found in small quantities in foods [24] that provide health benefits and additional nutritional components [25]. Examples of bioactive compounds include proteins, antioxidants, polyphenols, vitamins, minerals, polysaccharides and lipids [26, 27]. Bioactive compounds are extracted either from plants, animals, microorganisms, or from marine organisms, polyphenols, organic acids, bacteriocins, aqueous extracts of plant parts [20, 28] and

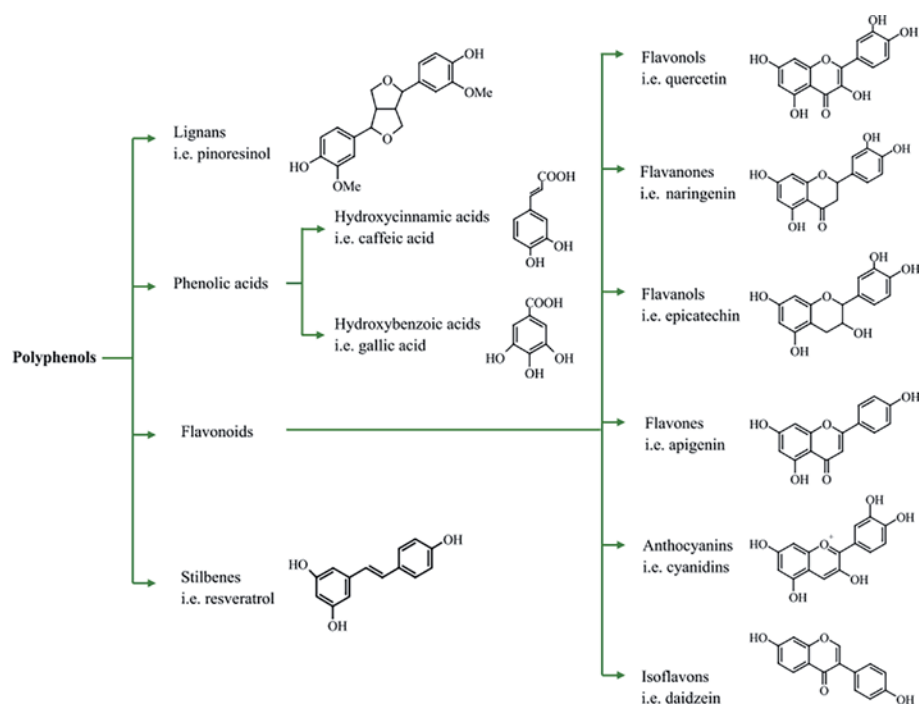
essential oils (EOs) extracted from plant sources [29, 30]. Coatings can also be used as carriers of functional ingredients, such as fungicides for fruit coatings [11]. Other antimicrobials, such as preservatives, anti-browning agents, antioxidants and firming agents, have all been added to coatings to improve the coated product's microbial stability. The incorporation of natural active ingredients, such as plant extracts and EOs, into edible coatings is an emerging trend for shelf-life extension of fruits (**Figure 2**) [11].

2.4 Aesthetics and sensory properties

Some edible coating or films enhance the appearance of coated fruits, for example, lipid-based coatings give fruits a glossy or shiny appearance, which is preferred by most consumers. For processed products, edible coatings have been used to impart sweet flavour and improve texture of cereals [11]. Mineral oil has been used to reduce stickiness or clumpiness of food particles and reduce moisture loss from dried fruit like raisins as well as to improve their appearance [11]. Edible coatings have been used with heterogeneous foods, separating components of a food with differing water activity, such as dry cereal and raisins [11].

3. Sources of edible biocoating agents

Polymers are the main ingredient of many edible coatings. Coating film formers are made from proteins, chitosan, polysaccharides, alginate, dextrose, lipids or resins. These can be the sole ingredient or as is more common, combined with other



ingredients. Polysaccharide coatings are a common constituent of edible coating agents. They are hydrophilic in nature and have poor moisture-barrier properties. Some of the common polysaccharide-based coatings include alginate, cellulose and its derivatives, starch and its derivatives, chitosan, pectin, carrageenans and gums. Proteins are another ingredient of coatings and like polysaccharides, they are also hydrophilic in nature. Protein-based coatings include zein (from corn), peanut, collagen, wheat gluten, soy, collagen, gelatin, egg, whey and casein. Waxes and lipids are another ingredient, but these ones are more permeable to gases than polysaccharides and proteins [11]. They also have better moisture-barrier properties. Examples of lipid- and wax-based coatings include carnauba, beeswax, candelilla, rice bran waxes; petroleum-based waxes such as paraffin and mineral oils; vegetable oils; acetoglycerides; and oleic acid [11]. Resins are less permeable to gases and moderately resistant to water vapour. Examples include shellac, wood resin and coumarone indene resin (Figure 3).

3.1 Polysaccharides

Polysaccharides are polymers of monosaccharides. They are widely used to fabricate edible coating and films. They are hydrophilic and possess good oxygen-barrier properties. Polysaccharide-based edible coatings are colourless and this becomes one of their advantages. Polysaccharide sources of edible coating include starch, cellulose and its derivatives; pectin, pullulan, and chitin- and chitosan-based edible coatings, gums (gum arabic, guar gum, xanthan gum), carrageenan and agar.

3.1.1 Starch

When used as a biocoating, polysaccharide-based coatings provide an oil-free surface. Starch is an example of a polysaccharide that is commonly used as a source of biocoating. While it has some or many desirable properties, starch cannot be solely used as an ingredient to make edible coating because of its hydrophilic nature. Instead, plasticisers and emulsifiers are incorporated into starch-based edible coating to improve flexibility and water-barrier properties. Starches are obtained from

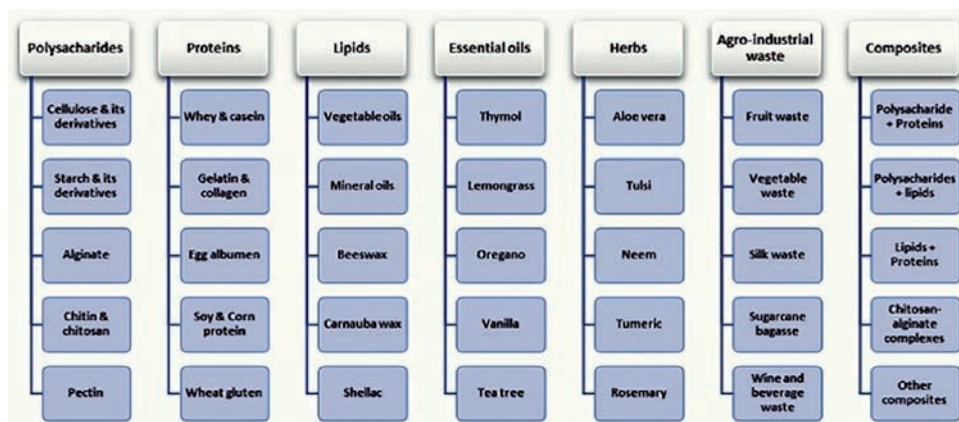


Figure 3. Sources of edible coating by type. Adapted and modified from [8].

cereals, such as wheat, maize and rice. Potato, sweet potatoes, other tubers and legumes are also good source of starch [32]. Starch has been applied as a coating for strawberries, apples, pineapples and mangoes, showing positive results in food storage [10]. Garcia et al. [33] evaluated the effect of starch-based coatings on the quality of refrigerated strawberry (*Fragaria ananassa*). They used two kinds of starch sources, namely, medium amylose content starch from potato and corn and high amylose content from amylomaize and amylose-rich product. They found that both coatings reduced the incidence of infected fruits and also extended the shelf life of strawberries. They also discovered the positive enhancing effect of adding about 20 g/litre of glycerol to the coating, which improved the coating functionality. The high amylose content starches had superior performance over the medium amylose starch, with significant reduction of weight loss, maintenance of strawberry firmness and reduced decay [33]. Bierhals et al. [34] investigated the effect of cassava starch coating on quality and shelf life of fresh-cut pineapple (*Ananas comosus* L. Merrill cv "Pérola"). They found that cassava starch coatings were efficient in reducing respiration rate, weight loss and juice leakage and maintained mechanical properties of fresh-cut pineapples. They however found that the cassava treatments had no significant effect on the shelf life of the minimally processed pineapple fruits. This could imply that various fruit processing methods could also impact on the performance of the edible coating. There is need for more investigation on the interaction of fruit processing methods and edible coating of various types.

3.1.2 Chitin and chitosan

Chitosan is derived from chitin, which is mainly found in crustacean animal shells and fungal cell walls. Chitin and chitosan are animal-based polysaccharides, with the latter being the most common natural non-toxic source for edible coating after cellulose [32]. It is made by treating chitin shells with an alkali such as sodium hydroxide [35]. Chitin-derived coatings have very good oxygen-barrier and carbon dioxide permeation properties. Chitin also has antimicrobial activity against microbes. In addition, chitosan has excellent mechanical properties, for example, its edible films are flexible, tough, highly durable and very difficult to tear. Its viscosity is very high and its coatings are transparent, clear, smooth, shiny, cohesive and without cracks on surface.

Qi et al. [36] investigated the effect of chitosan coatings coupled with anti-browning agents such as ascorbic acid and calcium on minimally processed apple slices. They discovered that chitosan-coating treatments effectively retarded enzymatic browning on minimally processed apples during storage. They also discovered that when they effectively retarded or avoided tissue softening, apple slices underwent a little loss of firmness [36]. Chitin has an important role to play in the edible coating and packaging industry, as it is the second abundant polymer next to cellulose over the world [37]. The chitin derivative, chitosan, however has more important applications in the food industry. It is produced by deacetylation of chitin. The structural properties of chitosan depend on the degree of deacetylation and the average molecular weight. Chitosan has a downside of low water solubility, which tends to limit its applications. However, Du et al. [37] found a way of producing a water-soluble form of chitosan by degrading crude chitin with hydrogen peroxide (H_2O_2). This water-soluble form of chitosan was found to bear antibacterial activity greater than that of crude chitosan without H_2O_2 degradation treatment [37]. Chitosan-derived edible coatings that are plasticised with glycerol (30%) demonstrated enhanced protection

of strawberries from fungal attacks without altering the flavour, aroma, texture and appearance of the strawberry fruit [38].

3.1.3 Pectin

Pectin is the major constituent of plant cell walls found in the middle lamella of plant cells. It is common in the peels of fruits, such as citrus fruits, guava and apple pomace. Pectin is chemically made up of D-galacturonic acid. It has very good thickening properties and is resistant to moisture loss [35]. High methoxy pectin is an excellent pectin compound for producing good film and coating. It is stable at the temperature of 180°C and a mixture of citrus pectin and high amylose starch provides a pliable film and coating [39]. Maftoonazad and Ramaswamy [40] discovered the quality loss reduction effect of pectin-based coating in lime fruits in a study aimed at quantifying the effect of pectin-based coating on the kinetics of quality change in stored lime fruits using a pre-established coating process. The quality attributes assessed included fruit texture, ascorbic acid content, pH, titratable acidity, total soluble solids (TSS) and the respiration rate. Weight losses and respiration rates in pectin-coated fruits were lower than in the control fruits [40].

3.1.4 Carrageenan

Carrageenan is a sulphur-containing polysaccharide that is extracted from the cell wall of different red seaweeds. Carrageenan coatings or films form a 3-dimensional (3D) network by polysaccharide double helical strands and to a solid coating or film after solvent evaporation [41]. Pamungkas [42] investigated the effect of a carrageenan-based edible incorporated with peppermint essential oils to increase the shelf life of bananas (*Musa acuminata cavendish*). It was observed that the application of a carrageenan edible coating resulted in a reduction in weight and TSS, as compared to bananas that were not coated [42]. Dwivany [43] also studied the effect of carrageenan edible coating on bananas but at different concentrations of carrageenan (0.5, 1.0 and 1.5%) and stored at two different temperatures, 26°C and 20°C. The optimum storage conditions for bananas were found to be treating the banana fruits with 1.5% carrageenan and storing them at a cool temperature (20°C) [43]. Carrageenan has also been tried on papaya (*Carica papaya* L. cv. Eksotika) [44], beef [45], strawberries, swordfish, chicken breast and sausage [46] with positive results in extending the shelf life of commodities.

3.1.5 Agar

Agar is a heteroglycan galactose hydrophilic colloidal polymer that is obtained from the red seaweed *Rhodophyceae* family. It also contains gelling and non-gelling mixtures of agarose and agarpectin, and it is readily soluble in a hot aqueous medium [15]. Gels from agar are known for making thermoreversible gels up to 55–60°C [15]. They are used widely to make microbiological media as a solidifying agent. Because of their capacity to form hard gels at a low concentration and because of their ease of extraction, agar is commonly used in the food industry and has found application as an edible coat. Agar gels have lower viscosity properties, which are an ideal feature of films and coatings. Although agar-based edible films and coatings are generally stable and transparent and have good mechanical properties [15], they have some downside, in that they are too brittle, have low elasticity, have less thermal stability and do have a relatively medium gas-barrier performance, and high water vapour permeability [15].

These concerns have been partly mitigated by combining agar with other ingredients, such as starch and malto-dextrin. The agar forms hydrogen-bonding and hydrophobic aggregates in starch films; while the malto-dextrin plasticises and decreases relaxation temperatures of the agar-based film [47]. Cassava starch was also found to improve the elongation and tensile strength of agar- and cassava-based films [48].

3.1.6 Alginate

Alginates are brown algae-derived structural 1,4-linked β -mannuronic acid (M) and α -guluronic acid (G) polysaccharides [49]. Alginates are a high-molecular polymer mass polysaccharide extracted from kelp. Kelps are large brown algae or seaweeds that make up the phylum Ochrophyta, class Phaeophyceae and order Laminariales. Kelps (order Laminariales) are the most widely exploited worldwide as raw materials for alginate production [50]. Alginates can form coatings with or without gelation through evaporation of the solvent. They can also be formed through electrolyte cross-linking with divalent cations such as calcium ions [51]. They have been used as coatings for meat products, to minimise dehydration and to protect against lipid oxidation [51]. They also have potential applications in the edible coating of fish [49].

3.1.7 Gums

The term “gum” is used to define naturally occurring polysaccharides that come across widespread industrial applications due to their ability to either form the gel or make the viscous solution or stabilise the emulsion systems [52]. The gums are soluble in aqueous solutions forming polymer-gum micelles, leading to hydrocolloids through solvent-polymer hydrogen bonding [15]. The gums include the exudate gums such as gum arabic, extractive gums such as guar gum and microbial fermentation gums such as xanthan and gellan [35]. Xanthan gum is synthesised by microbial fermentation process by a *Xanthomonas campestris* microbe that extrudes the gum as an exopolysaccharide for protecting during adverse conditions [53]. Microbial exopolysaccharides (EPS) are high-molecular-weight carbohydrate-based secretions that are produced and secreted to protect the cells of a microbe that has been exposed to stress, such as extreme temperatures, salinity, aridity, extreme pH, UV rays, phagocytosis, osmotic stress and the presence of chemical agents (**Figure 4**) [16].

Gum arabic is a polysaccharide that is utilised in food industries as coating, thickener and emulsifier because of its antioxidant capacity and antifungal characteristics against fungi and other pathogenic bacteria. Guar gum is derived from the seed endosperm of *Cyamopsis tetragonolobus* (cluster bean). It has a high mechanical ability and antibacterial properties, and it is used as a thickening agent and packing material. Gums are utilised in the manufacture of edible coatings, their texture and their capacity to shape gels, create viscous solutions and stabilise emulsion systems [53]. The usefulness of gum arabic as an edible coat has been studied on apple fruit during cold storage [54]. Gum arabic showed a significant delay in ripening and as a result, decayed slowly as compared to the control sample [54]. Gum arabic is the most widely used gum in the food industry because of its emulsifying, film and coating forming and encapsulating properties [55]. Maqbool et al. [55] studied the effect of a composite coat made from gum arabic and lemongrass and cinnamon oils for controlling anthracnose and quality of papaya during storage. Their results suggest an efficacy of using 10% gum arabic with 0.4% cinnamon oil as a biofungicide for controlling postharvest anthracnose of papaya [55].

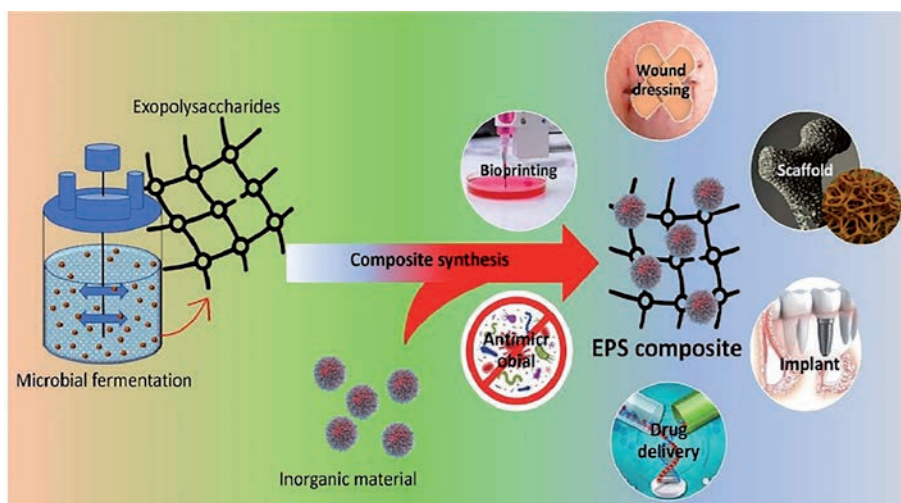


Figure 4.
Formation and secretion of microbial exopolysaccharides (EPS) [16].

3.2 Proteins

Proteins are macromolecules of high molecular mass made from thousands of amino acids. Proteins can come from plants and animals. Plant-based protein coating materials include zein from maize, gluten from wheat and soy protein, among others, while animal-based protein sources include casein protein, egg albumin, whey protein, egg albumin and gelatin. Protein-derived edible coatings and films have superior oxygen and carbon dioxide barrier properties [56]. Protein-based coatings are poor moisture barriers due to their hydrophilic characteristics. This downside can be improved by the introduction of hydrophobic substances such as lipids and oils to form composite coatings.

3.2.1 Casein protein

Casein is a major dairy protein, constituting about 80% of the entire milk protein [53]. Casein coatings are good barriers against oxygen and moisture and they dissolve quickly in water. Chen et al. [57] reported that caseins are desirable biomaterials for the preparation of edible coatings because of their water solubility, emulsification capability and their high dietary benefits. Casein is also added to composite coats of cellulose and pectin and other ingredients to improve the quality of the coatings. Villafañe [58] applied casein coating in combination with turmeric and Tween 80 as an emulsifier on carrots. They observed that this coat treatment maintained the colour, carotenoid concentration and texture for 10 days of storage [58]. In the food industry, casein is commonly utilised in the manufacture of emulsions due to its amphipathic characteristics and the presence of lipophilic and hydrophilic groups. The caseinate form of casein is commonly utilised because it dissolves easily in water.

3.2.2 Soy protein

Soy protein has very low permeability to oxygen and carbon dioxide, which makes it an excellent and cost-effective coating [35]. Amal et al. [59] tested the effect of soy

or gluten edible coating as a carrier of thymol oil and calcium chloride (CaCl_2) on the quality of strawberry fruits. They observed that strawberries coated with thymol carried by soy protein or white gluten and CaCl_2 showed the lowest weight loss percentage. Furthermore, they demonstrated that treating fruits with thymol carried by soy protein or white gluten did not exhibit any change in fruit appearance until 9 days of storage [59]. Soy-protein-derived edible coating helps to maintain the firmness and reduces the weight loss of the products by providing an excellent barrier against oxygen. Soy-protein coatings may be enhanced by incorporating other functional ingredients such as those with antioxidant and antimicrobial properties. Alves et al. [60] assessed the potential of incorporating ferulic acid as a cross-linking agent in soy-protein-based edible coating formulations in order to increase the quality and shelf life of fresh-cut apples (cv. Golden). They found that ferulic acid, due to its antioxidant properties, was effective when incorporated in soy-protein-based edible coating in the weight loss and firmness of fresh-cut apples. Their results emphasised the need to incorporate phenolic antioxidants in a biopolymer edible coating for enhanced functionality.

3.2.3 Corn zein

Zein is the corn storage protein, accounting for 45 to 50% of the protein in corn [53]. Zein is a hydrophobic protein derived from maize as a by-product of the bioethanol and oil industry. Although zein protein is hydrophobic, it is soluble in aqueous alcohol, glycols and glycol esters [35]. Zein coatings have even been applied to control undesired seed germination in broccoli and sugar beet seeds. Seeds coated with zein coating germinated more slowly than untreated seeds [53]. Zein coats also have exhibited antimicrobial properties. Baysal and Bilek [61] demonstrated that dipping intermediate moisture apricots in natural corn protein zein reduced microbial growth and colour changes. Corn-zein coating is a good barrier to oxygen and so may reduce respiration on coated fruits and vegetables. Park et al. [62] showed that zein-coated pears and apples had reduced the respiration rates, weight loss and improved the shelf life. The downside of zein as a coating agent is that its water vapour permeability is about 800 times higher than that of a typical shrink-wrapping film [63]. It has thus been coupled to other ingredients as a composite coat in order to counter the negative attributes of high water vapour permeability [63].

3.3 Lipid

The lipid-based edible coatings have been used for many years for the preservation of fruits and vegetables. Lipid-based coats give a shiny or glossy appearance to coated fruits. The most common lipid-based coating materials are carnauba wax, beeswax, paraffin wax and mineral or vegetable oil [32]. Although lipid-based edible coatings have good water-barrier properties, they are not easy to apply to fruits and vegetables due to their greasy nature [32]. In addition, lipid-based coatings are susceptible to rancidity [56].

3.3.1 Beeswax and paraffin wax

Beeswax is a natural wax produced by honey bees and is a mixture of hydrophobic, long-chain ester compounds, hydrocarbons and fatty acids [63]. Shahid and Abbasi [64] evaluated the influence of beeswax coating to maintain the physical and biochemical parameters of sweet orange. Beeswax was applied at a rate of 1.3 and 5% along with constant level of 0.5% benlate. Results indicated that all waxing

treatments maintained weight loss, firmness, pH, TSS, titratable acidity, TSS/acid ratio, reducing sugars, non-reducing sugars, total sugars and ascorbic acid [64].

Paraffin wax (PW) is made up of a mixture of long-chain saturated hydrocarbons and is made from a portion of crude petroleum. It has a limited application on raw fruits and vegetables, but it acts as a moisture barrier and gives a shiny, glossy appearance. Paraffin wax is one of the most effective waxes, followed by beeswax [63]. Hot-melt paraffin wax has been used in China since the 1930s to coat apples and pears [53]. The absence of polar groups in paraffin and low levels in beeswax account for their resistance to moisture [63]. Bahnasawy and Khater [65] studied the impact of paraffin wax coating on cucumber fruit. They found that waxing improves the shelf life of the fruits by decreasing the diameter change, length change, volume change, surface area change, weight loss, hardness change rate and total soluble solids (TSS) [65].

3.3.2 Carnauba wax

Carnauba wax is derived from the Carnauba palm (*Copernicia prunifera*). It is a natural wax, which is very tough and is the least soluble wax [53]. It is applied in the food industry as a carrier, bulking agent and anticaking agent. Carnauba wax is a potential composition of composite biocoating agents for fruits due to its low water solubility, its antioxidant properties and water-barrier properties. Singh et al. [66] evaluated the effectiveness of a carnauba wax-based edible coating in enhancing the shelf life and quality of the eggplant (*Solanum melongena*) fruits. Results were very positive, indicating that carnauba wax coating resulted in higher expression of antioxidant activity and thus the coating extends the shelf life of vegetables [66]. Miranda et al. [67] applied a carnauba wax nanoemulsion (CWN) as an edible coating on fresh tomato for postharvest quality evaluation. They found out that tomatoes coated with the carnauba wax nanoemulsion (CWN) enhanced the most glossy appearance on tomatoes, reduced weight loss and were preferred by consumers in sensory evaluations [67]. These studies indicate the potential of carnauba wax as an edible coating ingredient for postharvest applications.

3.3.3 Vegetable fat

Vegetable oils, such as sunflower oil, olive oil, rapeseed oil and maize oil, have wide applications as an edible coating. They are inexpensive, non-volatile and non-toxic. They are also a source of monounsaturated fatty acids and hence have been linked to a wide variety of health advantages [53]. Hasan et al. [68] fabricated a unique composite film by incorporating sugar palm starch (SPS), chitosan (CH) and extra virgin olive oil (EVOO). The study concluded that chitosan (CH)/sugar palm starch (SPS)-based blend films that incorporated various extra virgin olive oil (EVOO) ingredients had better surface roughness and mechanical properties, such as tensile strength (TS) and elongation at break (EB), thermal stability, barrier properties, antimicrobial and antioxidant activity [68].

3.3.4 Shellac

Shellac resins are coatings derived from secretions by an insect called *Laccifer lacca* [69]. The resins consist of a complicated aggregate of aliphatic alicyclic hydroxyl acid polymers. These resins are easily soluble in alcoholic alkaline solutions. The downside of these resins as edible coating is that they are not classified as generally recognised

as safe (GRAS) substance [69]. Shellac has been widely used in extending the shelf lives of fruits. Soradech et al. [70] developed a shellac and gelatin composite film for coating to extend the shelf life of banana. Results indicated that shellac composite films can be applied as an edible coating for postharvest fruits and have beneficial effects on retarding the ripening process. They act effectively as a physical barrier around the banana fruit reducing weight loss, softening and the amount of acid and sugar [70].

3.4 Essential oils

Essential oils (EOs) are lipophilic and volatile secondary metabolites produced by aromatic plants. The American Food and Drug Administration (FDA) considers most natural essential oils as generally recognised as safe (GRAS) [53]. Essential oils include methyl jasmonate, ethanol, tea tree oil, and garlic oil, lemongrass oil, thymol, lavender oil, cinnamon oil and cumin oil, among others. When essential oils were applied to tomatoes, they showed a reduction in microbial proliferation while preserving fruit characteristics, such as colour and firmness [10]. Essential oils are not directly applied to foods but are incorporated into other coatings, such as polysaccharide-based coatings. This is because their volatility limits their use as the sole component of coating agents. They must be encapsulated in order to retain most of their coating properties.

3.4.1 Thymol

Thymol (Thy) is a natural essential oil that has earned the “generally recognised as safe” status [53]. The oil exhibits antifungal properties and as such has been used against *Botrytis cinerea* [53]. The oil has been studied as a composite biocoating agent coupled to chitosan and also as a single component of the coat. Results showed a significant preservative effect on the peach fruit when thymol was used together with chitosan [53]. Rahimi et al. [71] studied the effect of chitosan and thymol essential oil on quality maintenance and shelf-life extension of peach fruits cv. They found that the combination treatment of chitosan and thymol presented a more effective preservative effect than chitosan or thymol coatings alone [71]. Su and Zhong [72] fabricated thymol nanoemulsions using the combination of casein hydrolysates (CH) and sucrose stearate (SS). The CH-SS combination improved the emulsification capacity, especially after heating.

3.4.2 Lemongrass oil

Lemongrass oil (LO) is derived from citrus lemon, limonene, ocimene and valencene [53]. Lemongrass oil (LO) exhibits an antibacterial effect against gram-positive and gram-negative bacteria, as well as against yeast and mould [53]. The application of lemongrass oil as an edible coat has shown promising results. Praseptianga et al. [73] found that a cassava starch-based edible covering integrated with 1% lemongrass can be utilised as a substitute for papaya preservation. Azarakhsh et al. [74] investigated the effects of different concentrations (0.1, 0.3 and 0.5%, w/v) of lemongrass essential oil incorporated into an alginate-based edible coating on the quality of fresh-cut pineapple. The results of this study showed a significant reduction of yeast and mould counts and total plate counts of coated samples containing 0.3 and 0.5% (w/v) lemongrass [74]. Higher lemongrass incorporations (0.5%) produced negative

sensory attributes and also decreased the firmness of the fruit, suggesting that higher concentrations of lemongrass could be detrimental to the quality of fruits.

3.4.3 Lavender oil

Lavender essential oil has been used as a medicinal treatment for decades, produced from the common herb Lavender (*Lavandula* spp.). As an essential oil, Lavender has been incorporated as an ingredient of edible coats. Gómez-Contreras et al. [75] developed a coating based on yam (*Dioscorea rotundata* L.) starch-containing lime, fennel and lavender essential oils to extend the shelf life of strawberries (*Fragaria vesca* L.). The results of this study showed that the incorporation of essential oils improved the elongation and water vapour permeability (WVP) of the fruit and also provided antioxidant capacity and antimicrobial activity in the films [75].

3.4.4 Cumin oil

Cumin (*Cuminum cyminum*) is a tiny, herbaceous plant in the *Umbelliferae* family. It has a peculiar scent and is often used as a spice and flavouring ingredient, because of this unique scent. It has also been used as an astringent, carminative and stimulant in medicine to treat gas, diarrhoea and indigestion [53]. Oyom et al. [76] incorporated cumin essential oil by modifying a sweet potato starch edible coating. The effectiveness of this modified coating was assessed on “early crisp” stored at 25°C for 28 days [76]. Results showed that cumin (EO) and potato starch composite was effective to maintain the internal quality, delayed changes in fruit colour, firmness, chlorophyll degradation and stomatal densities of “early crisp.” Results also showed that the incorporation of 0.2–0.4% (v/v) cumin essential oil (CEO) in modified sweet potato starch edible coatings significantly reduced rot lesion on infected pear caused by *Alternaria alternata*.

3.5 Herbs

Herbs are crude plant material, such as leaves, flowers, fruit, seed, stems, wood, bark, roots, rhizomes or other plant parts, which may be entire, fragmented or powdered. Herbs are commonly used for medicinal and culinary purposes, while herbal edible coating is a relatively new application for herbs in the food industry. The most common herbs used in edible coatings include Aloe Vera gel, Neem, Lemongrass, Rosemary, Tulsi and Turmeric [56]. Aloe Vera-based edible coating has demonstrated better results as compared to the traditional edible coatings. The Aloe Vera gel provides a protective layer against oxygen and moisture transport from fresh fruits or vegetables. It also has antimicrobial properties and is very highly regarded as a nutritional source [56]. Aloe Vera is reported to have 75 nutrients, sugars, anthraquinones, vitamins, minerals, salicylic acid, approximately 200 active compounds and amino acids that show medical properties [56].

4. Conclusion

This review has highlighted the various sources of edible coating agents, from polysaccharides, proteins, lipids, essential oils and herbs. Although these may be the major sources, they are not the only sources, as more novel sources are emerging.

Agro-industrial waste, for example, is emerging as a highly potent source of ingredients for edible coating formulation. The utilisation of food waste for applications such as edible coating formulation is known as valorisation. Waste valorisation enables the implementation of a Circular Bioeconomy, emphasising reducing and reusing food waste for sustainable applications. The use of biowaste to make valuable solutions enables a reduction of waste in dumpsites. It should be noted that food waste is one of the most polluting areas globally. According to recent data, food loss and waste generates 8–10% of annual global greenhouse gas (GHG) emissions—almost 5 times that of the aviation sector [77]. Waste valorisation for edible coating therefore helps reduce greenhouse gas emissions from the decomposing food waste, making edible coating agents a promising alternative and sustainable packaging technology. It should be pinpointed that edible coating as a technology does not seek to replace or compete with existing postharvest technologies such as cold chain, but rather to complement these strategies, to proffer even better postharvest storage of fruits and vegetables.

The main advantages of edible coat/films are the fact that they are biodegradable, edible, non-toxic and cost-effective as compared to synthetic films and coatings, which are mainly derived from the polluting oil industry value chain. Another additional advantage of edible coats is that they help to reduce waste materials in the packaging industry, which is currently a major challenge with most synthetic films and coatings. Various sources of edible coating have been assessed, including proteins, polysaccharides, lipids, essential oils and herbs. These sources have their own unique properties and hence advantages and disadvantages. The coupling of two or more types of components of edible coating enables the synthesis of effective coating with numerous functionalities. Additional components are usually added to enhance the properties of edible coating, for example, plasticisers, such as glycerol, mannitol, sorbitol and sucrose. The future of the edible coating industry may lie in the global rally to leverage on the potential of edible coating by investing in research and development of these coatings to optimise their extraction, processing and stability. Newer encapsulation methods to improve stability of coatings are being developed and more sources of edible coating are being screened. Overall, edible coating offers a more sustainable alternative to packaging that enhances the shelf life of fruits and vegetables in a more cost-effective and sustainable manner.

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References

- [1] Rojas MF, Houmy K, Fawole O. Post-Harvest Management: Bridging Gaps and Embracing Innovations. Rome, Italy: FAO; 2024. DOI: 10.4060/cd1185en
- [2] Buntong B, Srilaong V, Wasusri T, Kanlayanara S, Acedo ALJ. Reducing postharvest losses of tomato in traditional and modern supply chains in Cambodia. *International Food Research Journal*. 2013;**20**(1):233-238
- [3] Gogh JB, Aramyan LH. Reducing postharvest food losses in developing economies by using a network of excellence as an intervention tool. In: Paper Presented at IFAMA and CCA Food and Agribusiness World Forum, Kaapstad, Zuidafrika. Cape Town, South Africa: IFAMA; 2014
- [4] Gustavsson J, Cederberg C, Sonesson U. Global food losses and food waste: Extent, causes and prevention; study conducted for the international congress save food! at Interpack 2011, [16-17 May], Düsseldorf, Germany. In: International Congress Save Food! Rome: Food and Agriculture Organization of the United Nations; 2011
- [5] Hodges RJ, Buzby JC, Bennett B. Postharvest losses and waste in developed and less developed countries: Opportunities to improve resource use. *The Journal of Agricultural Science*. 2011;**149**(S1):37-45. DOI: 10.1017/S0021859610000936
- [6] Prusky D. Reduction of the incidence of postharvest quality losses, and future prospects. *Food Security*. 2011;**3**(4):463-474. DOI: 10.1007/s12571-011-0147-y
- [7] Kitinoja L, Saran S, Roy SK, Kader AA. Postharvest technology for developing countries: Challenges and opportunities in research, outreach and advocacy: Postharvest technology for developing countries. *Journal of the Science of Food and Agriculture*. 2011;**91**(4):597-603. DOI: 10.1002/jsfa.4295
- [8] Owusu-Akyaw Oduro K. Edible coating. In: Ahiduzzaman M, editor. *Postharvest Technology—Recent Advances, New Perspectives and Applications*. London, UK: IntechOpen; 2022. DOI: 10.5772/intechopen.101283
- [9] Priya K, Thirunavookarasu N, Chidanand DV. Recent advances in edible coating of food products and its legislations: A review. *Journal of Agriculture and Food Research*. 2023;**12**:100623. DOI: 10.1016/j.jafr.2023.100623
- [10] Nunes C, Silva M, Farinha D, Sales H, Pontes R, Nunes J. Edible coatings and future trends in active food packaging—fruits' and traditional sausages' shelf life increasing. *Foods*. 2023;**12**(17):1-23. DOI: 10.3390/foods12173308
- [11] Baldwin EA, Hagenmaier RD, Bai J. *Edible Coatings and Films to Improve Food Quality*. 2nd ed. Boca Raton, USA: CRC Press; 2012
- [12] Janik E, Niemcewicz M, Podogrocki M, Ceremuga M, Stela M, Bijak M. T-2 toxin—The most toxic trichothecene mycotoxin: Metabolism, toxicity, and decontamination strategies. *Molecules*. 2021;**26**(22):6868. DOI: 10.3390/molecules26226868
- [13] Dhall RK. Advances in edible coatings for fresh fruits and vegetables: A review. *Critical Reviews in Food Science and Nutrition*. 2013;**53**(5):435-450. DOI: 10.1080/10408398.2010.541568

- [14] López O, García MA, Zaritzky NE. Novel sources of edible films and coatings. *Stewart Postharvest Review*. 2010;**6**(3):1-8. DOI: 10.2212/spr.2010.3.2
- [15] Liyanapathirana A, Dassanayake RS, Gamage A, Karri RR, Manamperi A, Evon P, et al. Recent developments in edible films and coatings for fruits and vegetables. *Coatings*. 2023;**13**(7):1-34. DOI: 10.3390/coatings13071177
- [16] Ahuja V, Chauhan S, Dasgupta D, Wadhwa P, Raj T, Yang Y-H, et al. Microbial exopolysaccharide composites with inorganic materials and their biomedical applications: A review. *Carbohydrate Polymer Technologies and Applications*. 2024;**7**:100482. DOI: 10.1016/j.carpta.2024.100482
- [17] Khanal BP, Knoche M. Mechanical properties of cuticles and their primary determinants. *Journal of Experimental Botany*. 2017;**68**(19):5351-5367. DOI: 10.1093/jxb/erx265
- [18] Ruggeri E, Kim D, Cao Y, Farè S, De Nardo L, Marelli B. A multilayered edible coating to extend produce shelf life. *ACS Sustainable Chemistry and Engineering*. 2020;**8**(38):14312-14321. DOI: 10.1021/acssuschemeng.0c03365
- [19] Díaz-Montes E, Castro-Muñoz R. Edible films and coatings as food-quality preservers: An overview. *Food*. 2021;**10**(2):249. DOI: 10.3390/foods10020249
- [20] Kumar N, Pratibha Prasad J, Yadav A, Upadhyay A, Neeraj Shukla S, Petkoska AT, et al. Recent trends in edible packaging for food applications—Perspective for the future. *Food Engineering Reviews*. 2023;**15**(4):718-747. DOI: 10.1007/s12393-023-09358-y
- [21] Yadav A, Rehan D, Sharma A, Nair R, Uikey P. Techniques to reduce the postharvest losses of fruits and vegetables. In: *Advanced Technology of Horticulture*. New Delhi: Daya Publishing House® A Division of Astral International Pvt. Ltd; 2023. pp. 321-342
- [22] Botalo A, Inprasit T, Ummartyotin S, Chainok K, Vatthanakul S, Pisitsak P. Smart and UV-resistant edible coating and films based on alginate, whey protein, and curcumin. *Polymers*. 2024;**16**(4):447. DOI: 10.3390/polym16040447
- [23] Falguera V, Quintero JP, Jiménez A, Muñoz JA, Ibarz A. Edible films and coatings: Structures, active functions and trends in their use. *Trends in Food Science and Technology*. 2011;**22**(6):292-303. DOI: 10.1016/j.tifs.2011.02.004
- [24] Santos DI, Saraiva JMA, Vicente AA, Moldão-Martins M. Methods for determining bioavailability and bioaccessibility of bioactive compounds and nutrients. In: *Innovative Thermal and Non-Thermal Processing, Bioaccessibility and Bioavailability of Nutrients and Bioactive Compounds*. Sawston, UK: Elsevier; 2019. pp. 23-54. DOI: 10.1016/B978-0-12-814174-8.00002-0
- [25] Hamzalıoğlu A, Gökmen V. Interaction between bioactive carbonyl compounds and asparagine and impact on acrylamide. In: *Acrylamide in Food*. London, UK: Elsevier, Academic Press; 2016. pp. 355-376. DOI: 10.1016/B978-0-12-802832-2.00018-8
- [26] Carciochi RA, D'Alessandro LG, Vauchel P, Rodriguez MM, Nolasco SM, Dimitrov K. Valorization of agrifood by-products by extracting valuable bioactive compounds using green processes. In: *Ingredients Extraction by Physicochemical Methods in Food*. London, UK: Elsevier; 2017. pp. 191-228. DOI: 10.1016/B978-0-12-811521-3.00004-1

- [27] Faustino M, Veiga M, Sousa P, Costa E, Silva S, Pintado M. Agro-food byproducts as a new source of natural food additives. *Molecules*. 2019;**24**(6):1056. DOI: 10.3390/molecules24061056
- [28] Taher MA, Laboni AA, Shompa SA, Rahman MM, Hasan MM, Hasnat H, et al. Bioactive compounds extracted from leaves of *G. cyanocarpa* using various solvents in chromatographic separation showed anti-cancer and anti-microbial potentiality in in silico approach. *Chinese Journal of Analytical Chemistry*. 2023;**51**(12):100336. DOI: 10.1016/j.cjac.2023.100336
- [29] Peralta-Ruiz Y, Tovar CDG, Sinning-Mangonez A, Coronell EA, Marino MF, Chaves-Lopez C. Reduction of postharvest quality loss and microbiological decay of tomato “Chonto” (*Solanum lycopersicum* L.) using chitosan-E essential oil-based edible coatings under low-temperature storage. *Polymers*. 2020;**12**(8):1822. DOI: 10.3390/polym12081822
- [30] Tzortzakakis N, Xylia P, Chrysargyris A. Sage essential oil improves the effectiveness of Aloe vera gel on postharvest quality of tomato fruit. *Agronomy*. 2019;**9**(10):635. DOI: 10.3390/agronomy9100635
- [31] Watson RR. Preface. In: *Polyphenols in Plants*. London, UK: Elsevier; 2014. pp. xi-xii. DOI: 10.1016/B978-0-12-397934-6.05001-4
- [32] Ch. Momin M, Jamir A, Ankalagi N, Chanu T, Bijaya O. Edible coatings in fruits and vegetables: A brief review. *The Pharma Innovation Journal*. 2021;**10**:71-78
- [33] García MA, Martino MN, Zaritzky NE. Starch-based coatings: Effect on refrigerated strawberry (*Fragaria ananassa*) quality. *Journal of the Science of Food and Agriculture*. 1998;**76**(3):411-420. DOI: 10.1002/(SICI)1097-0010(199803)76:3<411::AID-JSFA965>3.0.CO;2-I
- [34] Bierhals VS, Chiumarelli M, Hubinger MD. Effect of cassava starch coating on quality and shelf life of fresh-cut pineapple (*Ananas Comosus* L. Merrill cv “Pérola”). *Journal of Food Science*. 2011;**76**(1):E62-E72. DOI: 10.1111/j.1750-3841.2010.01951.x
- [35] Reddy KS, Singh J. Edible coatings in fruits - a review. *International Journal of Current Microbiology and Applied Sciences*. 2020;**9**(11):2953-2969. DOI: 10.20546/ijcmas.2020.911.359
- [36] Qi H, Hu W, Jiang A, Tian M, Li Y. Extending shelf-life of fresh-cut ‘Fuji’ apples with chitosan-coatings. *Innovative Food Science and Emerging Technologies*. 2011;**12**(1):62-66. DOI: 10.1016/j.ifset.2010.11.001
- [37] Du Y, Zhao Y, Dai S, Yang B. Preparation of water-soluble chitosan from shrimp shell and its antibacterial activity. *Innovative Food Science and Emerging Technologies*. 2009;**10**(1):103-107. DOI: 10.1016/j.ifset.2008.07.004
- [38] Pavinatto A, De Almeida Mattos AV, Malpass ACG, Okura MH, Balogh DT, Sanfelice RC. Coating with chitosan-based edible films for mechanical/biological protection of strawberries. *International Journal of Biological Macromolecules*. 2020;**151**:1004-1011. DOI: 10.1016/j.ijbiomac.2019.11.076
- [39] Fang Q, Hanna M. Functional properties of polylactic acid starch-based loose-fill packaging foams 1. *Cereal Chemistry*. 2000;**77**:779-783. DOI: 10.1094/CCHEM.2000.77.6.779
- [40] Maftoonazad N, Ramaswamy HS. Application and evaluation of a

pectin-based edible coating process for quality change kinetics and shelf-life extension of lime fruit (*Citrus aurantifolium*). *Coatings*. 2019;**9**(5):285. DOI: 10.3390/coatings9050285

[41] Larotonda F, Hilliou L, Sereno A, Gonçalves M. Green edible films obtained from starch-domestic carrageenan mixtures. *Open Journal of Polymer Chemistry*. 2005;**10**:1-10

[42] Pamungkas A, Siregar ZA, Sedayu BB, Fauzi A, Novianto TD. A carrageenan-based edible coating incorporating with peppermint essential oils to increase shelf life of bananas (*Musa acuminata* cavendish). *Jurnal Ilmiah Rekayasa Pertanian Dan Biosistem*. 2023;**11**(2):232-245. DOI: 10.29303/jrpb.v11i2.543

[43] Dwivany FM, Aprilyandi AN, Suendo V, Sukriandi N. Carrageenan edible coating application prolongs Cavendish banana shelf life. *International Journal of Food Science*. 2020;**2020**:1-11. DOI: 10.1155/2020/8861610

[44] Hamzah HM, Osman A, Tan CP, Mohamad Ghazali F. Carrageenan as an alternative coating for papaya (*Carica papaya* L. cv. Eksotika). *Postharvest Biology and Technology*. 2013;**75**:142-146. DOI: 10.1016/j.postharvbio.2012.08.012

[45] Velásquez P, Montenegro G, Valenzuela LM, Giordano A, Cabrera-Barjas G, Martin-Belloso O. k-carrageenan edible films for beef: Honey and bee pollen phenolic compounds improve their antioxidant capacity. *Food Hydrocolloids*. 2022;**124**:107250. DOI: 10.1016/j.foodhyd.2021.107250

[46] Rodriguez, Carrillo SAA, Ruiz Olortino GP, Rafael Guevara DF, Chinchay Gallardo EH. Bio-based carrageenan composite coatings for food packaging application. In: *Proceedings of*

the 21th LACCEI International Multi-Conference for Engineering, Education and Technology (LACCEI 2023): “Leadership in Education and Innovation in Engineering in the Framework of Global Transformations: Integration and Alliances for Integral Development”. Buenos Aires, Argentina: LACCEI; 2023. DOI: 10.18687/LACCEI2023.1.1.849

[47] Wongphan P, Harnkarnsujarit N. Characterization of starch, agar and maltodextrin blends for controlled dissolution of edible films. *International Journal of Biological Macromolecules*. 2020;**156**:80-93. DOI: 10.1016/j.ijbiomac.2020.04.056

[48] Phan The D, Debeaufort F, Voilley A, Luu D. Biopolymer interactions affect the functional properties of edible films based on agar, cassava starch and arabinoxylan blends. *Journal of Food Engineering*. 2009;**90**(4):548-558. DOI: 10.1016/j.jfoodeng.2008.07.023

[49] Kamal I. Edible films and coatings: Classification, preparation, functionality and applications – A review. *Archives of Organic and Inorganic Chemical Sciences*. 2020;**4**:501-509. DOI: 10.32474/AOICS.2019.04.000184

[50] Peteiro C. Alginate production from marine macroalgae, with emphasis on kelp farming. In: Rehm BHA, Moradali MF, editors. *Alginates and their Biomedical Applications*. Vol. 11. Gateway East, Singapore: Springer Singapore; 2018. pp. 27-66. DOI: 10.1007/978-981-10-6910-9_2

[51] Suput D, Lazic V, Popović S, Hromis N. Edible films and coatings: Sources, properties and application. *Food and Feed Research*. 2015;**42**:11-22. DOI: 10.5937/FFR1501011S

[52] Salehi F. Edible coating of fruits and vegetables using natural gums: A review. *International Journal of Fruit*

Science. 2020;**20**(sup 2):S570-S589.
DOI: 10.1080/15538362.2020.1746730

[53] Armghan, Khalid M, Niaz B, Saeed F, Afzaal M, Islam F, Hussain M, et al. Edible coatings for enhancing safety and quality attributes of fresh produce: A comprehensive review. *International Journal of Food Properties*. 2022;**25**(1):1817-1847.
DOI: 10.1080/10942912.2022.2107005

[54] El-Anany AM, Hassan GFA, Ali FRA. Effects of edible coatings on the shelf-life and quality of Anna apple (*Malus domestica* Borkh) during cold storage. *Journal of Food Technology*. 2009;**7**:5-11

[55] Maqbool M, Ali A, Alderson PG, Mohamed MTM, Siddiqui Y, Zahid N. Postharvest application of gum arabic and essential oils for controlling anthracnose and quality of banana and papaya during cold storage. *Postharvest Biology and Technology*. 2011;**62**(1):71-76. DOI: 10.1016/j.postharvbio.2011.04.002

[56] Nain N, Katoch GK, Kaur S, Rasane P. Recent developments in edible coatings for fresh fruits and vegetables. *Journal of Horticultural Research*. 2021;**29**(2):127-140. DOI: 10.2478/johr-2021-0022

[57] Chen H, Wang J, Cheng Y, Wang C, Liu H, Bian H, et al. Application of protein-based films and coatings for food packaging: A review. *Polymers*. 2019;**11**(12):2039. DOI: 10.3390/polym11122039

[58] Villafañe F. Edible coatings for carrots. *Food Reviews International*. 2017;**33**(1):84-103.
DOI: 10.1080/87559129.2016.1150291

[59] Amal S, El-Mogy MM, Din Aboul-Anean HE, Alsanius BW. Improving strawberry fruit storability by

edible coating as a carrier of thymol or calcium chloride. *Journal of Horticultural Science & Ornamental Plants*. 2010;**2**(3):88-97. Available from: <https://api.semanticscholar.org/CorpusID:56343722>

[60] Alves MM, Gonçalves MP, Rocha CMR. Effect of ferulic acid on the performance of soy protein isolate-based edible coatings applied to fresh-cut apples. *LWT*. 2017;**80**:409-415.
DOI: 10.1016/j.lwt.2017.03.013

[61] Baysal T, Bilek SE. The effect of corn zein edible film coating on intermediate moisture apricot (*Prunus armenica* L.) quality. *GIDA*. 2010;**35**(4):245-249. Available from: <https://api.semanticscholar.org/CorpusID:55276947>

[62] Park HJ, Rhim J-W, Lee H. Edible coating effects on respiration rate and storage life of “Fuji” apples and “Shingo” pears. *Food Science and Biotechnology*. 1996;**5**:59-63

[63] Sonti S. Consumer perception and application of edible coatings on fresh-cut fruits and vegetables [thesis]. USA: Louisiana State University; 2003

[64] Shahid M, Abbasi NA. Effect of bee wax coatings on physiological changes in fruits of sweet orange cv. ‘Blood red’. *Sarhad Journal of Agriculture*. 2011;**27**:385-394. Available from: <https://api.semanticscholar.org/CorpusID:55162792>

[65] Bahnasawy, Adel H, Khater E. Effect of wax coating on the quality of cucumber fruits during storage. *Journal of Food Processing & Technology*. 2014;**05**(06):11271-11294.
DOI: 10.4172/2157-7110.1000339

[66] Singh S, Khemariya P, Rai A, Rai AC, Koley TK, Singh B. Carnauba wax-based

edible coating enhances shelf-life and retain quality of eggplant (*Solanum melongena*) fruits. LWT. 2016;**74**:420-426. DOI: 10.1016/j.lwt.2016.08.004

[67] Miranda M, Ribeiro MDMM, Spricigo PC, Pilon L, Mitsuyuki MC, Correa DS, et al. Carnauba wax nanoemulsion applied as an edible coating on fresh tomato for postharvest quality evaluation. Heliyon. 2022;**8**(7):e09803. DOI: 10.1016/j.heliyon.2022.e09803

[68] Hasan M, Rusman R, Khaldun I, Ardana L, Mudatsir M, Fansuri H. Active edible sugar palm starch-chitosan films carrying extra virgin olive oil: Barrier, thermo-mechanical, antioxidant, and antimicrobial properties. International Journal of Biological Macromolecules. 2020;**163**:766-775. DOI: 10.1016/j.ijbiomac.2020.07.076

[69] Hassan Z, Kasa M, Balang RV, Abdullah SM, Fong TS. Exploring mentoring skills to assist new nurses: Mentors' and mentees' perspectives. International Journal of Academic Research in Business and Social Sciences. 2020;**11**(14):124-141. DOI: 10.6007/IJARBS/v11-i14/8534

[70] Soradech S, Nunthanid J, Limmatvapirat S, Luangtana-anan M. Utilization of shellac and gelatin composite film for coating to extend the shelf life of banana. Food Control. 2017;**73**:1310-1317. DOI: 10.1016/j.foodcont.2016.10.059

[71] Rahimi R, Valizadeh Kaji B, Khadivi A, Shahrjerdi I. Effect of chitosan and thymol essential oil on quality maintenance and shelf life extension of peach fruits cv. 'Zaferani'. Journal of Horticulture and Postharvest Research. 2019;**2**:143-156. Available from: <https://api.semanticscholar.org/CorpusID:171084755>

[72] Su D, Zhong Q. Formation of thymol nanoemulsions with combinations of casein hydrolysates and sucrose stearate. Journal of Food Engineering. 2016;**179**:1-10. DOI: 10.1016/j.jfoodeng.2016.01.030

[73] Praseptianga D, Utami R, Khasanah LU, Evirananda IP, Kawiji. Effect of cassava starch-based edible coating incorporated with lemongrass essential oil on the quality of papaya MJ9. IOP Conference Series: Materials Science and Engineering. 2017;**176**:012054. DOI: 10.1088/1757-899X/176/1/012054

[74] Azarakhsh N, Osman A, Ghazali HM, Tan CP, Mohd Adzahan N. Lemongrass essential oil incorporated into alginate-based edible coating for shelf-life extension and quality retention of fresh-cut pineapple. Postharvest Biology and Technology. 2014;**88**:1-7. DOI: 10.1016/j.postharvbio.2013.09.004

[75] Gómez-Contreras P, Figueroa-Lopez KJ, Hernández-Fernández J, Cortés Rodríguez M, Ortega-Toro R. Effect of different essential oils on the properties of edible coatings based on yam (*Dioscorea rotundata* L.) starch and its application in strawberry (*Fragaria vesca* L.) preservation. Applied Sciences. 2021;**11**(22):11057. DOI: 10.3390/app112211057

[76] Oyom W, Xu H, Liu Z, Long H, Li Y, Zhang Z, et al. Effects of modified sweet potato starch edible coating incorporated with cumin essential oil on storage quality of 'early crisp'. LWT. 2022;**153**:112475. DOI: 10.1016/j.lwt.2021.112475

[77] UNEP. World Squanders Over 1 Billion Meals a Day—UN Report. 2024. Available from: <https://www.unep.org/news-and-stories/press-release/world-squanders-over-1-billion-meals-day-un-report>

Macroalgae-Derived Sugars and Polysaccharides: Innovations in Natural Sweeteners and Food Applications

Damiano Spagnuolo and Giuseppa Genovese

Abstract

This chapter explores the potential of macroalgae-derived sugars and polysaccharides as sustainable, functional alternatives to traditional sugars. Focusing on innovative extraction technologies, the chapter highlights the unique properties of macroalgal polysaccharides (such as agar, alginate, and carrageenan) as natural sweeteners and thickeners. Emphasis is placed on the nutritional benefits of macroalgae, including their low-glycemic impact and high content of bioactive compounds that promote health. It will also mention the integration of macroalgal derivatives into food products, enhancing both flavor and texture while contributing to reduced sugar dependence. This chapter aligns with modern trends in sustainable food innovation and nutritional enhancement, presenting macroalgae as a promising resource for the food industry.

Keywords: macroalgae-derived sweeteners, polysaccharide extraction, natural sugar substitutes, marine bioactive compounds, sustainable food innovation

1. Introduction

Macroalgae, commonly referred to as seaweeds, are photosynthetic organisms that thrive in marine and freshwater environments. They are classified into three main groups: Red (Rhodophyta), Green (Chlorophyta), and Brown (Phaeophyceae) algae. Each group possesses unique biochemical compositions, making them valuable resources for food science and technology [1, 2].

Rhodophyta are rich in sulfated polysaccharides like agar and carrageenan. These compounds are widely used as gelling and stabilizing agents in the food industry [3]. *Gracilaria*, for instance, is a primary source of agar, which is utilized in desserts, dairy products, and microbiological media [4].

Chlorophyta are characterized by their high chlorophyll content and the presence of Ulvans, a heterogeneous group of sulfated polysaccharides with potential prebiotic and antioxidant properties [5]. The species of the genus *Ulva* is increasingly being explored for its applications in functional foods and nutraceuticals [6].

Phaeophyceae are abundant in alginates and fucoidans. Alginates are widely used as thickeners and emulsifiers in products like ice cream and salad dressings, while fucoidans have gained attention for their bioactive properties, including anti-inflammatory and antiviral effects [7].

Furthermore, macroalgae have been integral to human diets for centuries, particularly in Asian cultures. In Japan, “Nori sheet,” obtained from processed *Porphyra/Pyropia* thalli, is a staple ingredient in sushi, while “Kombu” (*Laminaria* spp.) is used to flavor broths and soups [8]. Traditional Chinese medicine also incorporates seaweeds like *Sargassum* for their purported health benefits [9].

In modern food industries, macroalgae-derived polysaccharides have become indispensable. For example, carrageenan from red algae is a key ingredient in dairy alternatives and processed meats, providing texture and stability [10]. Similarly, alginate from brown algae is used in encapsulation technologies for the controlled release of bioactive compounds in functional foods [11]. The global demand for seaweed-based products is projected to grow significantly, driven by their sustainability and nutritional benefits [12].

2. Key macroalgae polysaccharides

Macroalgae are a rich source of structurally diverse polysaccharides, each with unique chemical properties and functional roles. These polysaccharides are categorized based on their algal origin and structural characteristics, with key examples including laminarin, fucoidan, alginate, carrageenan, agar, and ulvan. Understanding their chemical composition and functional properties is essential for their application in food science, particularly as natural sweeteners and functional ingredients.

2.1 Laminarin

Laminarin is a storage polysaccharide found predominantly in brown algae, such as *Laminaria* and *Saccharina* species. It consists of β -(1,3)-glucan with occasional β -(1,6)-linked branches, giving it a linear or slightly branched structure [13]. Laminarin is known for its prebiotic properties, promoting gut health by stimulating the growth of beneficial bacteria like *Bifidobacterium* and *Lactobacillus* [14]. Additionally, its low molecular weight and solubility make it a potential candidate for functional foods and nutraceuticals [15].

2.2 Fucoidan

Fucoidan is a sulfated polysaccharide found in brown algae, such as *Fucus* and *Ascophyllum* species. Its structure is composed of α -(1,3)-linked fucose units with sulfate groups attached at various positions, contributing to its bioactivity [16]. Fucoidan has been extensively studied for its antioxidant, anti-inflammatory, and antiviral properties, making it a valuable ingredient in health-promoting foods and supplements [17].

2.3 Alginate

Alginate is a linear copolymer of β -(1,4)-linked D-mannuronic acid (M) and α -(1,4)-linked L-guluronic acid (G) residues, extracted from brown algae species

like *Laminaria* and *Macrocystis* [18]. The ratio of M to G blocks determines its gelling properties, with high-G alginates forming strong, brittle gels and high-M alginates producing softer, more elastic gels [19]. Alginate is widely used as a thickener, stabilizer, and encapsulation agent in the food industry.

2.4 Carrageenan

Carrageenan is a family of sulfated polysaccharides derived from red algae, such as *Chondrus crispus* and *Eucheuma* spp. It is composed of alternating β -(1,3)-D-galactose and α -(1,4)-3,6-anhydro-D-galactose units, with varying degrees of sulfation depending on the type (kappa, iota, or lambda) [20]. Carrageenan is widely used as a gelling, thickening, and stabilizing agent in dairy products, plant-based alternatives, and processed meats [21].

2.5 Agar

Agar is a gelatinous polysaccharide extracted from red algae species, such as *Gracilaria* and *Gelidium*. It consists of two main components: agarose, a linear polymer of β -(1,3)-D-galactose and α -(1,4)-3,6-anhydro-L-galactose, and agaropectin, a more heterogeneous and sulfated form [22]. Agar is widely used as a gelling agent in food products like desserts, confectionery, and microbiological media due to its high gel strength and thermal stability [23].

2.6 Ulvan

Ulvan is a sulfated polysaccharide found in green algae, particularly *Ulva* spp. It is composed of rhamnose, xylose, glucuronic acid, and iduronic acid, with sulfate groups attached to the sugar backbone [24]. Ulvan has gained attention for its bioactive properties, including antioxidant, anti-inflammatory, and prebiotic effects, making it a promising ingredient for functional foods and nutraceuticals [25].

3. Sweetening potential

Macroalgae polysaccharides are not traditionally known for their sweetness, but certain derivatives and hydrolyzed forms exhibit sweetening potential. For example, oligosaccharides derived from laminarin and fucoidan have been reported to possess mild sweetness and low-calorie content, making them suitable for use in low-glycemic-index foods [26]. These compounds are metabolized slowly, preventing rapid spikes in blood glucose levels and offering benefits for individuals with diabetes or metabolic syndrome [27].

These types of sugars are gaining recognition as innovative natural sweeteners due to their unique functional properties, low-calorie content, and health benefits. Unlike conventional sweeteners, which often contribute to metabolic disorders, these polysaccharides offer a sustainable and health-promoting alternative. This section explores the sweetening potential of macroalgae polysaccharides, their comparative sweetness profiles, and their suitability for diabetic-friendly formulations [28].

Agar and ulvan, while not inherently sweet, can also be modified to produce oligosaccharides with enhanced functional properties. For instance, enzymatic hydrolysis of agar yields agaro-oligosaccharides (AOS), which have been shown to exhibit

prebiotic effects and mild sweetness [29]. Similarly, ulvan oligosaccharides (UOS) derived from green algae have demonstrated potential as natural sweeteners with added health benefits, such as antioxidant and immunomodulatory activities [30].

The metabolic benefits of macroalgae-derived sugars extend beyond their sweetening potential. Their low glycemic index, combined with their prebiotic and bioactive properties, positions them as innovative ingredients for functional foods and beverages aimed at promoting health and wellness [31].

3.1 Fucoidan and its derivatives

Fucoidan, a sulfated polysaccharide from brown algae, is not inherently sweet but can be hydrolyzed into oligosaccharides with mild sweetness. These fucoidan oligosaccharides (FOS) have a low-calorie content and exhibit prebiotic properties, making them suitable for functional foods aimed at gut health [32]. For example, FOS derived from *Fucus vesiculosus* has been shown to stimulate the growth of beneficial gut bacteria while providing a subtle sweetness comparable to 10–20% of sucrose [33].

3.2 Mannitol in brown algae

Mannitol, a sugar alcohol found in brown algae like *Laminaria* and *Saccharina*, is a naturally occurring low-calorie sweetener. It has approximately 50–70% of the sweetness of sucrose and is metabolized independently of insulin, making it suitable for diabetic-friendly formulations [34]. Mannitol also acts as a humectant, improving the texture and shelf life of food products.

3.3 Agar-oligosaccharides (AOS)

Agar, a polysaccharide from red algae, can be enzymatically hydrolyzed to produce agar-oligosaccharides (AOS), which exhibit mild sweetness and prebiotic effects. AOS derived from *Gracilaria* species has been reported to have a sweetness level of about 30% of sucrose, along with antioxidant and immunomodulatory properties [35].

3.4 Ulvan oligosaccharides (UOS)

Ulvan, a sulfated polysaccharide from green algae, can be broken down into ulvan oligosaccharides (UOS), which have a mild sweetness and bioactive properties. UOS from *Ulva lactuca* have demonstrated potential as natural sweeteners with added health benefits, such as anti-inflammatory and antioxidant effects [36].

3.5 Comparative sweetness profiles

The sweetness of macroalgae-derived polysaccharides and their derivatives varies significantly compared to conventional sweeteners like sucrose, fructose, and artificial sweeteners. Below is a comparative analysis:

- Fucoidan oligosaccharides (FOS): FOS have a sweetness level of 10–20% of sucrose, making them suitable for low-calorie applications. Their flavor profile is clean, with no bitter aftertaste, which is a common issue with some artificial sweeteners like stevia [37].

- Mannitol: With 50–70% of the sweetness of sucrose, mannitol provides a pleasant, cooling sensation in the mouth, making it ideal for sugar-free candies and chewing gums [38].
- Agaro-oligosaccharides (AOS): AOS offer about 30% of the sweetness of sucrose, along with a neutral flavor profile that blends well in beverages and dairy products [39].
- Ulvan oligosaccharides (UOS): UOS have a mild sweetness (approximately 20–30% of sucrose) and a slightly salty undertone, which can enhance the flavor complexity of savory foods and snacks [24].

These polysaccharides not only provide sweetness but also contribute functional properties, such as prebiotic effects, antioxidant activity, and texture enhancement, making them superior to conventional sweeteners in many applications.

3.6 Diabetic-friendly formulations

Macroalgae-derived polysaccharides are particularly well suited for diabetic-friendly formulations due to their low-glycemic index (GI) and metabolic compatibility. Key reasons include:

- Slow digestion and absorption: Polysaccharides like fucoidan, agar, and ulvan are resistant to human digestive enzymes, resulting in slow and controlled release of sugars. This prevents rapid spikes in blood glucose levels, making them ideal for diabetic diets [40].
- Insulin-independent metabolism: Mannitol, for example, is absorbed slowly in the intestine and metabolized independently of insulin, reducing the risk of hyperglycemia [41].
- Prebiotic effects: Many macroalgae polysaccharides, including FOS, AOS, and UOS, act as prebiotics, promoting the growth of beneficial gut bacteria. This not only supports gut health but also improves glucose metabolism and insulin sensitivity [42].

For instance, fucoidan oligosaccharides have been incorporated into diabetic-friendly beverages and snacks, providing sweetness without compromising blood sugar control [43]. Similarly, mannitol is widely used in sugar-free confectionery and baked goods, offering a safe and effective alternative to high-GI sweeteners [38].

3.7 Comparative insights

Fucoidan vs. Agar: While both fucoidan- and agar-derived oligosaccharides offer mild sweetness and prebiotic benefits, fucoidan has additional anti-inflammatory properties, making it more suitable for functional foods targeting metabolic syndrome [44]. Agar, on the other hand, is more versatile in gelling applications, allowing it to be used in a wider range of diabetic-friendly products like jellies and puddings [45].

Mannitol vs. Ulvan oligosaccharides: Mannitol provides a higher sweetness level and cooling effect, making it ideal for confectionery, while ulvan oligosaccharides offer a unique savory-sweet profile, suitable for innovative snacks and sauces.

4. Food texture and stability enhancers

Macroalgae-derived polysaccharides, such as carrageenan and alginate, are widely recognized for their ability to enhance food texture and stability. These natural hydrocolloids play a critical role in modern food formulations, particularly in dairy-free products, meat substitutes, and dessert gels. Their unique gelling, thickening, and emulsifying properties make them indispensable in creating products with desirable mouthfeel, consistency, and shelf stability. This section explores their applications, functional properties, and real-world examples in the food industry.

4.1 Carrageenan in dairy-free products

Carrageenan, extracted from red algae like *Chondrus crispus* and *Eucheuma*, is a key ingredient in dairy-free alternatives, such as plant-based milk, yogurt, and cheese. Its ability to form gels and stabilize emulsions makes it ideal for mimicking the creamy texture of dairy products [46]. For example, in almond milk, kappa-carrageenan forms a weak gel that prevents sedimentation of particles, ensuring a smooth and consistent texture [47].

4.2 Alginate in meat substitutes

Alginate, derived from brown algae like *Laminaria* and *Macrocystis*, is widely used in meat substitutes to improve texture and water retention. Its ability to form strong, heat-stable gels makes it suitable for creating plant-based burgers and sausages with a meat-like bite and juiciness [48]. For instance, alginate is used in the production of Beyond Meat products to enhance firmness and prevent moisture loss during cooking [49]. Alginate plays a crucial role in the texture and stability of plant-based meat products. *Beyond Meat*® uses alginate to bind ingredients and retain moisture, while *Impossible Foods*® incorporates carrageenan to enhance the fibrous texture of their burgers [49].

4.3 Dessert gels and confectionery

Both carrageenan and alginate are used in dessert gels, such as puddings, jellies, and custards, to provide a smooth and elastic texture. Iota-carrageenan, for example, forms soft, elastic gels that are ideal for dairy-based desserts, while sodium alginate is used in spherification techniques to create innovative textures like liquid-filled caviar pearls [50]. Carrageenan is used in vegan puddings and jellies to provide a smooth, gel-like texture without the need for animal-derived gelatin [51].

4.4 Emulsifying properties in dressings and sauces

Carrageenan and alginate are effective emulsifiers, preventing the separation of oil and water in dressings, sauces, and gravies. Lambda-carrageenan, with its high solubility and viscosity-enhancing properties, is commonly used in creamy salad dressings to maintain a homogeneous texture [52]. Similarly, propylene glycol alginate (PGA) is used in low-fat mayonnaise to stabilize the emulsion and provide a rich mouthfeel [53].

4.5 Plant-based milk

Carrageenan is widely used in commercial almond and oat milk products to stabilize the emulsion and improve mouthfeel. Brands like *Silk*® and *Oatly*® rely on carrageenan to prevent separation and create a smooth, creamy texture that mimics dairy milk [54].

5. Extraction and processing technique

The extraction and processing of macroalgae polysaccharides are critical steps in harnessing their functional and nutritional properties for food applications. These processes have evolved significantly over time, with traditional methods being supplemented or replaced by modern, more efficient techniques. This section explores the differences between conventional and modern extraction methods, highlights advancements in sustainable processing, and discusses the challenges of maintaining purity and quality control.

5.1 Conventional extraction methods

Traditional extraction techniques, such as aqueous extraction, have been widely used to obtain polysaccharides from macroalgae. These methods typically involve soaking the algae in hot water or alkaline solutions to dissolve the polysaccharides, followed by filtration and precipitation [55]. For example, carrageenan is traditionally extracted from red algae using hot water, while alginate is extracted from brown algae using sodium carbonate solutions [18]. Although these methods are simple and cost-effective, they often result in lower yields and may degrade heat-sensitive bioactive compounds [56].

5.2 Emerging extraction methods

- **Enzymatic hydrolysis:** Enzymatic methods use specific enzymes to break down algal cell walls and release polysaccharides under mild conditions, preserving their bioactivity. For instance, cellulases and proteases have been employed to extract ulvan from green algae with high efficiency and minimal degradation [57].
- **Microwave-assisted extraction (MAE):** MAE uses microwave energy to heat the algal biomass, accelerating the extraction process and improving yield [58]. This method is particularly effective for extracting fucoidan from brown algae, as it reduces processing time and energy consumption [59].
- **Supercritical fluid extraction (SFE):** SFE utilizes supercritical fluids, such as carbon dioxide, to extract polysaccharides under high pressure and temperature. This method is highly selective and environmentally friendly, making it suitable for obtaining high-purity compounds like laminarin [60].

These modern techniques offer advantages, such as higher yields, reduced processing times, and better preservation of bioactive properties, making them increasingly popular in the food industry.

5.3 Sustainability in processing

The growing demand for sustainable food production has driven innovations in eco-friendly processing techniques for macroalgae polysaccharides. Key advancements include:

- **Energy-efficient methods:** Techniques like MAE and SFE significantly reduce energy consumption compared to conventional methods, aligning with global sustainability goals [61].
- **Waste minimization:** By optimizing extraction parameters, modern methods maximize yield and minimize waste, ensuring efficient use of raw materials [62].
- **Green solvents:** The use of water-based or biodegradable solvents in extraction processes reduces environmental impact and enhances the safety of food products [63].
- **Circular economy approaches:** Some processing facilities are integrating macroalgae cultivation with wastewater treatment, using nutrient-rich wastewater to grow algae, which is then harvested for polysaccharide extraction [64].

These sustainable practices not only reduce the environmental footprint of macroalgae processing but also enhance the economic viability of the industry.

5.4 Purity and quality control

Maintaining consistent quality and purity of macroalgae polysaccharides is essential, especially for applications in health-sensitive food sectors. Key challenges include:

- **Variability in raw materials:** The chemical composition of macroalgae can vary depending on species, growing conditions, and harvesting time, leading to inconsistencies in polysaccharide quality [65].
- **Contaminant removal:** Impurities, such as heavy metals, proteins, and pigments, must be removed during processing to meet food safety standards. Techniques like ultrafiltration and ion-exchange chromatography are commonly used for this purpose [66].
- **Standardization of methods:** The lack of standardized extraction and purification protocols can result in variability in the final product. Establishing industry-wide standards is crucial for ensuring reproducibility and quality [67].
- **Analytical techniques:** Advanced analytical methods, such as high-performance liquid chromatography (HPLC) and nuclear magnetic resonance (NMR), are employed to characterize polysaccharides and verify their purity [68].

Addressing these challenges requires a combination of rigorous quality control measures, advanced processing technologies, and collaboration between researchers and industry stakeholders.

6. Health benefits and functional food potential

By selectively promoting the growth of beneficial bacteria, these prebiotic polysaccharides can contribute to several digestive health benefits:

- **Improved gut barrier function:** A healthy gut microbiota plays a crucial role in maintaining the integrity of the intestinal barrier. Prebiotic polysaccharides can strengthen the gut barrier by increasing the production of short-chain fatty acids (SCFAs) by beneficial bacteria. SCFAs have been shown to enhance gut barrier function and reduce intestinal permeability [69].
- **Improved immune function:** The gut-associated lymphoid tissue (GALT) is the largest immune organ in the body. A balanced gut microbiota is essential for proper immune function. Prebiotic polysaccharides can modulate the immune response by influencing the composition and activity of the gut microbiota [70].
- **Reduced risk of inflammatory bowel diseases (IBD):** IBDs such as Crohn's disease and ulcerative colitis are characterized by chronic inflammation of the gastrointestinal tract. Studies have shown that prebiotic polysaccharides can alleviate symptoms of IBD by reducing inflammation and improving gut barrier function [71].
- **Improved nutrient absorption:** A healthy gut microbiota is essential for the efficient absorption of nutrients from food. Prebiotic polysaccharides can enhance nutrient absorption by improving gut barrier function and modulating gut microbiota composition [72].

7. Future directions and innovations

Advances in biotechnology, particularly genetic engineering, are paving the way for optimizing algae yields and tailoring specific sugar profiles. Genetic modification techniques enable scientists to enhance sugar content and optimize their composition. Also, several challenges need to be addressed to fully realize the potential of algae-based sweeteners. Furthermore, consumer trends towards plant-based diets and health-oriented foods are driving innovation and acceptance of algae-based sweeteners. Consumers are increasingly seeking natural, healthy, and sustainable alternatives to traditional sweeteners like sugar. Algae-based sweeteners, with their potential health benefits and low environmental impact, align well with these consumer preferences.

7.1 Enhance productivity

By manipulating algal genomes, researchers can improve traits, such as growth rate, biomass yield, and stress tolerance. This can increase the efficiency of algae cultivation and production.

7.2 Optimize sugar composition

Genetic engineering allows for precise control over the types and amounts of sugars produced by algae. This is crucial for developing algae-based sweeteners with

specific functional properties, such as low-glycemic index or prebiotic effects. For example, researchers can modify algae to overproduce certain sugars like xylitol or mannitol, which have desirable properties for various applications.

7.3 Improve nutrient utilization

Genetic engineering can improve algae's ability to utilize nutrients more efficiently, reducing waste and minimizing environmental impact. This can be achieved by modifying genes involved in nutrient uptake and metabolism.

7.4 Scalability

Scaling up algae production to meet the demands of the food industry remains a significant challenge. Developing cost-effective and sustainable large-scale cultivation systems is crucial for commercial viability.

7.5 Flavor compatibility

Algae can have a distinct taste that may not be suitable for all applications. Research is ongoing to develop processing techniques and flavor masking strategies to improve the sensory properties of algae-based sweeteners.

7.6 Regulatory hurdles

The regulatory landscape for genetically modified organisms (GMOs) varies across different regions. Navigating regulatory approvals and ensuring consumer acceptance of GM algae can be complex.

7.7 Health benefits

Algae-based sweeteners, such as those derived from seaweeds like *Ulva* and *Laminaria*, offer potential health benefits beyond sweetness. They may have prebiotic properties, contribute to gut health, and provide essential nutrients.

7.8 Sustainability

Algae cultivation can be more sustainable than traditional agriculture, as it requires less land and water. Algae can also be cultivated in areas unsuitable for conventional agriculture, such as saltwater bodies.

7.9 Biotechnology innovation

The food industry is actively exploring innovative ways to incorporate algae-based sweeteners into various products, such as beverages, confectionery, and bakery items. Biotechnological advancements, coupled with a growing demand for natural and healthy sweeteners, are propelling the development of algae-based sweeteners. Addressing challenges related to scalability, flavor compatibility, and regulation will be crucial for their successful commercialization and widespread adoption.

8. Conclusion

Macroalgae present a vast and untapped potential as a sustainable source of natural sweeteners and functional food ingredients. Classified into red, green, and brown varieties, these marine organisms offer a unique array of bioactive compounds, including polysaccharides, such as agar, carrageenan, and ulvan. Historically utilized in Asian cuisines, macroalgae have found increasing applications in the global food industry as thickeners, stabilizers, and gelling agents. Red algae, rich in sulfated polysaccharides, are particularly valuable for their gelling properties, while green algae, like *Ulva*, contain ulvan, a polysaccharide with promising prebiotic and antioxidant characteristics. These compounds find applications beyond traditional culinary uses, extending into functional foods and nutraceuticals. In conclusion, macroalgae offer a sustainable and versatile solution for the food industry. Their unique properties, coupled with their abundance and renewability, make them an attractive alternative to synthetic additives. As research continues to uncover new applications and benefits of macroalgae-derived compounds, we can anticipate an increasing integration of these marine resources into our food systems, contributing to healthier and more sustainable diets.

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References

- [1] Elhafid N, editor. Biotechnological Applications of Seaweeds. Hauppauge, New York: Nova Science Publishers, Inc; 2017. 130 p. (Biotechnology in agriculture, industry and medicine)
- [2] Machado LP, Gasparoto MCDG, Santos Filho NA, Pavarini R. Seaweeds in the control of plant diseases and insects. In: Pereira L, Bahcevandziev K, Joshi NH, editors. Seaweeds as Plant Fertilizer, Agricultural Biostimulants and Animal Fodder. 1st ed. Boca Raton, FL: CRC Press; 2019. pp. 100-127. Available from: <https://www.taylorfrancis.com/books/9780429945120/chapters/10.1201/9780429487156-6>
- [3] Phillips GO, Williams PA. Handbook of hydrocolloids. 2nd ed. Boca Raton (Fla.) Oxford: CRC press Woodhead publ; 2009 (Woodhead publishing in food science, technology and nutrition)
- [4] Lee WK, Lim YY, Ho CL. *Gracilaria* as the major source of agar for food, health and biotechnology applications. In: Ranga Rao A, Ravishankar GA, editors. Sustainable Global Resources of Seaweeds Volume 2: Food, Pharmaceutical and Health Applications. Cham: Springer International Publishing; 2022. pp. 145-161. DOI: 10.1007/978-3-030-92174-3_7
- [5] Muthukumar J, Chidambaram R, Sukumaran S. Sulfated polysaccharides and its commercial applications in food industries—A review. Journal of Food Science and Technology. 2021;58(7):2453-2466
- [6] Kidgell JT, Magnusson M, De Nys R, Glasson CRK. Ulvan: A systematic review of extraction, composition and function. Algal Research. 2019;39:101422
- [7] Ahmed N, Sheikh MA, Ubaid M, Chauhan P, Kumar K, Choudhary S. Comprehensive exploration of marine algae diversity, bioactive compounds, health benefits, regulatory issues, and food and drug applications. Measurement: Food. 2024;14:100163
- [8] Hayes M. Chapter 14 - seaweeds: A nutraceutical and health food. In: Tiwari BK, Troy DJ, editors. Seaweed Sustainability. San Diego: Academic Press; 2015. pp. 365-387. Available from: <https://www.sciencedirect.com/science/article/pii/B9780124186972000143>
- [9] Saraswati GPE, Iskandriati D, Tan CP, Andarwulan N. *Sargassum* seaweed as a source of anti-inflammatory substances and the potential insight of the tropical species: A review. Marine Drugs. 2019;17(10):590
- [10] Hotchkiss S, Brooks M, Campbell R, Philp K, Trius A. The use of carrageenan in food. In: Carrageenans: Sources and Extraction Methods, Molecular Structure, Bioactive Properties and Health Effects. Hauppauge, NY, United States: Nova Science Publishers; 2016. pp. 229-243
- [11] Yerramathi BB, Muniraj BA, Kola M, Konidala KK, Arthala PK, Sharma TSK. Alginate biopolymeric structures: Versatile carriers for bioactive compounds in functional foods and nutraceutical formulations: A review. International Journal of Biological Macromolecules. 2023;253:127067
- [12] Nayar S, Bott K. Current status of global cultivated seaweed production and markets. World Aquaculture. 2014;45(2):32-37
- [13] Kadam SU, Álvarez C, Tiwari BK, O'Donnell CP. Chapter 9 - Extraction

- of biomolecules from seaweeds. In: Tiwari BK, Troy DJ, editors. *Seaweed Sustainability*. San Diego: Academic Press; 2015. pp. 243-269. Available from: <https://www.sciencedirect.com/science/article/pii/B978012418697200009X>
- [14] Devillé C, Gharbi M, Dandrifosse G, Peulen O. Study on the effects of laminarin, a polysaccharide from seaweed, on gut characteristics. *Journal of the Science of Food and Agriculture*. 2007;**87**(9):1717-1725
- [15] Karuppusamy S, Rajauria G, Fitzpatrick S, Lyons H, McMahon H, Curtin J, et al. Biological properties and health-promoting functions of Laminarin: A comprehensive review of preclinical and clinical studies. *Marine Drugs*. 2022;**20**(12):772
- [16] Li B, Lu F, Wei X, Zhao R. Fucoidan: Structure and bioactivity. *Molecules*. 2008;**13**(8):1671-1695
- [17] Wang Y, Xing M, Cao Q, Ji A, Liang H, Song S. Biological activities of fucoidan and the factors mediating its therapeutic effects: A review of recent studies. *Marine Drugs*. 2019;**17**(3):183
- [18] Bojorges H, López-Rubio A, Martínez-Abad A, Fabra MJ. Overview of alginate extraction processes: Impact on alginate molecular structure and techno-functional properties. *Trends in Food Science and Technology*. 2023;**140**:104142
- [19] Abourehab MAS, Rajendran RR, Singh A, Pramanik S, Shrivastav P, Ansari MJ, et al. Alginate as a promising biopolymer in drug delivery and wound healing: A review of the state-of-the-art. *International Journal of Molecular Sciences*. 2022;**23**(16):9035
- [20] Tuvikene R. Carrageenans. In: *Handbook of Hydrocolloids*. Amsterdam, Netherlands: Elsevier; 2021. pp. 767-804. Available from: <https://linkinghub.elsevier.com/retrieve/pii/B9780128201046000061>
- [21] Udo T, Mummaleti G, Mohan A, Singh RK, Kong F. Current and emerging applications of carrageenan in the food industry. *Food Research International*. 2023;**173**:113369
- [22] Padmesh S, Singh A. Agars: Properties and applications. In: Inamuddin Ahamed MI, Boddula R, Altalhi T, editors. *Polysaccharides*. 1st ed. Hoboken, NJ, USA: Wiley; 2021. pp. 75-93. Available from: <https://onlinelibrary.wiley.com/doi/10.1002/9781119711414.ch5>
- [23] Armisen R, Gaiatas F. Agar. In: *Handbook of Hydrocolloids*. Cambridge, UK: Elsevier; 2009. pp. 82-107. Available from: <https://linkinghub.elsevier.com/retrieve/pii/B9781845694142500047>
- [24] Li C, Tang T, Du Y, Jiang L, Yao Z, Ning L, et al. Ulvan and *Ulva* oligosaccharides: A systematic review of structure, preparation, biological activities and applications. *Bioresources and Bioprocessing*. 2023;**10**(1):66
- [25] Flórez-Fernández N, Rodríguez-Coello A, Latire T, Bourgougnon N, Torres MD, Buján M, et al. Anti-inflammatory potential of ulvan. *International Journal of Biological Macromolecules*. 2023;**253**:126936
- [26] Bayu A, Warsito MF, Putra MY, Karnjanakom S, Guan G. Macroalgae-derived rare sugars: Applications and catalytic synthesis. *Carbon Resources Conversion*. 2021;**4**:150-163
- [27] Kraan S. Algal polysaccharides, novel applications and outlook. In: Chang CF, editor. *Carbohydrates - Comprehensive Studies on Glycobiology and Glycotechnology*. London, UK: InTech; 2012. Available from:

<http://www.intechopen.com/books/carbohydrates-comprehensive-studies-on-glycobiology-and-glycotechnology/algal-polysaccharides-novel-applications-and-outlook>

[28] Venkatesan J, Lowe B, Anil S, Manivasagan P, Kheraif AAA, Kang K, et al. Seaweed polysaccharides and their potential biomedical applications. *Starch Stärke*. 2015;**67**(5-6):381-390

[29] Huang A, Wu X, Lu F, Liu F. Sustainable production of *Ulva* oligosaccharides via enzymatic hydrolysis: A review on Ulvan Lyase. *Food*. 2024;**13**(17):2820

[30] Pradhan B, Bhuyan PP, Ki JS. Immunomodulatory, antioxidant, anticancer, and pharmacokinetic activity of Ulvan, a seaweed-derived sulfated polysaccharide: An updated comprehensive review. *Marine Drugs*. 2023;**21**(5):300

[31] Tanna B, Mishra A. Metabolites unravel nutraceutical potential of edible seaweeds: An emerging source of functional food. *Comprehensive Reviews in Food Science and Food Safety*. 2018;**17**:1613-1624

[32] Senni K, Gueniche F, Foucault-Bertaud A, Igondjo-Tchen S, Fioretti F, Collic-Jouault S, et al. Fucoidan a sulfated polysaccharide from brown algae is a potent modulator of connective tissue proteolysis. *Archives of Biochemistry and Biophysics*. 2006;**445**(1):56-64

[33] Ren X, Cai S, Zhong Y, Tang L, Xiao M, Li S, et al. Marine-derived fucose-containing carbohydrates: Review of sources, structure, and beneficial effects on gastrointestinal health. *Food*. 2024;**13**(21):3460

[34] Hosseini SV, Dastgerdi HE, Tahergorabi R. Marine mannitol:

Extraction, structures, properties, and applications. *PRO*. 2024;**12**(8):1613

[35] Chen X, Fu X, Huang L, Xu J, Gao X. Agar oligosaccharides: A review of preparation, structures, bioactivities and application. *Carbohydrate Polymers*. 2021;**265**:118076

[36] Coste O, Malta E, Jan, López JC, Fernández-Díaz C. Production of sulfated oligosaccharides from the seaweed *Ulva* sp. using a new ulvan-degrading enzymatic bacterial crude extract. *Algal Research*. 2015;**10**:224-231

[37] Bulya ET, Alqubelat RS, Rao AR. Nutritional benefits of fucoidan and its applications (a review). *Russian Journal of Bioorganic Chemistry*. 2024;**50**(6):2107-2133

[38] Deis RC, Kearsley MW. Sorbitol and Mannitol. In: O'Donnell K, Kearsley MW, editors. *Sweeteners and Sugar Alternatives in Food Technology*. 1st ed. Chichester, West Sussex, UK: Wiley; 2012. pp. 331-346. Available from: <https://onlinelibrary.wiley.com/doi/10.1002/9781118373941.ch15>

[39] King BM, Arents P, Bouter N, Duineveld CA, Meyners M, Schroff SI, et al. Sweetener/sweetness-induced changes in flavor perception and flavor release of fruity and green character in beverages. *Journal of Agricultural and Food Chemistry*. 2006;**54**(7):2671-2677

[40] Cotas J, Lomartire S, Pereira L, Valado A, Marques JC, Gonçalves AMM. Seaweeds as nutraceutical elements and drugs for diabetes mellitus: Future perspectives. *Marine Drugs*. 2024;**22**(4):168

[41] Bocanegra A, Macho-González A, Garcimartín A, Benedí J, Sánchez-Muniz FJ. Whole alga, algal extracts, and compounds as ingredients of

functional foods: Composition and action mechanism relationships in the prevention and treatment of Type-2 diabetes mellitus. *International Journal of Molecular Sciences*. 2021;22(8):3816

[42] Wang S, Zhang B, Chang X, Zhao H, Zhang H, Zhao T, et al. Potential use of seaweed polysaccharides as prebiotics for management of metabolic syndrome: A review. *Critical Reviews in Food Science and Nutrition*. 2024;64(22):7707-7727

[43] Lu LW, Chen JH. Seaweeds as ingredients to lower glycemic potency of cereal foods synergistically—A perspective. *Food*. 2022;11(5):714

[44] Akter A, Sobuj MKA, Islam MS, Chakroborty K, Tasnim N, Ayon MH, et al. Seaweed polysaccharides: Sources, structure and biomedical applications with special emphasis on antiviral potentials. *Future Foods*. 2024;10:100440

[45] Riedel R, Böhme B, Rohm H. Development of formulations for reduced-sugar and sugar-free agar-based fruit jellies. *International Journal of Food Science and Technology*. 2015;50:1338-1344

[46] Campos BMF. Development of Semi-Hard Goat's Cheese and Plant-Based Cheese Supplemented with Seaweeds. PhD Thesis. Portugal: Universidade NOVA de Lisboa; 2022

[47] Yuan CR, Steele MN, Morrison NA, Chinn BL. Protein stabilizer systems comprising carrageenan for weakly acidic flavored milk drinks (European Union Patent EP2456317A2). 2012. Available from: <https://patents.google.com/patent/EP2456317A2/en>

[48] Wannasin D, Ryu J, McClements DJ. Innovative method for producing plant-based meat analogs: Acid/calcium-induced internal gelation of potato protein/alginate composites.

International Journal of Biological Macromolecules. 2024;270:132069

[49] Kyriakopoulou K, Keppler JK, van der Goot AJ. Functionality of ingredients and additives in plant-based meat analogues. *Food*. 2021;10(3):600

[50] Kuban State Technological University, Zhuravlev RA, Tamova MY, Kuban State Technological University, Bugayets NA, Kuban State Technological University, et al. Innovative encapsulation technology of food systems using a by-product of dairy production. *FRM*. 2017;5(1):81-89

[51] Peace Rhind J, Law G. *Cooking for the Senses: Vegan Neurogastronomy*. London: Jessica Kingsley Publishers; 2018. 1 p.

[52] Liao YC, Chang CC, Nagarajan D, Chen CY, Chang JS. Algae-derived hydrocolloids in foods: Applications and health-related issues. *Bioengineered*. 2021;12(1):3787-3801

[53] Pournaki SK, Aleman RS, Hasani-Azhdari M, Marcia J, Yadav A, Moncada M. Current review: Alginate in the food applications. *J*. 2024;7(3):281-301

[54] Pandalaneni K, Kahraman O, Kahraman O, Ding J, Kapoor R, Feng H. Plant-based foods. In: *Smart Food Industry: The Blockchain for Sustainable Engineering*. Boca Raton, FL, USA: CRC Press; 2024

[55] Olatunji O. *Aquatic Biopolymers: Understanding their Industrial Significance and Environmental Implications*. Cham: Springer International Publishing; 2020 (Springer Series on Polymer and Composite Materials). Available from: <http://link.springer.com/10.1007/978-3-030-34709-3>

- [56] Hernández-Carmona G, Freile-Pelegrín Y, Hernández-Garibay E. Conventional and alternative technologies for the extraction of algal polysaccharides. In: *Functional Ingredients from Algae for Foods and Nutraceuticals*. Cambridge, UK: Elsevier; 2013. pp. 475-516. Available from: <https://linkinghub.elsevier.com/retrieve/pii/B978085709512150014X>
- [57] Parsaeimehr A, Ozbay G. Enzymatic processing of algae for food applications. *Biocatalysis and Agricultural Biotechnology*. 2024;**56**:103042
- [58] Spagnuolo D, Di Martino A, Zammuto V, Armeli Minicante S, Spanò A, Manghisi A, et al. Conventional vs. innovative protocols for the extraction of polysaccharides from macroalgae. *Sustainability*. 2022;**14**(10):5750
- [59] Mussatto SI. Microwave-assisted extraction of Fucoidan from marine algae. *Methods in Molecular Biology*. 2015;**1308**:151-157
- [60] Cheriyan BV, Karunakar KK, Anandakumar R, Murugathirumal A, kumar AS. Eco-friendly extraction technologies: A comprehensive review of modern green analytical methods. *Sustainable Chemistry for Climate Action*. 2025;**6**:100054
- [61] Bello U, Adamu H, Amran NA, Qamar M. Green extraction technologies: Process systems, techno-economic and lifecycle analyses. *Cleaner Engineering and Technology*. 2025;**100881** (In press)
- [62] Behrooznia Z, Nourmohammadi J. Polysaccharide-based materials as an eco-friendly alternative in biomedical, environmental, and food packaging. *Giant*. 2024;**19**:100301
- [63] Lim C, Yusoff S, Ng CG, Lim PE, Ching YC. Bioplastic made from seaweed polysaccharides with green production methods. *Journal of Environmental Chemical Engineering*. 2021;**9**(5):105895
- [64] Pardilhó S, Cotas J, Pereira L, Oliveira MB, Dias JM. Marine macroalgae in a circular economy context: A comprehensive analysis focused on residual biomass. *Biotechnology Advances*. 2022;**60**:107987
- [65] Wu JY, Tso R, Teo HS, Haldar S. The utility of algae as sources of high value nutritional ingredients, particularly for alternative/complementary proteins to improve human health. *Frontiers in Nutrition*. 2023;**10**:1277343
- [66] Caballero E, Flores A, Olivares A. Sustainable exploitation of macroalgae species from Chilean coast: Characterization and food applications. *Algal Research*. 2021;**57**:102349
- [67] Salehi M, Rashidinejad A. Multifaceted roles of plant-derived bioactive polysaccharides: A review of their biological functions, delivery, bioavailability, and applications within the food and pharmaceutical sectors. *International Journal of Biological Macromolecules*. 2025;**290**:138855
- [68] Zhou QL, Wang Z, Chen WT, Liu XF, Cheong KL, Zou YX, et al. The structural characteristics, biological activities and mechanisms of bioactive brown seaweed polysaccharides: A review. *Journal of Functional Foods*. 2024;**119**:106303
- [69] Victoria Obayomi O, Folakemi Olaniran A, Olugbemiga OS. Unveiling the role of functional foods with emphasis on prebiotics and probiotics in human health: A review. *Journal of Functional Foods*. 2024;**119**:106337
- [70] Shannon E, Conlon M, Hayes M. Seaweed components as potential modulators of the gut microbiota. *Marine Drugs*. 2021;**19**(7):358

[71] Liyanage NM, Nagahawatta DP, Jayawardena TU, Jeon YJ. The role of seaweed polysaccharides in gastrointestinal health: Protective effect against inflammatory bowel disease. *Life (Basel)*. 2023;**13**(4):1026

[72] Zhan J, Liu K, Yu H, Xing R, Liu S, Chen X. Bridging seaweed-derived polysaccharides and gut health: An integrated perspective on intestinal morphology, microbiota, and immunity. *Process Biochemistry*. 2025;**151**:146-151

Nixtamalized Corn Stew Gordita: A Traditional Mexican Delicacy from Zacatecas

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Abstract

This chapter explores the *nixtamalized corn stew gordita*, a traditional dish from Zacatecas, highlighting the centuries-old process of nixtamalization and its cultural significance. Beginning with traditional nixtamalization and the detailed preparation of gorditas, the chapter examines how this method enhances flavor, texture, and nutritional value. The second section introduces extrusion technology as an innovative alternative, demonstrating its ability to modernize nixtamalization while preserving essential qualities. Extrusion offers several advantages, including greater production efficiency, consistent product quality, and reduced water and energy consumption, making it a sustainable option for large-scale manufacturing. Extrusion also allows precise control over texture and nutrient retention, ensuring a final product that resembles traditionally made gorditas. The *nixtamalized corn stew gordita* is a unique Mexican dish cooked in a wood-fired oven, featuring a crispy exterior and a soft, moist interior. Using a wood oven enhances the gordita's flavor by imparting a distinct smoky aroma and a golden-brown crust, which is difficult to achieve with other cooking methods. The high, even heat distribution allows for better caramelization, improving both taste and texture. Additionally, wood-fired cooking is an energy-efficient, natural method that aligns with traditional cooking practices, preserving authenticity while minimizing artificial processing. Made from nixtamalized corn masa, this dish benefits from improved digestibility and enhanced mineral availability. Traditionally enjoyed during celebrations, they symbolize culinary heritage while offering opportunities for innovation through modern processing techniques.

Keywords: Nixtamalization, corn stew gordita, corn masa, extrusion, nixtamalized instant corn flour

1. Introduction

Maize, an ancient plant domesticated and originally cultivated in Mexico, has been a staple of Mexican cuisine since pre-Columbian times [1]. The inhabitants of Mexico have relied on maize as a key ingredient in their stews and traditional dishes. Across the Mesoamerican region, diverse maize varieties have been cultivated for centuries,



Figure 1.
Detail of texture of corn stew gordita just baked.

playing a pivotal role in the advent of formal agriculture and the rise of early civilizations, including the Mexica, Totonac, and Zapotec cultures [2]. Several theories have been proposed regarding the origin of maize, with the most widely accepted suggesting that maize evolved from the ancient teosinte plant, including *Zea luxurians* and related groups [1]. Today, more than 200 races of maize are recognized globally, with approximately 60 specifically associated with Mexico.

Corn stew gordita is a delicious traditional Mexican dish known for its authentic flavor and versatility. Its key component is masa, prepared from corn grain and cooked in an oven until a crispy texture is achieved inside and out. Gorditas are filled traditionally with various ingredients, such as cheese, meat, guacamole, or salsa, and are enjoyed across Mexico as shown in **Figure 1**. In Zacatecas, gorditas are often filled with chorizo, refried beans, and melted cheese with chile chilaca, a combination cherished by families in Mexico and among the Latin American population settled in various cities across the United States [3].

Gorditas have a rich and extensive history deeply rooted in Mexican cuisine. Originally crafted in the central region of Mexico, this delicious dish has undergone dynamic transformations over the years, earning a prominent place in the country's culinary diversity. More details about the traditional process using wood ovens are available in Video 1 (<https://bit.ly/4hNQESV>). Gorditas are primarily prepared using corn masa, obtained through the nixtamalization process (TNP). Their versatility makes them suitable for being used on many occasions, from breakfast to dinner, and they hold a special presence in cultural celebrations and family festivals, reflecting the essence of Mexican gastronomic culture [4].

2. Traditional nixtamalization process for gorditas

2.1 Preparing nixtamalized corn

Boiling corn kernels with calcium hydroxide (lime) enhances their nutritional value and facilitates processing by improving protein quality and increasing the bioavailability of niacin and iron. Additionally, this process reduces the required cooking temperature and enhances hydration during the steeping phase, which lasts between 8 and 16 hours, as shown in **Figure 2**. Steeping allows the lime to penetrate the corn, improving both texture and flavor [5]. The traditional nixtamalization process also promotes gradual starch gelatinization and enhances the viscoelastic behavior of the masa.



Figure 2.
Cooking of corn kernel.

The preparation of corn involves cooking dried grains in an alkaline solution, typically water and edible lime (calcium hydroxide) [6]. The corn is heated to approximately 92°C and cooked for 45 minutes. After cooking, the nixtamal is removed from the heat and left to rest for 12 hours [7]. Cold water is then added, followed by a rinsing and carving process to remove the pericarp. Partial pericarp removal can help reduce mycotoxin intake [6]. Finally, the nixtamal is washed to eliminate loose husks and lime residues.

During nixtamalization, starch undergoes structural modifications, with calcium interacting primarily with amylose, delaying gelatinization. Gelatinized corn starch due to alkaline cooking enhances the flexibility, rollability, and structural consistency of nixtamalized products [5, 8]. Rinsing and grinding nixtamal to produce masa (corn dough) is essential for achieving optimal moisture, extensibility, and resistance as shown in **Figure 3** [9].

The process of washing the pericarp (husks) from nixtamal grains determines the “washing ratio”, which refers to the amount of husks removed. When preparing corn stew gorditas, it is advisable to leave some husks intact, as they contain natural gums that help bind the dough. According to Mora-Rochin et al. [10], a 50% washing ratio is recommended as a starting point.

The resistance of masa is influenced by maize type and physicochemical characteristics, including kernel hardness, water absorption capacity, and degree of gelatinization [11–13]. Additionally, the adhesiveness and cohesiveness of masa are directly



Figure 3.
Washing of nixtamal.

affected by starch granule properties, requiring careful control during cooking to achieve the desired texture and consistency.

2.2 Dough preparation and resting

Combining nixtamalized masa with water and salt creates a soft, malleable dough. Achieving the ideal consistency requires a careful balance between the mechanical work of the volcanic stone mill and the operator's expertise as shown in **Figure 4**. Excess water can cause issues with the metal screen, leading to masa sticking and clogging the equipment, while insufficient water results in a dry, crumbly dough, producing tortillas that lack the desired texture and pliability [14, 15]. Additionally, Chel-Guerrero et al. [16] identified significant differences in hydration and machinability between traditional corn masa formulations and those incorporating other flours, such as cassava and Malanga.

Resting nixtamalized masa for approximately 10 minutes is a critical step in preparing corn-based products, as it allows for proper hydration and structural development of the dough. In the resting period, the starch granules fully absorb water, improving the masa's cohesiveness and elasticity. Research published by Narváez-González et al. [17] indicates that the hardness of corn kernel impacts water absorption during nixtamalization, ultimately affecting the dough's properties. By allowing the masa to rest, the water interacts more effectively with the gelatinized starch, resulting in a dough that is easier to shape and less prone to cracking. This step is essential for achieving the desired texture and pliability in the final product [18]. The kneading is done in a wooden pan or plastic container to which vegetable oil or lard, salt, and baking powder are added; it is adjusted until the final consistency is achieved by beating the dough manually or with a mixer until it is ready to be used in the preparation of corn stew gorditas.

2.3 Forming and filling the gorditas

This step involves shaping the dough into small balls, flattening them into discs, and filling them with traditional ingredients such as beans, cheese, or chili strips. The edges are then manually pressed to seal the gorditas. This delicious dish is widely enjoyed in Mexico and Central America and by many people in the United States. The demand is particularly high among those who feel less connected to American cuisine, often associated with fast food such as hot dogs, tacos, pizza, and burgers.



Figure 4.
Grinding and kneading of nixtamal to produce masa.

As a result, many people transport frozen gorditas by airplane, bus, or car to enjoy them abroad. **Figure 5** explains the forming and filling of corn stew gorditas.

The dough is obtained through grinding and is then ready to be kneaded and shaped into flat disks, characteristic of the region. These are later filled with various stews, such as beans with red chili, chili slices with cheese, or beef and pork stews. This process not only produces a versatile dough but also preserves the additional nutrients released during nixtamalization, enhancing the final nutritional value of the product.

2.4 Baking in a wood-fired oven

Corn gorditas baked in a wood-fired oven capture the essence of traditional Mexican cuisine, offering a distinctive smoky aroma and rich flavor that modern baking methods often lack. The intense, even heat of the wood fire ensures a perfectly



Figure 5.
Forming and filling of corn stew gordita.



Figure 6.
Cooking.

crisp outer layer while keeping the inside soft and tender. For an enhanced golden finish and a slight crunch, gorditas can be brushed with oil before baking. The gorditas are cooked in a clay oven and placed on previously greased sheets of foil. The oven temperature ranges between 180 and 200°C, with a baking time of approximately 15–25 minutes. This process results in corn stew gorditas with appealing sensory characteristics, making them ready for consumption as shown in **Figure 6**.

The final texture of the gordita is crucial, as it undergoes several physicochemical and morphological changes in the starch molecules. Its outer surface is crispy and golden-yellow, while the inner portion remains soft and moist, similar to a tamal. This textural contrast results from the temperature profile during the baking process in the wood oven.

3. Traditional nixtamalization: Nutritional textural and sensory impact on maize-based products

Nixtamal, masa, and “gorditas” are derived from various processes, including traditional nixtamalization, industrial production of fresh masa, and dry masa flour. These nixtamalized maize-based products are traditionally made using three basic ingredients: maize, water, and lime, with industrial versions adding minor additives. Variations in methods and ingredients influence their nutritional, textural, and sensory qualities [19, 20].

3.1 Nutritional benefits of nixtamalization

Traditional nixtamalization enhances maize nutrition by increasing soluble fiber, resistant starch, and calcium bioavailability.

- **Enhanced Calcium Bioavailability:** Calcium accumulates as calcium carbonate in the pericarp, and heat and soaking enhance its diffusion into the endosperm. As temperature and soaking time increase, hydrolysis and solubilization of pericarp components also rise, forming microholes that further facilitate calcium diffusion. Lime-treated corn contains 2.9 times more calcium, with up to 85% bioavailability, contributing to the growth and maintenance of healthy bones. Nixtamalization undoubtedly helps prevent deficiencies like rickets and osteoporosis [5, 21, 22].
- **Improved Digestibility and Protein Quality:** Nixtamalization improves digestibility and boosts essential amino acids like lysine, tryptophan, and niacin. While corn lacks these nutrients, the process to make “gorditas” enhances their availability, increasing the protein efficiency ratio (PER) and the biological value of corn protein, making it an important contributor to human nutrition.
- **Prevention of Micronutrient Deficiencies:** Nixtamalization also plays a crucial role in preventing micronutrient deficiencies, particularly pellagra, by increasing niacin bioavailability. In raw corn, niacin is bound to complex molecules and unavailable for absorption. The alkaline cooking process breaks these bonds, converting niacin into its bioavailable form, nicotinic acid, a bioavailable form of vitamin B₃ that the human body can readily absorb and utilize [5, 19, 22].
- **Dietary Fiber Modification and Gut Health:** Nixtamalization modifies dietary fiber and promotes resistant starch formation, which resists digestion and

ferments in the colon, producing short-chain fatty acids (SCFAs) such as butyric, propionic, and acetic acids that support colon health and reduce colorectal cancer risk [5]. Though fiber loss occurs during cooking, the remaining soluble fiber, mainly arabinoxylans, enhances prebiotic properties and gut health [20, 23].

- **Impact on Bioactive Compounds and Antioxidants:** Nixtamalization reduces bioactive compounds and antioxidant capacity. While raw corn is rich in phenolics, carotenoids, and phytosterols, processing can cause significant nutrient loss, decreasing total phenolic compounds by 35–45% [6], antioxidant activity by 0.5–14% [10], anthocyanin content by 46–88% [7], β -carotene, lutein, zeaxanthin between 38 and 65%, and β -cryptoxanthin by 84% [6]. This highlights the need for maize varieties that retain nutritional quality during processing. These compounds are essential in enhancing health and reducing oxidative stress, a key factor in chronic diseases [23, 24].

3.2 Textural and sensory characteristics of traditionally nixtamalized products

Nixtamalization enhances the sensory qualities of maize-based foods like gorditas, influencing color, flavor, texture, and aroma. The lime treatment and steeping modify taste and texture while baking deepens flavor and browning through Maillard reactions. These attributes contribute to the unique appeal, and cultural and culinary significance of nixtamalized corn-based foods [22, 25].

One of the most noticeable changes during nixtamalization is the yellowing of the pericarp, which significantly influences the color of nixtamal, masa, and, consequently, the “gordita’s consistency”. This may result from lignin oxidation or flavonoid transformation in alkaline conditions. The type of maize used also impacts the final color, while processing methods such as baking further influence color development through Maillard reactions [19, 21].

Flavor development in nixtamalized products is shaped by maize variety and processing techniques. Native varieties are often preferred for their superior flavor. The lime treatment enhances the distinctive flavor while cooking and steeping releases volatile compounds. Baking further enriches the flavor through browning reactions, contributing to the final gordita’s sensory appeal [19, 22].

Water absorption during nixtamalization is crucial for nixtamal and masa quality, influenced by pericarp permeability, grain structure, and processing conditions. Softer grains absorb water faster, aiding gelatinization, while harder grains need longer cooking. Proper hydration ensures the desired masa consistency, as excess water makes it too sticky and adhesive “gorditas” production. Grain structure affects texture, requiring adjustments in cooking time, lime concentration, and steeping conditions [21, 22].

The texture of masa and gorditas is shaped by nixtamalization. Arabinoxylans enhance viscoelasticity, but excessive hydrolysis can cause pericarp loss. Overcooking or steeping leads to over-gelatinized nixtamal, making masa too sticky and prone to faster staling. Additionally, the degree of starch gelatinization and the formation of crosslinks between starch chains and calcium during nixtamalization are critical in determining the handling properties of masa. These structural changes confer the elasticity and pliability required for “gorditas” production while ensuring that the final product maintains its characteristic texture.

Moisture loss (10–12%) during baking transforms masa into “gorditas” and promotes starch gelatinization, protein denaturation, and flavor and color development.

Baking also sterilizes the product while creating a crispy exterior and a soft, pliable interior, defining its characteristic taste [5, 21, 22].

4. Environmental impact of the traditional nixtamalization process

The traditional nixtamalization process (TNP) is a highly polluting due to its high water consumption and waste generation. It requires about 3 liters of water with 1–2% calcium hydroxide per kilogram of corn, producing large amounts of nejayote waste. In Mexico alone, nearly 14,800 million liters of nejayote are generated annually, posing a significant environmental challenge [26].

The wastewater exhibits extremely high pollutant concentrations, including biological oxygen demand (BOD: 14,219 mg/L), total suspended solids (8342 mg/L), chemical oxygen demand (COD: 40,058 mg O₂/L), alkalinity (5768 mg CaCO₃/L), pH levels ranging from 8 to 12, and calcium hydroxide concentration approximately 13.09%. Most small-scale processors discharge nejayote directly into sewage systems, contributing to environmental degradation [25, 27].

These metrics reflect the substantial environmental load associated with nejayote, affecting economic, ecological, nutritional, and public health dimensions. Furthermore, the TNP is highly resource-intensive, requiring significant time, water, and energy.

The transition to sustainable nixtamalization methods is essential to meet the growing demand for maize-based products like “gorditas” while reducing the environmental and nutritional drawbacks of the traditional nixtamalization process.

4.1 Alternative process for nixtamalization

Innovative methods such as extrusion, ohmic heating, microwave processing, and infrared cooking have emerged as promising alternatives for producing corn masa and dry masa flour (DMF) and other nixtamalized maize products. These novel approaches offer significant advantages over traditional nixtamalization processes, primarily by reducing energy and water consumption and requiring less industrial space. An important benefit of these green technologies is wastewater reduction, removing the need to manage or treat high-alkaline effluents, a critical drawback of traditional nixtamalization processes [26].

Modern consumers are shifting toward nontraditional corn-based foods like fast food, cereals, and extruded nixtamalized snacks. This trend presents opportunities and challenges for emerging nixtamalization technologies, which must balance efficiency and sustainability.

4.2 Introduction to extrusion technology

Extrusion technology has emerged as an important tool in food production, standing out for its efficiency, versatility, and ability to transform raw materials into products with desired physical-chemical properties. This process combines thermal and mechanical energy to produce a semi-solid mass that passes through a die, acquiring defined shapes and textures [24].

This method integrates multiple stages, including heating, mixing, and material transport. Controlled temperatures and humidity levels enable efficient starch gelatinization and cooking. Key operational factors, such as corn particle size, flour granulometry, and screw speed, significantly impact product quality. Optimizing

these parameters ensures consistent materials with functional properties suited for various food applications [26].

In the context of industrial nixtamalization, extrusion offers an innovative solution by addressing the challenges associated with the traditional process.

4.3 Comparison between traditional and extrusion-based nixtamalization

Traditional and extrusion-based nixtamalization differ significantly in nutritional, sensorial, economic, and environmental impacts.

The extrusion process applies high pressure and temperatures (100–180°C) with humidity levels of 20–30%. Whole cornmeal or refined corn grits are mixed with lime, conditioned for high moisture content, and fed into an extruder. A rotating screw transports the mixture through a stationary barrel, accelerating cooking and chemical reactions. The resulting semi-solid mass is shaped through a die, with optional cooling to prevent over-gelatinization. Unlike traditional methods requiring hours, extrusion completes the process in minutes. The extrudate is dried to 10–12% moisture and then milled into dry masa flour with different granulations tailored for various applications. [28].

Extrusion-based nixtamalization differs from the traditional method in several key aspects:

- **Sensory:** Foods made with extruded flours differ in flavor, texture, and aroma. While this poses a challenge, it also allows the development of new sensory profiles appealing to diverse consumer segments [29, 30].
- **Nutritional:** Extrusion preserves bioactive compounds and dietary fiber lost in traditional nixtamalization due to its shorter cooking time and the absence of alkaline water discharges [31, 32].
- **Economic:** The process improves resource efficiency by eliminating nejayote, reducing waste treatment costs, and lowering water and energy consumption, making it more accessible for small and medium-sized producers [26].
- **Sustainability:** Unlike traditional nixtamalization, which generates over 14.8 billion liters of nejayote annually in Mexico, extrusion produces no liquid waste, significantly reducing its environmental impact [26].
- **Traditional nixtamalization** has partial gelatinization and retrogradation [33]. **Extrusion** has a sudden gelatinization and retrogradation due to high temperatures [34].
- **Traditional nixtamalization** has a proper cooking and resting time (pericarp removal). **Extruded products** experience rapid cooking time with low moisture.
- The formation of resistant starch [35] and damaged starch [33] occurs due to the fragmentation and fusion of starch granules. However, traditional nixtamalization exhibits a lower degree of starch damage compared to Extrusion [36].

A comparison between traditional nixtamalization process and extrusion is shown in **Figure 7**.

Although both technologies have advantages and limitations, extrusion is a viable alternative for nixtamalization, especially where sustainability, efficiency,

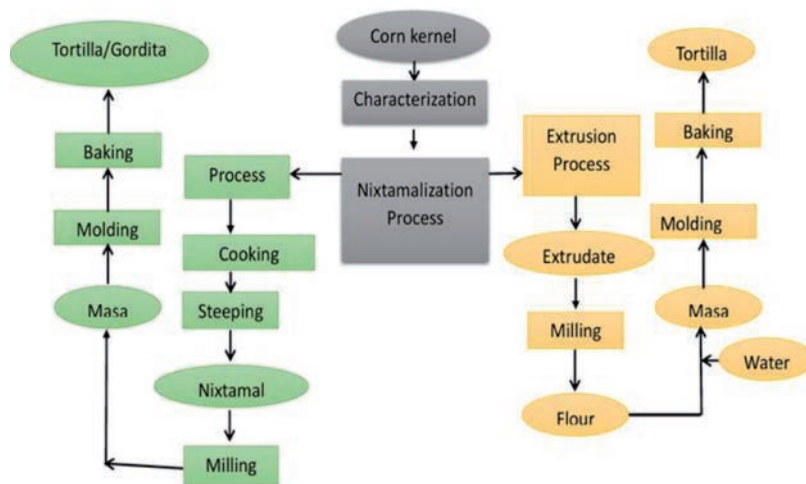


Figure 7.
Flow diagram for traditional nixtamalization process and extrusion.

and innovation are priorities. Successful implementation requires understanding operational variables to balance consumer expectations, quality, and environmental impact. By optimizing these variables, it is possible to produce fresh dough or nixtamalized dry flour with excellent quality, suitable for “gorditas” production. Low-shear extruders are recommended to prevent excessive starch damage, preserving the final product’s desirable texture and functional properties.

4.4 Challenges of extrusion-based nixtamalization

Although extrusion offers many advantages for nixtamalized flour production, studies show that the resulting products often lack the texture, flavor, and aroma of traditionally nixtamalized flour. This has slowed industrial adoption, as the process struggles to replicate the functionality and organoleptic properties of the traditional nixtamalization process [25, 37].

High temperatures and shear forces during extrusion can cause starch dextrinization, increasing solubility but reducing viscosity. This results in overly sticky doughs with poor firmness, and pliable texture of traditional masa [8, 9, 26]. These physical and chemical changes negatively impact the properties of the resulting nixtamalized dough. For instance, the unique qualities of traditionally prepared masa favor the production of “gorditas” with the desired texture and flavor, which remain difficult to achieve with this emerging technique. Further research and innovation are needed to refine extrusion processes, preserving traditional sensory attributes while adapting to modern dietary trends.

5. Conclusions

Our study on nixtamalization highlights significant variations in the thermal-alkaline process used in the preparation of “gorditas”, a traditional dish from Zacatecas, underscoring the need for further research in this area. The importance of the physical and chemical changes that occur during this process in human nutrition is undeniable. Understanding the functionality and preparation of gorditas is important to avoid

the loss of the enormous nutritional and nutraceutical benefits that come with the consumption of traditional nixtamalized corn products. In recent years, emerging technologies such as extrusion have been employed to produce nixtamalized flours for various Mexican dishes. These innovations aim to preserve the inherent nutritional benefits of corn while preserving the organoleptic characteristics of the traditional process. Additionally, extrusion offers benefits, including reduced environmental impact, improved nutritional retention, and enhanced efficiency. The transition to extrusion-based nixtamalization is essential for meeting the growing demand for maize-based products while preserving cultural authenticity and addressing sustainability concerns.

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References

- [1] Pérez Ruiz RV, Aguilar-Toalá JE, Cruz-Monterrosa RGC, Amor AAR, Rodríguez MH, Villasana YC, et al. Mexican native maize: Origin, races and impact on food and gastronomy. *International Journal of Gastronomy and Food Science*. 2024;**37**:100978
- [2] García-Lara S, Serna-Saldivar SO. Corn history and culture. In: *Corn. Chemistry and Technology*. 3rd ed. Elsevier Inc.; 2019. pp. 1-18. DOI: 10.1016/B978-0-12-811971-6.00001-2
- [3] Fundación Tortilla. Annual Report of the Fundación Tortilla [Internet]. 2021 [accessed January 2, 2025]. Available from: https://fundaciontortilla.org/Informe_Anual_2021_Fundacion_Tortilla.pdf
- [4] Subiria-Cueto R, Larqué-Saavedra A, Reyes-Vega ML, de La Rosa LA, Santana-Contreras LE, Gaytán-Martínez M, et al. *Brosimum alicastrum* Sw. (Ramón): An alternative to improve the nutritional properties and functional potential of the wheat flour tortilla. *Food*. 2019;**8**(12):613
- [5] López P, Octavio GLF, Bello Pérez LA. La nixtamalización y el valor nutritivo del maíz. 2009. [Internet]. Available from: <https://www.revistacienciasunam.com/es/41-revistas/revista-ciencias-92-93/205-la-nixtamalizacion-y-el-valor-nutritivo-del-maiz-05.html> [Accessed: January 30, 2025]
- [6] de la Parra C, Serna Saldivar SO, Liu RH. Effect of processing on the phytochemical profiles and antioxidant activity of corn for production of masa, tortillas, and tortilla chips. *Journal of Agricultural and Food Chemistry*. 2007;**55**(10):4177-4183. DOI: 10.1021/jf063
- [7] De Arriola MDC, De Porres E, De Cabrera S, De Zepeda M, Rolz C. Aflatoxin fate during alkaline cooking of corn for tortilla preparation. *Journal of Agricultural and Food Chemistry*. 1988;**36**(3):530-533
- [8] Enríquez-Castro CM, Torres-Chávez PI, Ramírez-Wong B, Quintero-Ramos A, Ledesma-Osuna AI, López-Cervantes J, et al. Physicochemical, rheological, and morphological characteristics of products from traditional and extrusion nixtamalization processes and their relation to starch. *International Journal of Food Science*. 2020;**2020**(1):5927670
- [9] Arámbula VG, Mauricio SRA, Figueroa CJD, González-Hernández J, Ordorica FCA. Corn masa and tortillas from extruded instant corn flour containing hydrocolloids and lime. *Journal of Food Science*. 1999;**64**(1):120-124
- [10] Martínez-Bustos F, Sánchez-Sinencio F, González-Hernández J, Martínez JD, Ruiz-Torres M. Extrusion process for producing instant maize flour (U.S. Patent No. 5532013). Washington, DC: U.S. Patent and Trademark Office; 1996
- [11] Bedolla S, Rooney LW. Characteristics of US and Mexican instant maize flours for tortilla and snack preparation. *Cereal Foods World*. 1984;**29**:337-343
- [12] Jiménez-Pérez C, Ramírez-Romero G, Morán-Bañuelos SH. Instant flour from red and blue nixtamalized maize: Production and textural properties of tortilla. *Journal of Food Processing and Preservation*. 2015;**39**(1):38-46

- [13] Martinez-Bustos F, Sanchez-Sinencio F, Gonzalez-Hernandez J, Martinez JD, Ruiz-Torres M. U.S. Patent No. 5,532,013. Washington, DC: U.S. Patent and Trademark Office; 1996
- [14] Ramirez-Wong B, Sweat VE, Torres PI, Rooney LW. Cooking time, grinding, and moisture content effect on fresh corn masa texture. *Cereal Chemistry*. 1994;**71**:337-337
- [15] Santos EM, Quintanar-Guzman A, Solorza-Feria J, Sanchez-Ortega I, Rodriguez JA, Wang YJ. Thermal and rheological properties of masa from nixtamalized corn subjected to a sequential protein extraction. *Journal of Cereal Science*. 2014;**60**(3):490-496
- [16] Chel-Guerrero L, Parra-Pérez J, Betancur-Ancona D, Castellanos-Ruelas A, Solorza-Feria J. Chemical, rheological and mechanical evaluation of maize dough and tortillas in blends with cassava and malanga flour. *Journal of Food Science and Technology*. 2014;**52**(7):4387. DOI: 10.1007/s13197-014-1504-6
- [17] Narváez-González ED, de Dios Figueroa-Cárdenas J, Taba S, Sánchez FR. Kernel microstructure of Latin American races of maize and their thermal and rheological properties. *Cereal Chemistry*. 2006;**83**(6):605-610. DOI: 10.1094/CC-83-0605
- [18] Figueroa JDC, Rodriguez-Chong A, Veles-Medina JJ. Proceso ecológico de nixtamalización para la producción de harinas, masa y tortillas integrales. Mexican Patent. 2011;**289**(339):1-22. Available from: [http://refhub.elsevier.com/S0733-5210\(18\)30069-9/sref16](http://refhub.elsevier.com/S0733-5210(18)30069-9/sref16)
- [19] Serna-Saldivar SO. Understanding the functionality and manufacturing of nixtamalized maize products. *Journal of Cereal Science*. 2021;**99**:103205. DOI: 10.1016/j.jcs.2021.103205
- [20] Palacios-Fonseca AJ, Vazquez-Ramos C, Rodríguez-García ME. Physicochemical characterizing of industrial and traditional nixtamalized corn flours. *Journal of Food Engineering*. 2009;**93**:45-51. DOI: 10.1016/j.jfoodeng.2008.12.030
- [21] Santiago-Ramos D, Figueroa-Cárdenas JD, Mariscal-Moreno RM, Escalante-Aburto A, Ponce-García N, Vélez-Medina JJ. Physical and chemical changes undergone by pericarp and endosperm during corn nixtamalization—A review. *Journal of Cereal Science*. 2018;**81**:108-117. DOI: 10.1016/j.jcs.2018.04.003
- [22] Palacios-Pola G, Perales H, Estrada Lugo EI, Figueroa-Cárdenas JD. Nixtamal techniques for different maize races prepared as tortillas and tostadas by women of Chiapas, Mexico. *Journal of Ethnic Foods*. 2022;**9**:2. DOI: 10.1186/s42779-022-00116-9
- [23] Serna-Saldívar SO, Gutiérrez-Uribe JA, Mora-Rochin S, García-Lara S. Nutraceutical potential of native maize and changes during traditional and extrusion processing. *Revista Fitotecnica Mexicana*. 2013;**36**(Suppl. 3-A):295-304
- [24] Chaidez-Laguna LD, Torres-Chavez P, Ramírez-Wong B, Marquez-Ríos E, Islas-Rubio AR, Carvajal-Millan E. Corn proteins solubility changes during extrusion and traditional nixtamalization for tortilla processing: A study using size exclusion chromatography. *Journal of Cereal Science*. 2016;**69**:351-357. DOI: 10.1016/j.jcs.2016.04.004
- [25] Acosta-Estrada BA, Serna-Saldívar SO, Gutiérrez-Uribe JA. Chemopreventive effects of feruloyl putrescines from wastewater (Nejayote) of limecooked white maize (*Zea mays*). *Journal of Cereal Science*. 2015;**64**:23-28. DOI: 10.1016/j.jcs.2015.04.012

- [26] Ramírez-Araujo H, Gaytán-Martínez M, Reyes-Vega ML. Alternative technologies to the traditional nixtamalization process: Review. *Trends in Food Science and Technology*. 2019;**85**:34-43. DOI: 10.1016/j.tifs.2018.12
- [27] Valderrama-Bravo C, López-Ramírez Y, Jiménez-Ambríz S, Oaxaca-Luna A, Domínguez-Pacheco A, Hernández-Aguilar C. Changes in chemical, viscoelastic, and textural properties of nixtamalized dough with nejayote. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology*. 2015;**61**(2):496-502. DOI: 10.1016/j.lwt.2014.12.038
- [28] Bazua CD, Guerra R, Sterner H. Extruded corn flour as an alternative to lime-heated corn flour for tortilla preparation. *Journal of Food Science*. 1979;**44**(3):940-941. DOI: 10.1111/j.1365-2621.1979.tb08547.x
- [29] Escalante-Aburto A, Mariscal-Moreno RM, Santiago-Ramos D, Ponce-García N. An update of different nixtamalization technologies, and its effects on chemical composition and nutritional value of corn tortillas. *Food Review International*. 2020;**36**(5):456-498. DOI: 10.1080/87559129.2019.1649693
- [30] García-Lara S, Serna-Saldivar SO. Historia y cultura del maíz. In: Serna-Saldivar SO, editor. *Corn: Chemistry and Technology*. 3rd ed. The journal *Cereal Chemistry* is published by AACC International, which is based in St. Paul, Minnesota, USA: Elsevier; 2019. pp. 1-18. DOI: 10.1016/B978-0-12-811971-6.00001-2
- [31] Gaxiola-Cuevas N, Mora-Rochín S, Cuevas-Rodríguez EO, León-López L, Reyes-Moreno C, Montoya-Rodríguez A, et al. Phenolic acids profiles and cellular antioxidant activity in tortillas produced from Mexican maize landrace processed by nixtamalization and lime extrusion cooking. *Plant Foods for Human Nutrition*. 2017;**72**(3):314-320. DOI: 10.1007/s11130-017-0624-3
- [32] Mora-Rochin S, Gaxiola-Cuevas N, Gutierrez-Urbe JA, Milan-Carrillo J, Milan-Noris EM, Reyes-Moreno C, et al. Effect of traditional nixtamalization on anthocyanin content and profile in Mexican blue maize (*Zea mays* L.) landraces. *LWT - Food Science and Technology*. 2016;**68**:563-569. DOI: 10.1016/j.lwt.2016.01.009
- [33] Martínez-Flores HE, Martiánez-Bustos F, Figueroa JDC, González-Hernández J. Studies and biological assays in corn tortillas made from fresh masa prepared by extrusion and nixtamalization processes. *Journal of Food Science*. 2002;**67**(3):1196-1199. DOI: 10.1111/j.1365-2621.2002.tb09476.x
- [34] Guy R, editor. *Extrusion Cooking: Technologies and Applications*. Vol. 61. Washington, DC, USA: American Chemical Society; 2001. ISBN 1855735598
- [35] Sajilata MG, Singhal RS, Kulkarni PR. Resistant starch—A review. *Comprehensive Reviews in Food Science and Food Safety*. 2006;**5**(1):1-17. DOI: 10.1111/j.1541-4337.2006.tb00076.x
- [36] Lai LS, Kokini JL. Physicochemical changes and rheological properties of starch during extrusion (a review). *Biotechnology Progress*. 1991;**7**(3):251-266. DOI: 10.1021/bp00009a009
- [37] Serna-Saldivar SO, Canett R, Vargas J, Gonzalez M, Bedolla S, Medina C. Effect of soybean and sesame addition on the nutritional value of maize and decorticated sorghum tortillas produced by extrusion cooking. *Cereal Chemistry*. 1988;**65**(1):44-48

Chapter 6

New Technologies in Meat Preservation

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Abstract

Meat preservation has been one of the main challenges for the food industry. It involves several traditional methods, such as drying, smoking, fermentation, refrigeration, freezing, curing, and salting, to prevent losses and ensure safety. These conservation processes aim to prevent microbial development, control oxidative deterioration, and improve or preserve the meat's organoleptic characteristics. This chapter discusses new technologies for meat preservation, including thermal methods such as ohmic heating, microwave, and radio frequency heating, as well as non-thermal methods like high hydrostatic pressures, pulsed electric fields, ultrasonication, cold plasma, and bioactive packaging. It also covers the advantages and disadvantages of each technique and the barrier technologies that can be used to optimize these processes.

Keywords: meat preservation, traditional preservation methods, thermal methods, non-thermal methods, barrier technologies

1. Introduction

Meat preservation has been a concern for many years. Conservation objectives include inhibiting microorganisms, using fewer additives, and avoiding enzymatic deterioration [1]. These would extend the shelf life of products and reduce food waste. Conservation methods can be divided into traditional and new technologies. Among the conventional methods, we can mention salting and curing, which are based on reducing a_w , which achieves better product stability [2]. This is because some microorganisms, such as bacteria, cannot grow below 0.9 [3].

Temperature can also be used. Low temperatures, such as those used in freezing, cause ice crystals to form that prevent microorganisms from developing. Pasteur uses pasteurization to inactivate microorganisms. Some other methods use microorganisms as preservatives, such as fermentation using lactic acid bacteria, which reduces the pH and settles the food's redox potential, thereby extending the shelf life [4]. However, all methods have advantages and disadvantages. **Table 1** shows the main advantages and disadvantages of some traditional conservation methods.

Conservation methods	Advantages	Disadvantages
Salted and drying	They inhibit the growth of microorganisms. Weight and volume are reduced. Transportation and storage are facilitated.	Loss of flavor and odor. Vitamin loss. Rancidity occurs.
Curing	Characteristic color and flavor. Bacteriostatic against <i>Clostridium botulinum</i> and <i>Staphylococcus aureus</i> . They inhibit oxidative rancidity.	Nitrosamines can be produced. Methemoglobinemia.
Pasteurization	Extending shelf life. Eliminate microorganisms.	Affectation of the organoleptic properties of the product Vitamins are destroyed.
Freezing	Organoleptic characteristics are not affected. Enzymatic reactions stop. Bactericidal or bacteriostatic.	High cost.
Fermentation	Flavors and smell.	High cost.

Table 1.
Advantages and disadvantages of some traditional conservation methods.

2. Hurdle technologies

Microbial contamination of foods is a serious health problem; in some cases, it can cause severe poisoning. Since foods are rich in nutrients that good and bad microorganisms need to grow, their control is important. The microorganisms must be in a hostile environment that decreases their development or causes death. Food preservation is based on the combination of several environmental factors, or hurdles, to maintain the microbiological quality before, during, and after processing and the food reaches the consumers' tables. The most critical hurdles in food preservation are temperature (high or low), water activity (a_w), acidity (pH), redox potential (Eh), preservatives (such as nitrite, sorbate, and sulfite), and competitive microorganisms (lactic acid bacteria, mainly), and more than 60 potential hurdles can be applied to foods to improve the stability and/or quality of food products [5, 6]. **Figure 1** shows an example of hurdle technology applied to a cooked meat product. The first hurdle is salt's effect on water availability for microorganisms' development. Some

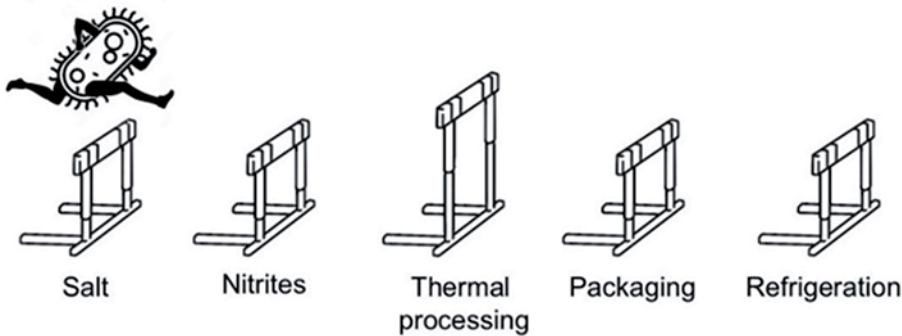


Figure 1.
Example of barrier hurdle applied to a cooked meat product.

microorganisms can survive the salt effect, so using preservatives, such as nitrites, can help reduce the growth of pathogenic microorganisms, such as *Clostridium botulinum*, in meat products. Since one of the most effective hurdles is temperature, cooking or thermal processing is necessary to ensure the destruction of most of the microorganisms present. After thermal processing, meat products must be vacuum packaged and kept under refrigeration to avoid the growth of probably good microorganisms, such as lactic acid bacteria, but that can affect the flavor of this product due to lactic acid production.

Fundamental aspects of this technology are listed below [6]:

1. Homeostasis: This is the internal balance of the microorganisms, which, if broken using some barrier, the microorganisms cannot multiply.
2. Metabolic exhaustion: When microorganisms act against any barrier to which they have been subjected, defense mechanisms are activated, and they are metabolically exhausted, allowing self-sterilization to occur.
3. Stress: Microorganisms respond to stress in different ways. In response to stress, some microorganisms can produce heat shock proteins (HSP) induced by pH, temperature, etc. This makes them show cross-tolerance, showing synergy. The selection and combination of different barriers are necessary to achieve greater food safety and stability.

Factor quantification can be carried out through a response surface model. The gamma hypothesis has been reported as an adequate basis for these analyses because it is contemplated that the effects of different antimicrobial factors are combined independently [7]. The most common barriers can be applied to develop shelf-stable RTE (ready-to-eat) in dairy, fruits, vegetables, meat, and meat products [8]. The objective is to increase the shelf life of products by reducing their microbial load. Rochetti et al. [9] reported the impact of barrier technologies in producing pork salami using lactic acid bacteria to avoid nitrates. They concluded that these products can be made with LAB, obtaining adequate microbiological profiles and avoiding additives that can be dangerous for health, like nitrites.

3. New technologies

There is currently a growing awareness among consumers for healthier living, which leads to a greater demand for minimally processed, free chemical additives, ready-to-eat, high-quality, fresh-looking, with natural aromas and flavors, as well as accessible, innovative, safe, and long shelf life [10–12]. In addition, there is an increasing demand for less salty, less acidified products with less or no use of chemical preservatives [10]. However, to meet all these demands, the meat industry must put aside conventional methods of preservation and implement alternative technologies, among which are new thermal and non-thermal methods and bioactive packaging; all of them together are faster alternatives that meet current consumer demands and are environmentally friendly, since they save energy and water, in turn obtaining more sensory attractive products [10, 13]. Since this perspective, considerable attention has been paid to developing new thermal and non-thermal technologies. **Figure 2** shows the classification of the latest technologies used in meat preservation.

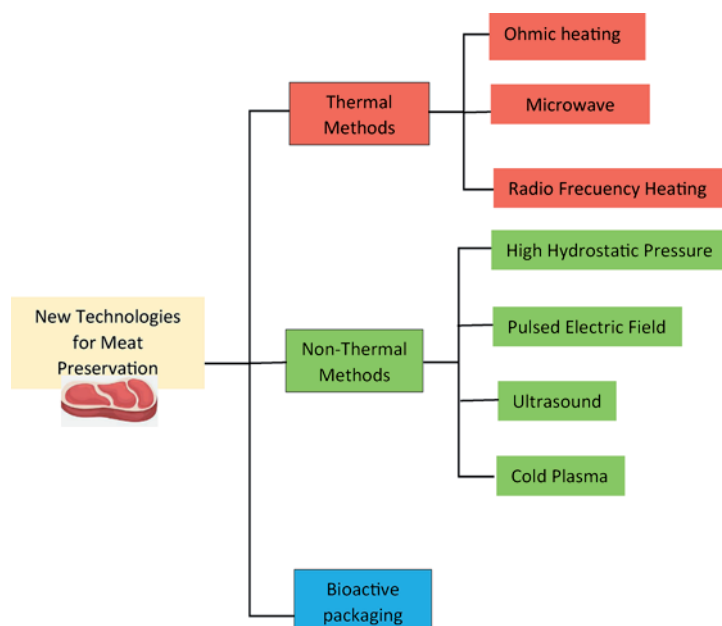


Figure 2.
New technologies for meat preservation [12].

3.1 Novel thermal methods

pH, water retention capacity (WHC), texture, oxidative stability, and sensory attributes are the main characteristics evaluated to determine meat quality; however, many of these properties decrease or are lost during thermal processing at high temperatures. These can adversely affect the physicochemical properties and nutritional and functional aspects of meat or its products, such as protein denaturation, loss of water-soluble vitamins, and changes in texture and flavor [13, 14].

On the other hand, heating, one of the most common methods in the industry for processing raw meat, presents challenges. It causes myofibrillar degeneration, muscle fiber contraction, agglutination and gelation of sarcoplasmic proteins, and collagen dissolution in connective tissue [15]. For many years, conventional heat treatments have been preferred to maintain quality and extend the shelf life of food; however, these methods can harm product characteristics, be costly, and cause environmental problems [16]. The biggest challenge in applying thermal technologies is to avoid the loss of nutritional quality and preserve the freshness of food, thus maximizing the use of clean energies, reducing waste generation, and reducing the carbon footprint. This urgency for innovative solutions in meat preservation is a key driver for developing new thermal and non-thermal technologies [11, 14].

New thermal methods are characterized by using alternative heat sources that can offer faster heating rates, minimizing nutrient degradation and adverse reactions. These techniques include ohmic, radiofrequency, and microwave. Ohmic heating is direct electro-heating, where electrical current is applied directly to the food. In contrast, microwave processing and radiofrequency heating are indirect electro-heating, where the electrical energy is first converted to electromagnetic radiation that generates heat within a product [12].

3.1.1 Ohmic heating

Ohmic heating is an emerging technology alternative thermal process that uniformly generates internal heat. It uses the resistance of liquid or solid products to convert electric energy into heat; as a result, microorganisms are inactivated by heating and electroporation. Electroporation is a process where an electric field is applied to cells, causing temporary pores to form in the cell membrane, leading to cell death [12, 16, 17]. The heat rate is directly proportional to the intensity of the electric field and the electric conductivity of the sample, allowing the pasteurization and sterilization of food. It is based on the passage of electricity through food with high resistance to conductivity. One of the main advantages of this technology is that it allows continuous production without heat transfer [10, 18].

Compared to conventional heat treatment, ohmic heating minimizes heat damage. It provides better nutritional and sensory qualities, maintains product safety, produces a higher feeling of freshness, and reduces heat exposure time. In addition, since the treatment is fast, it allows pasteurization or sterilization at lower cooking temperatures [10]. Also, it is clean technology, environmentally friendly, and has low energy costs. It can be produced using renewable energy sources such as hydroelectric, solar, and wind power [16]. The ohmic system's primary drawbacks stem from the need to handle pumpable products and the associated high energy costs. The recommended intensity density, which measures the electric field strength, is 4000 A/m^2 [18]. This parameter is crucial for the efficiency and safety of the process. Some disadvantages of ohmic heating are that if the food has compounds with poor conductivity and a big size of a piece of meat, they could create cold spots [10], such as the fat globules and blood cells that cause heterogeneous electrical conductivity in meat products [17, 19]. They do not generate heat at the same rate as muscle and change the cooking characteristics in those sections. Also, other composition parameters that modify the electrical conductivity of the food are acidity, hardness, presence of salts, and water activity, which affect the best working conditions of the electrodes and reduce the system's efficiency [16].

Ohmic treatment finds applications in various food processing tasks, including preheating, cooking, blanching, pasteurization, sterilization, and extraction of food products [19, 20]. It offers numerous advantages for processing meat products, such as reducing production time, minimizing protein denaturation, and improving sensory and textural characteristics [12, 16]. Importantly, it is considered environmentally friendly as it can eliminate or significantly reduce the need for boilers or steam generation systems, resulting in significant savings in both water and energy during meat processing.

Ohmic cooking (OC) has been explored as an innovative and energy-efficient technique in meat cooking. This method influences meat's microstructural and sensory properties. Lower heat or shorter processing times could prevent or minimize myofibrillar protein denaturation and reduce the removal of adipose tissue, resulting in lower cooking loss and maintenance or increased tenderness, juiciness, and flavor intensity compared with conventional cooking methods [16]. The versatility of ohmic cooking is evident in its successful application in various meat products, including meat emulsion, beef muscle (biceps femoris, semitendinosus), whole turkey meat, semi-cooked meatballs, hamburger patties, and ground beef with 2–9% fat, all of which have shown promising results in cooking yield, cooking loss, fat retention, and water holding capacity [19, 20].

This alternative can revolutionize the way meat is processed, helping to increase productivity and reduce the food industry's environmental impact. However, more

research is required with different conditions of OC to maintain a uniform heat generation rate and avoid cold spots, considering the various compositions of meat and its products.

3.1.2 High-frequency heating

In dielectric heating, the energy of high-frequency alternating electromagnetic fields is transferred to polar materials, such as water (dipoles) inside muscle tissue, to produce thermal energy. High-frequency energy includes microwave and radio-frequency energy and belongs to non-ionizing radiation [10, 17]. Microwaves utilize electromagnetic waves with electric fields of much higher frequency and shorter wavelength (433, 915, 2450, and 5800 MHz) than radiofrequency heaters (13.56, 27.12, and 40.68 MHz), and both have been used for cooking, drying, blanching, tempering, pasteurizing, and thawing [10].

3.1.2.1 Microwave treatments

The microwave method is considered a novel heat treatment whose use has recently increased in the food industry. It is a form of electromagnetic waves with a frequency range (300 MHz–300 GHz) and wavelength (0.1–100 cm) emitted by magnetons with magnetic fields that vary according to the orientation of the molecules polarized in an electric field [10, 17, 18, 21]. Microwave heating has become widespread in the meat industry for defrosting, tempering, and cooking [21, 22]. It is distinguished by generating heat instantaneously, significantly reducing processing time and operating costs compared to conventional dry heating methods [12]. High temperatures quickly give meat products nutritional and sensory advantages [10].

Thawing has significant advantages over conventional methods, such as the processing time from hours to minutes, the reduction of the plant space and the elimination of thawing chambers, and a decrease in the microbial load of the thawed products. When microwaves are used as a cooking method, there is a reduction in temperature and time and, consequently, a reduction in cooking losses, saving time, energy consumption, and better product quality in terms of taste, color, and nutritional value [18]. Still, this method's principal application is its effective reduction of foodborne pathogens and the assurance of the microbiological safety of products [21].

Cooking fresh meat in a microwave can be challenging due to the cool air surrounding the meat, which prevents proper browning. While the beef heats up inside, there is a mass transfer from the interior to the outside, resulting in a tough, dry, and flavorless product with a higher cooking loss and the deterioration of the meat color quality by decreasing L^* and elevating values [15]. However, some authors showed that microwaves retain higher amounts of vitamins such as retinol, thiamin, and riboflavin and improve the texture quality by lowering meat shear force and alleviating the heat damage to muscle fiber structure in comparison to those cooked by conventional methods [15, 22]. In the cooking process, the contractile proteins of meat (myosin and actin) will denature, and the connective tissue (collagen) undergoes solubilization; microwaves can solubilize more collagen than boiling [22].

Some disadvantages of this treatment are the dehydration of the meat and the non-uniform temperature distribution, which results in hot and cold spots in the product; this limits its effectiveness when used to cook foods that contain raw ingredients [12, 22].

3.1.2.2 Radiofrequency treatments

The radiofrequency (RF) method is a dielectric heating technology that uses selected electromagnetic waves at 13.56, 27.12, and 40.68 MHz for industrial, scientific, domestic, and medical applications [12, 23]. It can generate heat inside the samples through polar molecules' rotation and ionic movement. Due to its longer wavelength and penetration depth, it is more suitable for treating large-volume samples than microwave treatment [24]. The energy penetrates non-metallic packaging, enabling non-contact heating [25]. It is an emerging technology for pasteurization and has been carried out as an effective method for microbial inactivation in different food materials [24]. RF can be performed in batch and continuous processes inside packaging materials, such as carton boxes and polyethylene bags [26].

The electromagnetic generator has a periodic oscillation of wave polarity that causes a voltage in the ions, atoms, and molecules, which are converted into heat; consequently, the higher the force field, the greater the global heat generation [12]. The main advantages of dielectric heating concerning conventional systems are an increment in the heating speed, uniformity of heating with no gradients, precise control of the heating process, and the ability to start and stop the heating process instantly while regulating the applied power. An improvement in the quality of the products susceptible to surface overheating in the traditional systems; changes in the functionality of proteins (denaturation) and starch (gelation) [18].

Radiofrequency heating has been studied for pasteurization, drying, enzyme inactivation, and thawing/tempering meat, and some studies suggest that it can replace conventional convection and conduction heating methods in the food industry [25]. The tempering of frozen meat at the wrong temperature would cause quality degradation, changes in texture, flavor, color, lipid and protein oxidations, as well as possible microbial growth and spoilage. However, the RF treatment, making the meat more malleable and easier to handle for further mechanical operations (e.g., size reduction, slicing, tenderizing, breading, and frying), also reduced time and damage to product quality without compromising the microbiological safety [26]. The effect of the radiofrequency method for cooking meat rolls was evaluated. The results showed no loss of texture, color, and sensory properties; the total expressible fluid, moisture, and suspended solids were significantly lower, suggesting a higher WHC than steam-cooked meat [23]. **Table 2** shows some examples of applications for RF heating on beef.

Radiofrequency heating has similar advantages to ohmic and microwave treatments. However, RF has some disadvantages, such as higher equipment and operating costs, and research is limited regarding determining the dielectric properties of meat products [12]. Radiofrequency heating is a rapid and uniform heating method for different meat products. It has greater penetration than microwaves, presenting cold spots inside the meat due to the penetration stops where all the microwave energy has been converted to heat in the beef tissue [17].

3.2 Non-thermal methods

Meat is susceptible to deterioration with limited shelf life, microbial growth, oxidation, and other enzymatic reactions. Microbial deterioration is the main factor determining safety and storage life, as many foodborne diseases have been associated with consuming contaminated meat and meat products. Several non-thermal technologies have been developed around the world over the past two decades to control meat deterioration, allowing the reduction of food waste. These technologies have

Conditions	Treatment
Center temperature of 72°C in a 1.5 kW RF heater operating at 27.12 MHz.	RF cooking of ground, comminuted, and muscle meat products.
Power of 500 W, a heating time of 30 min with circulating water at a temperature of 80°C.	Effect of RF cooking on the texture, color, and sensory properties of luncheon roll of lean pork shoulders and pork back fat.
27.12 MHz with an internal temperature of 75–85°C.	Pasteurization by RF heating of ham to enhance shelf life in vacuum packaging.
Power of 500 W, endpoint temperature 73°C by 40 min.	The effect of RF heating on chemical, physical, and sensory aspects of quality in turkey breast rolls.
A pilot-scale 6 kW 27 MHz 1–1800 MHz and from 20 to 121°C, 6 kW 27 MHz.	Sterilized packaging of meat lasagna in large polymeric containers.
Frequency of 27.12 MHz, 400 W, by 35 min of RF heating oven.	Comparison of conventional and radio frequency defrosting of lean beef meats.
Cooked in a steam oven (80°C, power 500 W, 27.12 MHz).	Heating of beef rolls from <i>biceps femoris</i> muscle.
Constant frequency of 27.12 MHz and at 6 kW. The heating stopped at 60°C.	Effect of RF heating on characteristics of beef homogenate blends.
Endpoint temperatures (55, 65, and 75°C) using a 6 kW pilot-scale RF oven.	Quality of tenderized steaks of different thicknesses cooked in an RF oven.
27.12 MHz and a power of 6 kW in an RF oven, 60 to 65°C for 15 minutes	Inactivation of Shiga toxin-producing and non-pathogenic <i>Escherichia coli</i> in non-intact steaks cooked in an RF oven.

Table 2.
Applications for radiofrequency heating on meat [23, 26].

a lower impact on nutritional and sensory characteristics than traditional thermal methods employed in meat conservation. Therefore, the non-thermal methods guarantee the production of high-quality, safe, nutritious, and sustainable products with lower environmental impact, less energy consumption, and minimal waste compared to traditional processes. Consumers choose safe, clean-label, and minimally processed foods; therefore, non-thermal procedures are gaining significant interest in the food industry. Some of these technologies include the use of cold atmospheric plasma (CAP), hydrostatic pressure processing (HPP), ozone technology, pulsed electric fields (PEF), pulsed-UV light, and ultrasonication, among other methods, each with specific advantages and limitations [27–30].

3.2.1 Cold atmospheric plasma (CAP)

Plasma is known as the fourth state of matter present in the ionosphere and in the solar wind, as well as in plasma screens and neon lamps, and refers to a complex gaseous mixture of high-energy charged and neutral particles derived from de complete or partial ionization of a gas by the action of an electrical discharge [31]. Charged particles include electrons, ions, peroxide and superoxide free radicals, gas atoms, excited state molecules, and UV photons that collide, generating a variety of reactive oxygen and nitrogen species (ROS and RNS). The ROS species include atomic oxygen (O), excited oxygen (O₂), singlet oxygen (¹O₂), and superoxide anion (O⁻²). In contrast, RNS species include nitric oxide (NO), atomic nitrogen (N), and excited

nitrogen (N_2), among others [32]. The level of these reactive species varies according to the type of gas, the humidity, and the operating parameters. Several methods can generate plasma by applying electrical, optical, radiation, or microwave fields at extremely high temperatures (thermal plasma) or ambient temperatures. For CAP, a carrier gas (oxygen, air, nitrogen, argon, or helium) passes between electrodes spaced at about 1 cm, generating an electric discharge of 30 kV/cm at atmospheric pressure or under vacuum. Electric discharge induces acceleration of free electrons that ionize the gas components, releasing more free electrons and creating a cascade of ionization and molecular dissociation, generating new molecules and free radicals. Atoms and molecules in a high-energy state return to their baseline state by emitting electromagnetic energy over a broad spectrum range, including UV radiation [33]. Several devices are employed to generate electric discharge. Still, the common ones for meat products include dielectric barrier discharge (DBD), glow discharge, corona discharge (CD), plasma jet (APPJ), and piezoelectric direct discharge (PDD) [34–36].

CAP technology has been evaluated as a surface decontamination process in several areas with lethal and non-lethal effects on microorganisms and mammalian cells according to exposure time. Some applications include sterilizing medical devices to heal burn wounds and diabetic ulcers [32, 37]. In the food industry, CAP is employed to disinfect food packaging, fruits, vegetables, and meat products due to its excellent efficacy and low-cost operation [38]. Antimicrobial action relies on the combined action of ionized species, free radicals, ROS, and RNS species that induce oxidation and peroxidation at various levels within bacterial cells, causing alteration of the cell membrane, as well as denaturation of proteins, DNA, RNA, and lipids. The thin peptidoglycan layer of Gram-negative bacteria is more sensitive to ROS and UV radiation than the thick peptidoglycan layer of Gram-positive bacteria, rapidly releasing intracellular components like proteins, lipids, and DNA. In addition, CAP reactive species can enter the cell through the interstitial spaces of the Gram-positive cell wall, followed by alteration of intracellular molecules. The double layer of lipo-polysaccharides present in the bacterial cell membrane is highly susceptible to oxidation. Several reports have probed the CAP inactivation of pathogens and drug-resistant bacteria such as *Listeria monocytogenes*, *Salmonella Typhimurium*, *Pseudomonas aeruginosa*, *Staphylococcus aureus* and *E. coli* O157:H7 [33, 34, 37, 38].

Therefore, CAP is highly recommended as a non-thermal intervention with a similar effect as pasteurization for superficial decontamination of several foods, packaging materials, and in-package systems, including meat and meat products, at low temperatures, thus maintaining the flavor and nutritional attributes [38, 39]. However, some reports indicate that the application of CAP may diminish the red CIE, a^* color component, and may accelerate lipid oxidation due to ROS and other free radicals forming during the treatment, particularly in products containing greater unsaturated lipids. In this case, it is recommended to employ short treatments, less than 9 min, to reduce color and flavor changes [36, 38].

The CAP intervention generates RNS and nitrite oxides (NO_2 , NO_3 , N_2O , N_2O_5) that can produce nitric and nitrous acids in the presence of water; therefore, some authors have explored the potential use of CAP as an alternative for curing sausages and other meats, or a way to enrich the nitrite content in soy and pea-activated protein preparation and other vegetable products intended to be used as a source of natural nitrite for reaction with myoglobin [36, 40]. In addition, some authors mention that applying CAP as part of a curing technology had little influence on lipid oxidation and odor and did not increase the heterocyclic amine content in roasted and grilled beef [41, 42].

3.3 High pressure processing (HPP)

High pressure processing (HPP) is one of the most successful non-thermal pasteurization processes employed in the food industry to extend the shelf life of several foods, including meat products. HPP is cheaper regarding energy and operating costs, but the initial investment is relatively high compared to other traditional processes. HPP commercial applications claim to produce fresh, safe, innovative, nutritious, high-quality, clean-label, and convenient minimally processed meat products. Nonetheless, HPP can also be applied for meat tenderization, gel-like structuration, retention of fat and water, and to accelerate thawing [43–45]. The HPP process involves introducing the product into a pressurization chamber in which a fluid is pumped at 50,000 psi to generate an isostatic high pressure between 100 and 1000 MPa (1 MPa = 9.869 atm). Usually, water or a glycol-water mixture is employed as a pressure transmission fluid that occupies all the space around the product and generates an isostatic high pressure transmitted homogeneously and instantaneously to compress the product without deformation.

The pressurization process can last from a few seconds to several minutes, and it is also possible to control temperature depending on the desired objective. The higher pressure causes a temperature increase of about 3°C for every 100 MPa derived from the compression work. The HPP process can modify the interatomic distances of the product components, leading to changes in macromolecule functionality, inactivation of enzyme systems, and inactivation of microorganisms, as the cell membranes are highly susceptible to pressure damage [44]. Moderate HPP treatments (up to 180 MPa) produce sublethal cellular damage and decrease microbial growth. However, microbial inactivation requires processes above 300–500 MPa, as it increases the cytoplasmic viscosity, induces protein denaturation, and changes the membrane transport processes. At about 200 MPa, it initiates protein dissociation, destruction of cell membranes, and changes in the enzymic reactions; from 200 to 300 MPa, the enzymic inactivation is irreversible; at 400 MPa, most bacteria, yeast, molds, and viruses are inactivated. At 400–500 MPa, starch is gelatinized, and proteins are denatured, forming aggregates; but above 500 MPa, enzymes are fully inactivated, as well as bacterial spores [46]. All these modifications lead to the inactivation of spoilage and pathogenic microorganisms such as *Listeria monocytogenes*, *Salmonella* spp., *Campylobacter* spp., *Enterococcus* spp., and *E. coli*, among others [30, 46, 47]. Therefore, HPP can increase the shelf life of meat, fish, dairy products, juices, fruits, and vegetables without affecting the nutritional quality and general acceptability [43, 48]. However, microbial inactivation is multifactorial; Gram-negative bacteria are generally more vulnerable than Gram-positive bacteria, but bacterial spores have great tolerance against HPP.

On the other hand, HPP above 200 MPa induces dissociation of the thin and thick filaments of myofibrils and the release of myosin and formation of new protein-protein interactions leading to aggregation by the formation of hydrogen bonds, disulfide cross-links, and hydrophobic interactions in the treated meat that may affect the texture and induce gelation-like associated to the formation of protein aggregates. In addition, the use of HPP can affect the color of raw and cured meats due to the partial denaturation of myoglobin, disruption of the porphyrin ring, and change of the myoglobin redox chemistry on the surface of the product with an increase in luminosity (L^*) and decrease in the red color component (a^*), especially when applying pressures above 300–500 MPa; in general, beef becomes brownish with a cooked meat texture and color, whereas pork and poultry become brighter [49]. An HPP process of low (300

Mpa) and moderate (450 MPa) pressure for 90 seconds improved the color in raw dark-cutting meat compared to the control without affecting the eating qualities and acceptability, but a pressure of 600 MPa increased toughness, lipid oxidation, and a browned or lighter appearance [50]. However, HPP treatments of 50–350 MPa can increase red a^* values that favor the formation of myoglobin in its reduced state due to the inactivation of the enzyme systems responsible for the formation of methemoglobin [28]. Recently, some authors claimed that HPP can partially compensate for the loss of functionality and sensory properties in sodium and nitrite-reduced meat products [44, 47, 51].

3.4 Ozone treatment

Ozone (O_3) is an allotrope of oxygen and a powerful oxidant with great antimicrobial activity, effective against various pathogens and spoilage microorganisms, including Gram-positive and Gram-negative bacteria, viruses, and fungi, and capable of degrading mycotoxins. The ozone treatment is economical and eco-friendly, and it can be applied on-site as gas or dissolved in water. Ozone is an unstable gas that rapidly decomposes to oxygen, thus leaving the product without any residue, which needs to be generated on-site. The Food and Drug Administration (FDA) approved ozone treatment in the food industry, including fish, beef, and poultry, in 2001 [52]. Microbial inactivation of the ozone derives from progressive oxidation that initiates from the oxidation of the cell wall and membrane, increases cell permeability, and eventually leads to cell lysis. Damaged membranes facilitate the oxidation of intracellular components such as proteins, enzymes, unsaturated lipids, and nucleic acids, thus causing microbial destruction [53]. Ozone induces oxidation of sulfhydryl groups in proteins, enzymes, and peptides but also oxidizes the double bonds of unsaturated fatty acids of membrane lipoproteins and lipopolysaccharides; Gram-positive bacteria are more resistant than Gram-negative. However, antimicrobial efficacy varies with the ozone concentration, temperature, and product nature (pH, aw, and the presence of other additives). Ozone is also employed for deodorization because it can destroy several organic compounds [54, 55].

The ozone concentration can be expressed by volume (1 ppmv O_3 = 2.14 mg O_3 /m³) or weight (1% O_3 = 7.284 ppm O_3). Methods for ozone generation depend on the required concentration. The UV photochemical method in which oxygen molecules are photodissociated by the action of a UV lamp (185 nm) produces low ozone concentration (0.3–0.4% by weight). The corona discharge method, or plasma, produces higher ozone concentration and is the most common commercial treatment and electrolysis [53, 56]. However, high ozone concentrations and long-term ozone exposure are unsafe for humans, causing irritation, headache, respiratory illness, reproductive issues, cancer, and cardiovascular mortality; therefore, care must be taken to avoid human exposure to this gas [53]. Several authors have evaluated the efficiency of ozone treatments in beef, pork, poultry meats, and processed meat products with good results in microbial inactivation of pathogens such as *Salmonella*, *L. monocytogenes*, *E. coli*, *Staphylococcus* sp., *Bacillus* sp., *Enterobacter* sp., *Proteus* sp., *Providencia* sp., *Pseudomonas* sp by using 10–100 ppm gaseous ozone for 1–10 min [57, 58]. In addition, ozone treatment can be used for equipment disinfection and to control airborne microorganisms to reduce cross-contamination. However, high ozone doses or prolonged exposure could affect meat and meat products' physico-chemical, sensory, and nutritional quality, as ozone can accelerate oxidation and color deterioration. Ozone is a strong oxidant that may accelerate myoglobin oxidation, causing meat discoloration and rancidity [53].

High-voltage electrical pulse or pulsed electric field (PEF) technology involves the application of high-voltage electrical pulses (1–10 kV/cm) for short periods (micro to milliseconds) to food placed between two electrodes inside a chamber. The process can be applied at room temperature and lower or higher temperatures, unlike other technologies, it is possible to maintain temperature control. This emerging technique focuses on two objectives: the non-thermal inactivation of the polluting microbiota and the transfer of mass through the disruption of structures. Depending on the intensity of the treatment, the side effects of PEF include a moderate increase in temperature and the development of electrochemical reactions that can cause modifications in the sensory properties of the meat. PEF acts directly on the cell membrane, forming pores in the lipid bilayer, consequently leading to cell death, depending on the intensity and time. The equipment is made up of a pulse generator and a treatment chamber where the product is placed between the electrodes. The applications in meat and meat products include, in addition to the preservation effect, the acceleration of curing processes by increasing the rate of mass transfer and tenderization by increasing the rate of proteolysis. This technology is still under development, particularly in industrial equipment design [59].

3.5 Pulsed electric field (PEF)

Pulsed electric field technology involves the application of high-voltage electrical pulses (0.5–80 kV/cm) for a short time (micro to milliseconds) on a liquid or semi-solid food such as beef, pork, and poultry placed between two electrodes to reduce the microbial population that can be applied at low or high [60, 61]. PEF produces permeabilization of microbial membranes by the formation of pores. This emerging technique focuses on two objectives: the non-thermal inactivation of the spoilage microorganism and the transfer of mass through the disruption of structures. PEF can inactivate spoilage and pathogenic bacteria, including *Salmonella Typhimurium*, *Salmonella enteritidis*, *E. coli* 0157:H7, *Bacillus cereus*, *Lactiplantibacillus plantarum*, *Listeria monocytogenes*, *Saccharomyces cerevisiae*, and mold spores [60]. The antimicrobial action is directly associated with the formation of pores on the cell membrane lipid bilayer, consequently leading to cell death, depending on the intensity and time. The low-intensity PEF process (0.5–1.5 kV/cm) induces stress and sublethal injury. Therefore, some microorganisms can survive by resealing their cytoplasmic membranes. Irreversible microbial inactivation requires a field strength between 10 and 40 kV/cm; microbial cells swell as the electric field increases, and if the PEF exceeds the critical electric field threshold, the microbial cell loses the membrane integrity [46, 62]. Depending on the intensity of the treatment, the side effects of PEF include a moderate increase in temperature and the development of electrochemical reactions that can cause modifications in the pH and sensory properties of the meat [63]. High-intensity PEF may increase meat drip loss due to membrane damage, protein denaturation, and myofibril fragmentation [64]. In addition to the preservation effect, PEF can accelerate the curing and marinating processes by increasing the rate of mass transfer and as a means for tenderization by increasing the rate of proteolysis. This technology is still under development, particularly in industrial equipment design [59, 62, 65]. Recently, a PEF pretreatment was employed to improve safety and facilitate the absorption of food colorants (betanin, red yeast, and roselle) in nitrite-free bacon [66].

3.6 Pulsed-UV light

UV light is the portion of the electromagnetic spectrum between X-rays and visible light, with four regions: UV-vacuum (100–200 nm), UV-C (200–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm). Only UV-C and UV-B shortwave UV light have germicidal power, although they have low penetration power. This technique is commonly used to disinfect air, water, contact surfaces, food packaging, and a decontamination agent on the surface of some foods without altering their properties. Shortwave UV light, “particularly 254 nm UV,” produces photochemical damage to DNA and RNA that can lead to cell death if the light source is between 3 and 18 cm from the surface to be treated. Shortwave UV (UV-C) light induces the formation of cross-bridges between thiamine and cytosine, forming cyclobutyl-pyrimidine dimers between adjacent nucleotides that prevent replication and transcription. However, some bacteria can survive treatment without radiation due to a photo-reactivation mechanism.

A variant of this technique is pulsed UV light (PUV), also called high-intensity, broad-spectrum UV light (BSPL) or pulsed light (PL), in which pulses of high intensity from an inert gas lamp in the wavelength of 100–1100 nm with high energy in the UV range [67]. Short-duration continuous-spectrum light is used in pulses of 1–10 per second. Pulsed UV light has proven its antimicrobial action at levels of 1.24–18 J/cm² against *Salmonella enteritis*, *Listeria monocytogenes*, *Staphylococcus aureus*, *Carnobacterium divergens*, *Escherichia coli*, and bacterial spores in chicken fillets. The pulses are generated in a xenon gas lamp with microsecond pulses, which emit radiation in the 200–1100 nm range, in which 25% of the radiation is in the range of UV light (<400 nm). The U.S. Food and Drug Administration (FDA) approved the use of pulsed UV light technology in Code 21CFR179.41 at levels up to 12 J/cm² and in an emission spectrum between 200 and 1100 nm with pulses less than 2 milliseconds for contact surface control in food production and handling processes. The inhibitory effect of pulsed UV light is greater than that of UV-C since, in addition to generating DNA and RNA damage, it also alters the structure of the cell membrane by hydroperoxidation, apoptosis, and heat stress. However, there are still restrictions regarding its application and approval. It is a low-cost and easy-to-use technique, but its operation requires protective equipment since it can damage eyesight and cause operator burns [67].

3.7 Ultrasonication

Ultrasound is a form of mechanical acoustic energy, a non-invasive, non-destructive, sustainable, and easily applied technique. Ultrasound systems transform electrical energy into vibrational energy transmitted to the surrounding environment. Part of the energy is lost in heat and the re-emission of sound; the rest produces cavitation and shock waves that can modify the physicochemical characteristics of the material according to the frequency used. In general, three categories are used: high intensity and low frequency (20–100 kHz), medium intensity and intermediate frequency (100 kHz–1 MHz), and low intensity and high frequency (1–10 MHz). Since the 1950s, low-intensity ultrasound has been used to evaluate the composition of animals before slaughter, and a diagnostic method with frequencies of 1–10 MHz, either in the form of a continuous beam or pulses [13, 68].

High-intensity systems interact with the environment, producing cavitation, which consists of the mechanical rupture of the molecules of the surrounding

environment, forming bubbles of water vapor that burst violently, so ultrasound is used for cleaning equipment and removing impurities. Recently, high-intensity ultrasound systems have been implemented to accelerate mass and heat transfer processes in the meat industry's freezing, thawing, marinating, tenderizing, and cooking processes. High-energy ultrasound processes (20–500 kHz) are commonly used in biochemistry and microbiology for cell breakdown. Still, it is also an alternative for meat decontamination, as the cavitation phenomenon can alter bacterial cell membranes in conjunction with producing free radicals and ROS. Gram-positive bacteria are more resistant to ultrasound due to the peptidoglycan layer that exerts a protective effect [13]. The ultrasound-assisted chilling process to reduce *Salmonella* and *E. coli* in poultry has been successfully applied and offered an environmentally friendly approach to controlling these bacteria during poultry chilling [69].

3.8 Edible films

Packaging has been a barrier to food conservation for years because it protects food from external agents and microorganisms, extending its shelf life. Usually, the packaging is made with oil-based plastics, which are not degradable, resulting in an environmental issue. In recent years, consumers have seen a demand for more environmentally friendly packaging with renewable ingredients, and edible films have emerged as a good option for fresh meat and meat foods.

Edible films are made from polysaccharides such as chitosan, agar, carboxymethylcellulose, pectin, starch, cellulose, gums, etc., and proteins such as egg, soy, casein, gelatin, etc. Some compounds with antioxidant or microbial activity can be added to these films, called active films. Typically, these films are thin and transparent [70]. Edible films are a great way to reduce environmental pollution caused by traditional packaging, and because of this, they can be considered sustainable foods that enter a circular economy [71]. Edible films have significant advantages for use in meat and meat products: they are economical and safe, they are classified as GRAS and eco-friendly, depending on the substance added, can be removed with water, are very effective in controlling microorganisms, and can inhibit pathogens. More studies need to be done on meat and meat products, and nanoencapsulation is a technology that would help increase these edible films' stability and bioactive potential [72]. Edible films can be produced dry or wet. Heat and extrusion are used first but subsequently molded without solvents. In the wet process, solvents dissolve the ingredients, and then they are dried to remove these solvents [73]. Adding a plasticizer increases the film's strength and flexibility and prevents pores. The most used are glycerol and sorbitol, which make edible films elastic and permeable by reducing hydrogen bonds in polymer chains. Starch is a polysaccharide widely used in developing edible films because it is low-cost, abundant, renewable, biodegradable, etc. It is obtained from various sources such as potato, maize, rice, cassava, tapioca, oats, and banana, which give them distinctive characteristics due to the levels of amylose and amylopectin [74].

Meat and meat products are rich in nutrients, which means they can have high microorganism loads, which is why various natural antimicrobials have been studied to be added to edible films in meat and meat products, such as lysozyme, bacteriocins (pediocin and nisin), organic acids such as lactic acid, chitosan, essential oils of oregano, clove, sunflower, green tea extract, etc. [75]. Chitosan edible films added 1% sunflower oil to cover pork burgers that were tested. The results showed that the burgers covered with film reduced the microbial count of Enterobacteriaceae during storage. Still, they concluded that the films' permeability to oxygen caused metmyoglobin

to be produced, which is not a desirable compound in hamburgers [76]. Studies with *Rubia cordifolia*, a medicinal plant of the coffee family used as a bioactive ingredient in India as a food supplement, was tested to produce edible films for chicken use. Nuggets for improved lipid oxidation. *R. cordifolia* affects the physicochemical properties of edible films, increasing the thickness, opacity, and moisture content and decreasing the solubility of the films. It also improves lipid oxidation and acts as an antimicrobial, so it can be concluded that it can be used as a bioactive ingredient in the development of edible films for meat products [77]. Others studied the effect of an edible film with chitosan, 2.5% nanocellulose, and 1% essential oils of *Aloysia citrodora* and *Cymbopogon citratus* on fresh chicken meat for 13 days. They found that edible films added with chitosan and essential oils had very high antioxidant activity and high phenolic content and that the number of mesophiles, psychrophiles, and Enterobacteriaceae was lower than the control, which they attributed to chitosan and essential oils [78]. Edible films are a good alternative for incorporating probiotics (lactic acid bacteria) and prebiotics (inulin, fructooligosaccharides) and thus having a symbiotic [79].

Although they are a great alternative in the meat industry, more studies are necessary since there are still some limitations. For example, chitosan, widely used in edible films, must be combined with other materials because it has high water vapor permeability due to its hydrophilic nature. Soy protein has low mechanical properties and high water solubility [80].

4. Conclusion

The demand for safer, less processed, and more natural foods is one of the main demands of consumers; in this sense, the meat industry has been innovative in the implementation of novel thermal or non-thermal technologies in the preservation of meat products, although more research is needed to define the conditions of the process. In addition, incorporating these technologies allows us to have foods with good physicochemical, sensory, and microbiological properties, be environmentally friendly, and reduce the carbon footprint in their applications.

Conflict of interest

The authors declare no conflict of interest.

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References

- [1] Ahmad J, Qasim AM, Rehan AM, Iftikhar S, Iqra-Hussain M, Javed S, et al. Review article on traditional and modern techniques for food preservation. *International Journal of Modern Agriculture*. 2021;**10**(3):219-234
- [2] Ariyamuthu R, Rupa AV, Sangeetha J. An overview of food preservation using conventional and modern methods. *Journal of Food and Nutrition Sciences*. 2022;**10**(3):70-79. DOI: 10.11648/j.jfns.2021003.13
- [3] Kamal AS, Uddin MM, Rahman R, Rezwanul ISM, Sanad KM. A review of mechanisms and commercial aspects of food preservation and processing. *Agriculture & Food Security*. 2017;**6**:51. DOI: 10.1186/s40066-017-0130-8
- [4] Sharif ZIM, Mustapha FA, Jai J, Yusof NM, Zaki NAM. Reviews on methods for preservation and natural preservatives for extending food longevity. *Chemical Engineering Research Bulletin*. 2017;**19**:145-153
- [5] Leistner L, Gorris LGM. Food preservation by hurdle technology. *Trends in Food Science Technology*. 1995;**6**:41-46. DOI: 10.1016/S0924-2244(00)88941-4
- [6] Leistner L. Basic aspects of food preservation by hurdle technology. *International Journal of Food Microbiology*. 2000;**55**:181-186. DOI: 10.1016/S0168-1605(00)00161-6
- [7] Bidlas E, Lambert JW. Quantification of hurdles: Predicting the combination of effects-interaction vs. non-interaction. *International Journal of Food Microbiology*. 2008;**128**:78-88. DOI: 10.1016/j.ijfoodmicro.2008.06.030
- [8] Pundhir A, Murtaza N. Hurdle technology approach towards food preservation. *International Journal of Current Microbiology and Applied Sciences*. 2015;**4**(7):802-809
- [9] Rocchetti G, Falasconi I, Dallolio G, Lorenzo JM, Lucini L, Rebecchi A. Impact of hurdle technologies and low temperatures during ripening on the production of nitrate-free pork salami: A microbiological and metabolomic comparison. *LWT-Food Science and Technology*. 2021;**141**:110939-1-110939-8. DOI: 10.1016/j.lwt.2021.110939
- [10] Aymerich T, Picouet PA, Monfort JM. Decontamination technologies for meat products. *Meat Science*. 2008;**78**(1-2):114-129. DOI: 10.1016/j.meatsci.2007.07.007
- [11] Díaz-Almanza S, Alarcón-Rojo AD, García-Galicia IA. Non-thermal methods for the preservation of fresh meat and meat products. *Tecnociencia, Chihuahua*. 2021;**15**(2):829-829. DOI: 10.54167/tecnociencia.v15i2.829
- [12] Lajnaf R. Introductory chapter: Novel thermal and non-thermal technologies for food processing. In: Lajnaf R, editor. *Food Processing and Preservation*. London, UK: IntechOpen; 2023. DOI: 10.5772/intechopen.110433
- [13] Alarcon-Rojo AD, Carrillo-Lopez LM, Reyes-Villagrana R, Huerta-Jiménez M, Garcia-Galicia IA. Ultrasound and meat quality: A review. *Ultrasonics Sonochemistry*. 2019;**55**:369-382. DOI: 10.1016/j.ultrasonch.2018.09.016
- [14] Yudhistira B, Punthi F, Gavahian M, Chang CK, Hazeena SH, Hou CY, et al. Nonthermal technologies to maintain food quality and carbon footprint

- minimization in food processing: A review. *Trends in Food Science & Technology*. 2023;**141**:104205. DOI: 10.1016/j.tifs.2023.104205
- [15] Li S, Tang S, Yan L, Li R. Effects of microwave heating on physicochemical properties, microstructure and volatile profiles of yak meat. *Journal of Applied Animal Research*. 2019;**47**(1):262-272. DOI: 10.1080/09712119.2019.1624553
- [16] Balthazar CF, Pimentel TC, Silva R, Prudencio ES, Cruz AG, Mársico ET. Recent findings on the ohmic heating application in meat products. *Current Opinion in Food Science*. 2024;**58**:101180. DOI: 10.1016/j.cofs.2024.101180
- [17] Xiong YL. The storage and preservation of meat: I—Thermal technologies. In: Toldrá F, editor. *Lawrie's Meat Science*. 9th ed. United Kingdom: Woodhead publishing; 2023. pp. 219-244. DOI: 10.1016/B978-0-323-85408-5.00019-4
- [18] Hugas M, Garriga M, Monfort JM. New mild technologies in meat processing: High pressure as a model technology. *Meat Science*. 2002;**62**(3):359-371. DOI: 10.1016/S0309-1740(02)00122-5
- [19] Yildiz-Turp G, Sengun IY, Kendirci P, Icier F. Effect of ohmic treatment on quality characteristic of meat: A review. *Meat Science*. 2013;**93**(3):441-448. DOI: 10.1016/j.meatsci.2012.10.013
- [20] Richa R, Shahi N, Singh A, Lohani U, Omre P, Kumar A, et al. Ohmic heating technology and its application in meaty food: A review. *Advances in Research*. 2017;**10**(4):1-10. DOI: 10.9734/AIR/2017/33799
- [21] Akkaya E, Bingol EB, Muratoglu K, Hampikyan H, Cetin O, Colak H. Impact of microwave heating on product safety and quality in meatballs. *Innovative Food Science & Emerging Technologies*. 2014;**93**:103643. DOI: 10.1016/j.ifset.2024.103643
- [22] Yarmand MS, Homayouni A. Microwave processing meat. In: Chandra U, editor. *Microwave Heating*. London, UK: IntechOpen; 2011. pp. 107-134. DOI: 10.5772/20857
- [23] Di Rosa AR, Bressan F, Leone F, Falqui L, Chiofalo V. Radio frequency heating on food of animal origin: A review. *European Food Research and Technology*. 2019;**245**:1787-1797. DOI: 10.1007/s00217-019-03319-8
- [24] Wang K, Huang L, Xu Y, Cui B, Sun Y, Wang Y. Evaluation of pilot-scale radio frequency heating uniformity for beef sausage pasteurization process. *Foods*. 2022;**11**(9):1317. DOI: 10.3390/foods11091317
- [25] Gao J, Wu M, Du S, Zhang H, Wang S, Ling B. Recent advances in food processing by radio frequency heating techniques: A review of equipment aspects. *Journal of Food Engineering*. 2023;**357**:111609. DOI: 10.1016/j.jfoodeng.2023.111609
- [26] Llave Y, Erdogdu F. Radio frequency processing and recent advances on thawing and tempering of frozen food products. *Critical Reviews in Food Science and Nutrition*. 2022;**62**(3):598-618. DOI: 10.1080/10408398.2020.1823815
- [27] Troy DJ, Ojha KS, Kerry JP, Tiwari BK. Sustainable and consumer-friendly emerging technologies for application within the meat industry: An overview. *Meat Science*. 2016;**120**:2-9. DOI: 10.1016/j.meatsci.2016.04.002
- [28] Ahn DU, Mendonça AF, Feng X. The storage and preservation of meat: II.

- Nonthermal technologies. In: Toldrá F, editor. *Lawrie's Meat Science*. 9th ed. United Kingdom: Woodhead publishing; 2023. pp. 245-280. DOI: 10.1016/B978-0-323-85408-5.00013-3
- [29] Bolumar T, Orlie V, Sikes A, et al. High-pressure processing of meat: Molecular impacts and industrial applications. *Comprehensive Reviews in Food Science and Food Safety*. 2021;**20**:332-368. DOI: 10.1111/1541-4337.12670
- [30] Nema PK, Sehrawat R, Ravichandran C, Kaur BP, Kumar A, Tarafdar A. Inactivating food microbes by high-pressure processing and combined nonthermal and thermal treatment: A review. *Journal of Food Quality*. 2022;**1**:5797843. DOI: 10.1155/2022/5797843
- [31] López M, Calvo T, Prieto M, Múgica VR, Muro-Fraguas I, Alba-Elias F, et al. A review on non-thermal atmospheric plasma for food preservation: Mode of action, determinants of effectiveness and applications. *Frontiers in Microbiology*. 2019;**10**:622. DOI: 10.3389/fmicb.2019.00622
- [32] Oliver MA, Hussein LK, Molina EA, Keyloun JW, McKnight SM, Jimenez LM, et al. Cold atmospheric plasma is bactericidal to wound-relevant pathogens and is compatible with burn wound healing. *Burns*. 2024;**50**:1192-1212. DOI: 10.1016/j.burns.2023.12.012
- [33] Thirumdas R, Kothakota A, Annapurna U, Siliveru K, Blundell R, Gatt R, et al. Plasma activated water (PAW): Chemistry, physicochemical properties, applications in food and agriculture. *Trends in Food Science and Technology*. 2018;**77**:21-31. DOI: 10.1016/j.tifs.2018.05.007
- [34] González-González CR, Labo-Popoola O, Delgado-Pando G, Theodoridou K, Doran O, Stratakis AC. The effect of cold atmospheric plasma and linalool nanoemulsions against *Escherichia coli* O157:H7 and *Salmonella* on ready-to-eat chicken meat. *LWT*. 2021;**149**:111898. DOI: 10.1016/j.lwt.2021.111898
- [35] Akhtar J, Abrha MG, Teklehaimanot K, Gebrekirstos G. Cold plasma technology: Fundamentals and effect on meat quality and its products. *Food and Agricultural Immunology*. 2022;**33**(1):451-478. DOI: 10.1080/09540105.2022.2095987
- [36] Jayasena DD, Kang T, Wijayasekara KN, Jo C. Innovative application of cold plasma technology in meat and its products. *Food Science of Animal Resources*. 2023;**43**:1087-1110. DOI: 10.5851/kosfa.2023.e31
- [37] Das S, Gajula VP, Mohapatra S, Singh G, Kar S. Role of cold atmospheric plasma in microbial inactivation and the factors affecting its efficacy. *Health Sciences Review*. 2022;**4**:100037. DOI: 10.1016/j.hsr.2022.100037
- [38] Barjasteh A, Kaushik N, Choi EH, Kaushik NK. Cold atmospheric pressure plasma solutions for sustainable food packaging. *International Journal of Molecular Sciences*. 2024;**25**(12):6638. DOI: 10.3390/ijms25126638
- [39] Zhou R, Rezaeimotlagh A, Zhou R, Zhang T, Wang P, Hong J, et al. In-package plasma: From reactive chemistry to innovative food preservation technologies. *Trends in Food Science & Technology*. 2022;**120**:59-74. DOI: 10.1016/j.tifs.2021.12.032
- [40] Marcinb kowska-Lesiak M, Wojtasik-Kalinowska I, Onopiuk A, Stelmasiak A, Wierzbicka A, Poltorak A. Application of atmospheric pressure cold plasma activated plant protein

- p preparations solutions as an alternative curing method for pork sausages.
- Meat Science*
- . 2022;
- 187**
- :108751. DOI: 10.1016/j.meatsci.2022.108751
- [41] Hu Y, Tian H, Hu S, Dong L, Zhang J, Yu X, et al. The effect of in-package cold plasma on the formation of polycyclic aromatic hydrocarbons in charcoal-grilled beef steak with different oils or fats. *Food Chemistry*. 2022;**371**:131384. DOI: 10.1016/j.foodchem.2021.131384
- [42] Hui T, Fang Z, Ma O, Hamid N, Li Y. Effect of cold atmospheric plasma-assisted curing process on the color, odor, volatile composition, and heterocyclic amines in beef meat roasted by charcoal and superheated steam. *Meat Science*. 2023;**196**:109046. DOI: 10.1016/j.meatsci.2022.109046
- [43] Kameník J, Salakova A, Hulankova R, Borilova G. The effect of high pressure on the microbiological quality and other characteristics of cooked sausages packed in a modified atmosphere or vacuum. *Food Control*. 2015;**57**:232-237. DOI: 10.1016/j.foodcont.2015.04.010
- [44] Bolumar T, Lohmayer R, Peukert M, Thiemann K, Münch S, Brüggemann DA. High-pressure processing enhances saltiness perception and sensory acceptability of raw but not of cooked cured pork loins-leveraging salty and umami taste. *Frontiers in Nutrition*. 2024;**15**(11):1352550. DOI: 10.3389/fnut.2024.1352550
- [45] Inanoglu S, Barbosa-Cánovas GV, Sablani SS, Zhu MJ, Keener L, Tang J. High-pressure pasteurization of low-acid chilled ready-to-eat food. *Comprehensive Reviews in Food Science and Food Safety*. 2022;**21**:4939-4970. DOI: 10.1111/1541-4337.13058
- [46] Lee S, Lee J, Shin J, Choi MJ. Effects of high-pressure processing on the physicochemical properties of prosciutto and microbe inactivation. *LWT*. 2023;**187**:115294. DOI: 10.1016/j.lwt.2023.115294
- [47] Shakil MH, Trisha AT, Rahman M, Talukdar S, Kobun R, Huda N, et al. Nitrites in cured meats, health risk issues, alternatives to nitrites: A review. *Foods*. 2022;**11**(21):3355. DOI: 10.3390/foods11213355
- [48] Chmiel M, Cegiełka A, Świder O, Roszko M, Hać-Szymańczuk E, Adamczak L, et al. Effect of high-pressure processing on biogenic amines content in skin-packed beef during storage. *LWT*. 2023;**175**:114483. DOI: 10.1016/j.lwt.2023.114483
- [49] Bak KH, Bolumar T, Karlsson AH, Lindahl G, Orlén V. Effect of high-pressure treatment on the color of fresh and processed meats: A review. *Critical Reviews in Food Science and Nutrition*. 2017;**59**(2):228-252. DOI: 10.1080/10408398.2017.1363712
- [50] Reesman C, Sullivan G, Danao MG, Mafi GG, Pfeiffer M, Ramanathan R. Effects of high-pressure processing on cooked color and eating qualities of dark-cutting beef. *Applied Food Research*. 2023;**3**:100260. DOI: 10.1016/j.afres.2022.100260
- [51] Nuygen M, Arvaj L, Balamurugan S. The use of high pressure processing to compensate for the effects of salt reduction in ready-to-eat meat products. *Critical Reviews in Food Science and Nutrition*. 2024;**64**(9):2533-2547. DOI: 10.1080/10408398.2022.2124398
- [52] Pandiselvam R, Subhashini S, Banuu Priya EP, Kothakota A, Ramesh SV, Shahir S. Ozone based food preservation: A promising green technology for enhanced food safety. *Ozone: Science & Engineering*. 2019;**4**:17-34. DOI: 10.1080/01919512.2018.1490636

- [53] Giménez B, Zaritzky N, Graiver N. Ozone treatment of meat and meat products: A review. *Frontiers in Food Science and Technology*. 2024;**4**:1351801. DOI: 10.3389/frfst.2024.1351801
- [54] Lan W, Chen X, Zhao Y, Xie J. Insights into the antibacterial mechanism of ozone water combined with tea polyphenols against *Shewanella putrefaciens*: Membrane disruption and oxidative stress. *International Journal of Food Science and Technology*. 2022;**57**:7423-7433. DOI: 10.1111/ijfs.16106
- [55] Zhang L, Zhang M, Yu Q, Su S, Wang Y, Fang Y, et al. Optimizing winter air quality in pig-fattening houses: A plasma deodorization approach. *Sensors*. 2024;**2**:324. DOI: 10.3390/s24020324
- [56] Roobab U, Madni GM, Ranjha MM, Khan AW, Selim S, Almuhayawi MS, et al. Applications of water activated by ozone, electrolysis, or gas plasma for microbial decontamination of raw and processed meat. *Frontiers in Sustainable Food Systems*. 2023;**7**:1007967. DOI: 10.3389/fsufs.2023.1007967
- [57] Devatkal SK, Kumar C, Juneja V, Inbaraj S. Effect of aqueous ozone on inactivation of bacteria isolated from the meat products and equipment. *Biologia: Botany, Zoology and Cellular and Molecular Biology*. 2023;**78**:3295-3304. DOI: 10.1007/s11756-023-01495-3
- [58] Matłok N, Zapałowska A, Durał B, Balawejder M. Effect of ozon treatment on shelf-life of poultry meat in the logistic chain. *Acta Universitatis Cinbinesis, Series E : Food Technology*. 2023;**27**:155-161. DOI: 10.2478/aucft-2023-0013
- [59] Gómez B, Munekata PES, Gavahian M, Barba FJ, Martí-Quijal FJ, Bolumar T, et al. Application of pulsed electric fields in meat and fish processing industries: An overview. *Food Research International*. 2019;**123**:95-125. DOI: 10.1016/j.foodres.2019.04.047
- [60] Li Z, Yang O, Du H, Wu W. Advances of pulsed electric field for foodborne pathogen sterilization. *Food Reviews International*. 2023;**39**:3603-3619. DOI: 10.1080/87559129.2021.2012798
- [61] Jeong SH, Lee HB, Lee DU. Effects of pulsed electric field on meat tenderization and microbial decontamination: A review. *Food Science of Animal Resources*. 2024;**44**:239-254. DOI: 10.5851/kosfa.2023.e82
- [62] Lytras F, Psakis G, Gatt R, Cebrián G, Raso J, Valdramidis V. Exploring the efficacy of pulsed electric fields (PEF) in microbial inactivation during food processing: A deep dive into the microbial cellular and molecular mechanisms. *Innovative Food Science & Emerging Technologies*. 2024;**95**:103732. DOI: 10.1016/j.ifset.2024.103732
- [63] Karki R, Oey I, Bremer P, Silcock P. Pulsed electric fields application in meat processing. In: Raso J, Heinz V, Alvarez I, Toepfl S, editors. *Pulsed Electric Fields Technology for the Food Industry*. Food Engineering Series. Switzerland: Springer International Publishing; 2022. pp. 399-438. DOI: 10.1007/978-3-030-70586-2_14
- [64] Tomasevic I, Heinz V, Djekic I, Terjung N. Pulsed electric fields and meat processing: Latest updates. *Italian Journal of Animal Science*. 2023;**22**:857-866. DOI: 10.1080/1828051X.2023.2206834
- [65] He Y, Wang Y, Cai C, Liu Z, Zhu Y. Enhancement of pork marinating efficiency through pulsed electric field pretreatment: Integration of parameter optimization, kinetic modeling and quality characteristics. *Innovative Food Science and Emerging Technologies*.

2024;**96**:103788. DOI: 10.1016/j.ifset.2024.103788

[66] Molina JR, Frías Celayeta JM, Bolton DJ, Botinestean C. Effects of natural colourants and pulsed electric field technology on the quality parameters of nitrite-free bacon. *Food and Feed Research*. 2024;**51**:211-218. DOI: 10.5937/ffr0-53899

[67] Keklik NM. Treatment of pastirma with pulsed UV light: Modeling of *Staphylococcus aureus* inactivation and assessment of quality changes. *Food Science and Technology International*. 2019;**26**:185-198. DOI: 10.1177/1082013219889231

[68] Fernández BS, Labarca G, Lanza M, Folch E, Majid A. A review on thoracic ultrasound. *Aplicaciones torácicas del ultrasonido. Revista Médica de Chile*. 2016;**144**:903-909. DOI: 10.4067/S0034-98872016000700012

[69] Al F, Haskaraca G, Yildiz S. Ultrasound-assisted chilling to minimize sodium hypochlorite use while reducing pathogens and preserving quality in chicken breast meat. *LWT*. 2021;**213**:117107. DOI: 10.1016/j.lwt.2024.117107

[70] Hamann D, Saorin Puton BM, Colet R, Steffens J, Ceni GC, Cansian RL, et al. Active edible films for application in meat products. *Research Society and Development*. 2021;**10**(7):e13610716379. DOI: 10.33448/rsd-v10i7.16379

[71] Summo C, De Angelis D. The importance of edible films and coatings for sustainable food development. *Food*. 2022;**11**:3231. DOI: 10.3390/foods11203221

[72] Heras M, Huang C-C, Chang C-W, Lu KH. Trends in chitosan-based films and coatings: A systematic review of the

incorporated bio preservatives, biological properties, and nanotechnology applications in meat preservation. *Food Packaging and Shelf Life*. 2024;**42**:101259. DOI: 10.1016/j.fpsl.2024. 101259

[73] Song D-H, Hoa VB, Kim HW, Khang SM, Cho SH, Ham JS, et al. Edible films on meat and meat products. *Coatings*. 2021;**11**:1344. DOI: 10.3390/coatings11111344

[74] Rahamadi PT, Adhitasari A, Paramita V, Yulianto ME, Ariyanto HD. Effect of different starch in the characteristics of edible film as functional packaging in fresh meat on meat products: A review. *Materials Today: Proceedings*. 2023;**87**:192-199. DOI: 10.1016/j.matpr.2023.02.396

[75] Sánchez-Ortega I, García-Almendarez BE, Santos-López EM, Amaro-Reyes A, Barboza-Corona JE, Regalado C. Antimicrobial Edible Films and Coatings for Meat and Meat Product Preservation. *The Scientific World Journal*. 2014;**1**:248935. DOI: 10.1155/2014/248935

[76] Vargas M, Albors A, Chiralt A. Application of chitosan-sunflower oil edible films in two pork meat hamburgers. *Procedia Food Science*. 2011;**1**:39-43. DOI: 10.1016/j.profoo.2011.09.007

[77] Sharma R, Bhat Z, Kumar A, Kumar S, Bhatti MA, Jayawardena R. *Rubia cordifolia*-based novel edible film for improved lipid oxidative and microbial stability of meat products. *Journal of Food Processing and Preservation*. 2021;**45**(7):e15654. DOI: 10.1111/jfpp.15654

[78] Silva SJ, Sanba N, Mendes J, Pires JRA, Rodrigues C, Curto Gomes A, et al. Sustainable food packaging with chitosan biofilm reinforced with

nanocellulose and essential oils.
Macromolecules. 2023;**3**:704-722.
DOI: 10.3390/macromol3040040

[79] Hashemi SS, Khorsidiam N, Mohammadi M. An insight into the potential application of symbiotic edible films and coatings in food products. Frontiers in Nutrition. 2022;**9**:875368. DOI: 10.3389/fnut.2022.875368

[80] Antonio C, Difonzo G, Faccia M, Caponio F. Effect of edible coatings and films enriched with plant extracts and essential oils on preserving animal-derived foods. Journal of Food Science. 2023;**89**:748-772. DOI: 10.1111/1750-3841.16894

Exploring the Crucial Role of the Gut Microbiome in Advancing Food Processing Technologies

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Abstract

The human gastrointestinal tract contains trillions of microorganisms called the gut microbiome, which is essential for preserving health and affecting the results of nutrition. Beyond its physiological roles, it is now clear that the gut microbiota has a major influence on food processing technologies, creating new opportunities for innovation in the food sector. This review explores the complex interactions between food systems and the gut microbiota, highlighting how it influences nutrient absorption, propels fermentation, and aids in the creation of functional meals. The development of probiotic and prebiotic-enriched products has been influenced by advances in our understanding of microbial metabolism, improving gut health and nutrition in general. Gut microbiota insights are now being used to refine traditional fermentation methods, improving product quality, flavor, and health benefits. Furthermore, personalized nutrition is now possible because of advanced omics technologies, which enable the development of customized food items that suit each person's unique microbiota makeup and medical requirements. Beyond its health benefits, the application of microbiome science to food processing tackles sustainability issues including creating nutrient-dense foods for the world's population and minimizing food waste through microbial bioconversion. However, maintaining the stability, safety, and legal compliance of meals that target the microbiome is still a major obstacle. The potential of gut microbiome research to revolutionize food processing technologies is highlighted in this book chapter, highlighting its ability to spur innovation and promote a healthier, more sustainable future for the global food business.

Keywords: gut microbiota, probiotic, prebiotic, food processing, microbial conversion

1. Introduction

The group of bacteria that live in the gut, referred to as the gut microbiota, has become an important factor in coordinating complex interactions with organs outside of the gut. The gut microbiota significantly impacts basic physiological functions and a person's vulnerability to different diseases through complex interactions with

endocrine, humoral, immunological, metabolic, and neurological pathways. There are more than 100 bacterial species in this complex community, home to trillions of microorganisms. These species have almost 150 times more genes than the human genome. Notably, the makeup of the microbiota has been found to vary greatly among several anatomical locations; of these, the gut microbiota is particularly significant in preserving host health [1].

By coordinating a symphony of vital processes, including preserving intestinal integrity, producing mucus, encouraging intestinal epithelium regeneration, fermenting food and generating bioactive metabolites like those from phenolic compounds, synthesizing vitamins, boosting the immune system, and protecting against infections, the gut microbiome plays a critical role in preserving general health. Additionally, it contributes to the development of the innate immune system and serves as a mediator for the body's processing and reaction to environmental cues [2, 3].

Numerous human disorders, such as inflammatory, metabolic, cardiovascular, hepatic, neurological, urinary, respiratory, and skin conditions and various cancers, have been linked to gut dysbiosis, according to population-based research as mentioned in **Figure 1**. So, it is essential to comprehend the elements that affect the composition of the gut microbiome in order to create plans for fostering a diversified and healthy gut microbiota, which can improve general health and guard against a

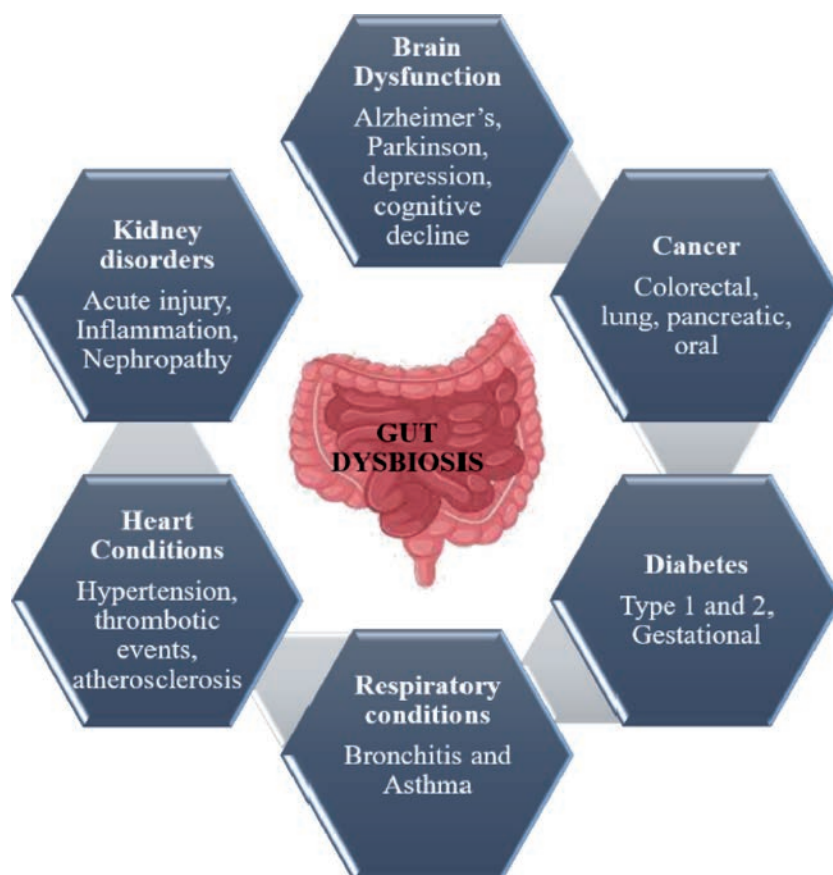


Figure 1.
Multiple conditions reported on the onset of gut dysbiosis.

number of diseases. Although the gut microbiota is greatly impacted by the host's genetic makeup and early stages of life, it is still flexible and can be impacted by exposure to a variety of environmental factors, including nutrition. As a result, the microbes that comprise the gut microbiota react differently depending on the kind and amount of food consumed. Dietary factors actually affect the number of different microbial species that live in the gut, which in turn produce vital metabolites and signals that regulate the host's health [4].

For decades, anthropologists have worked to understand nutritional history, in part because dietary shifts were likely associated with important cultural and physical changes. It is believed that dietary practices have a significant impact on the variety of the human gut microbiota. Consequently, a variety of co-evolutionary mechanisms lead to host-bacterial relationships over an extended period of time, with the microbe and host interacting favorably due to their mutual advantages. Although food processing has always been necessary for human society to guarantee the safety, security, palatability, and digestibility of food products, recent socioeconomic advancements have led to the creation of food items and eating patterns that raise questions about possible health effects [5].

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Since the nineteenth century, a range of physical, thermal, and chemical techniques have been developed, starting with canning and pasteurization. These techniques include milk centrifugation, sterilization, and oil bleaching. The food industry's management boards focused on consumer satisfaction while pursuing convenience and profit, especially after World Wars I and II. Furthermore, our food system has grown increasingly global since the 1980s, with massive multinational firms dispersing goods and crops worldwide. Due to these advancements, a wide range of highly processed foods have emerged [7]. These foods are usually delicious and reasonably priced, but they contain many calories, sugar, fat, salt, and little fiber. They are incredibly sterile, containing the fewest microorganisms possible for preservation. The fundamental premise is that stomach microbes flourish on substances that the human body is unable to utilize. Stated differently, inaccessible dietary components serve as the real sustenance for commensal bacteria in the stomach. The host may benefit from a food processing design that reduces bioaccessibility when consuming too many macronutrients and high-calorie meals. It is commonly known that eating a wide variety of foods increases microbiota diversification and the array of microbial genes that may be indicators of health status [8, 9].

Human microbiomes and their interactions with other microbial ecosystems have been the focus of recent worldwide projects aiming at improving our understanding of their impact in global health. Identifying dietary factors that may damage (or be influenced by) the gut microbiota and the underlying molecular pathways were the primary objectives of these programs, as was defining the ways in which the human microbiome influences health [10]. The interaction between the gut microbiota and dietary xenobiotics—such as specific food additives and microplastics—and their

possible effects on human health are the main topics of this article. It also identifies research goals to fill in knowledge gaps and outlines a number of research components that might be included in safety studies to guide risk assessment.

The impact of certain dietary components on microbial diversity, the potential modulation of the gut microbiota through probiotics and prebiotics, and the need for personalized microbiome analysis to account for individual variations in microbial composition are just a few of the important aspects of the gut microbiome that are overlooked in today's nutritional guidelines for a healthy diet in this developing field. It is still difficult to modify a proper diet in order to create a "healthy gut microbiota." In order to close information gaps regarding community dynamics, the interaction between the microbiome and its host, its function in disease pathogenesis, and its potential therapeutic applications, the analysis of the human gut microbiome is still in its infancy [11]. To uncover this intriguing and mysterious field of study, more thorough investigation is required.

2. Influence of the gut microbiome on macronutrient and micronutrient metabolism

Microbial metabolism accounts for most of the gut microbiota's contributions to human superorganism physiology, with bacteria being the main contributors to ecosystem functioning in relative genetic content. The immediate benefit is usually the microbial metabolism of both endogenous and exogenous substrates to nutrients that the host can use. Still, metabolites can also influence host cell physiology and gene expression to modify the immune system [12]. The colon is the primary location of this fermentation because of its comparatively high pH and transit time, low cell turnover, and redox potential, which create more conducive circumstances for bacterial growth. That does not, however, negate the significance of the microbiota at other locations; for instance, it has been demonstrated that the small intestinal microbiota controls the host's metabolism and absorption of nutrients. Additionally, various metabolic activities can enable the microbiota to occupy as many ecological niches as possible and competitively prevent pathogen colonization at all locations [13]. The pH is locally lowered by the high concentrations of the primarily acidic fermentation byproducts, making the environment less welcoming to these arriving intruders. However, certain gut microorganisms' fermentation processes might produce harmful substances that can harm the host's epithelium and induce inflammation [14].

The three macronutrients found in the human diet—carbohydrates, proteins, and fat—can either resist primary digestion entirely because of the intrinsic structural complexity of certain biomolecules or escape primary digestion once the amount consumed surpasses the rate of digestion. The form and size of food particles, the composition of the meal (affected by the relative ratios of macronutrients and the presence of anti-nutrients like α -amylase inhibitors), and transit time are some of the factors that can affect digestive efficiency, which in turn modulates the substrates available to the gut microbiota for consumption [15]. The beneficial metabolites produced from the gut microbiota are depicted in **Figure 2**. Also, the metabolic activities of gut microbes can potentially affect the bioavailability of micronutrients to the host. Essential co-factors for host energy metabolism and gene expression regulation, including B vitamins, can be endogenously synthesized by colonic bacteria [16].

The enormous number of carbohydrate-activating enzymes that have been revealed in the human gut microbiota demonstrates how complex dietary

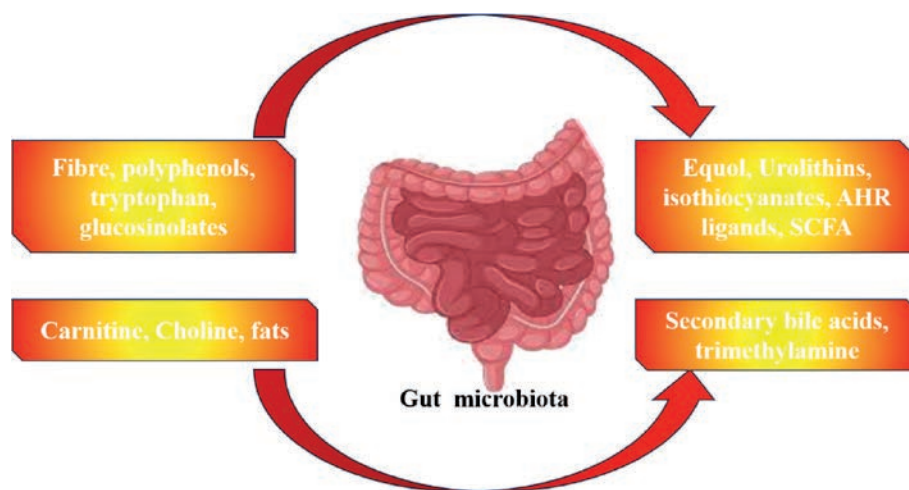


Figure 2.
 Gut microbiota-produced dietary precursors and potentially beneficial metabolites.

polysaccharides can be connected through a wide variety of linkages between monosaccharide units. The fact that *Bacteroides thetaiotaomicron* has 260 glycoside hydrolases in its genome alone, for instance, highlights the need for adaptation in evolution to optimize the use of resistant starch and the variety of fibers that are available for human consumption. Human cells, on the other hand, only make a small number of these enzymes, so they must rely on gut microorganisms to convert the remaining complex carbohydrates into energy [17]. After the rate-limiting step of primary degradation is completed, the gut microbiota can quickly consume the resulting monosaccharides with little to no interconversion required for substrates to enter the Pentose Phosphate, Entner-Doudoroff, or Embden-Meyerhof-Parnas pathways for pyruvate and subsequent ATP production. On the other hand, proteases can break down conserved peptide bonds found in dietary proteins. While gut bacteria can produce aspartic, cysteine, serine, and metalloproteases, the number of these bacterial enzymes in a typical fecal sample is greatly outnumbered by proteases originating from human cells. However, compared to monosaccharide units, the 20 proteinogenic amino acid building blocks need more interconversion steps to be incorporated into biochemical pathways. As a result, it is uncommon for a particular gut microbial species to be able to ferment all of the amino acids in order to produce energy. Furthermore, the poorly understood host digestion processes in the small intestine have an equally important impact on how these substrates are presented to the gut microbiota [18–20].

The significance of the gut microbiota in preserving the equilibrium of host vitamins and minerals must also be discussed, as must any potential therapeutic advantages and health consequences. Micronutrients are essential to the growth and biological processes of microbes. Therefore, it should come as no surprise that the micronutrient intake can influence the composition and functional organization of the gut microbiota. By encouraging the growth and colonization of the intestinal mucosa by advantageous genera like *Bifidobacterium*, *Lactobacillus*, and *Roseburia*, for instance, dietary supplementation with vitamins B, C, D, and E significantly influences the composition of the microbiome [21]. Minerals like calcium, iron, zinc, magnesium, and phosphorus can also influence the human gut microbiome. Specifically, iron supplementation may cause a decrease in *Bifidobacterium* and an

increase in *Lactobacillus* levels in children, high calcium intake has been linked to a higher percentage of *Clostridium* cluster XVIII in men, and phosphorous supplementation increases microbial diversity and short-chain fatty acid (SCFA) levels in the stool. However, by regulating their absorption, especially that of phosphorous and calcium, and synthesizing vitamins, including vitamin K and the water-soluble fraction of B vitamins, different members of the intestinal microbial ecosystem have been demonstrated to affect the bioavailability of micronutrients [22–24].

Also, the gastrointestinal tract's mineral absorption during digestion is directly influenced by the gut microbiota, and it also produces a variety of enzymes that are unique to the colonic microorganisms and aid in the release of minerals from meals. These include the bacterial phytases that catalyze the hydrolysis of phytic acid, which is present in many plant tissues, and release forms of minerals including calcium, magnesium, and phosphate that can be used [25]. The genus *Lactobacilli* is comparatively less when comparing the gut microbiota of women with iron deficiency to controls. Further research in humans showed that *Lactobacillus plantarum* increases the amount of hydrated ferric iron Fe (III) *via* lactic fermentation, which leads to enhanced iron absorption, even though it is unclear whether less abundant *Lactobacilli* cause iron deficiency or if the genus is reduced as a result of iron deficiency. Furthermore, two investigations in *Caenorhabditis elegans* demonstrated that the bacterially generated siderophore enterobactin production promotes mitochondrial iron uptake, enhancing host iron intake. By identifying a clear advantageous function of a chemical produced by commensal bacteria in supporting the host's iron homeostasis, this discovery brought about an unexpected advantage for the host [26, 27]. More research should be done on the actions of particular bacterial species to improve or avoid micronutrient insufficiency. Given this, comparing the contributions of endogenous micronutrients derived from bacteria to exogenous micronutrients obtained from diet and supplements would be intriguing.

3. Role of probiotics and prebiotics in food processing

Prebiotics are non-digestible food ingredients like inulin or different oligosaccharides that have been demonstrated to increase beneficial bacterial populations in the colon. At the same time, probiotics are bacterial species especially beneficial to human health (primarily the gastrointestinal tract) when taken in sufficient quantities by individuals. Therefore, maintaining homeostasis and the balance of intestinal microbiota eubiosis are essential to the proper operation of the gastrointestinal system and, consequently, to the organism's health. Many microbes that inhabit the gastrointestinal tract have the potential to either favorably or unfavorably affect how well the digestive system and other bodily systems operate [28]. Additionally, taking probiotics and prebiotics separately or in combination can help restore the intestinal microbiota's imbalance in quality and quantity (dysbiosis), which can lessen the negative effects of poor diet, antibiotic use, infections, and sepsis. Because oral administration can assist in enhancing intestinal microbiota balance, it is the most convenient approach to administer probiotic products. Two kinds of bacteria found in foods high in probiotic strains (such as Greek yogurt and kefir) are crucial for intestinal function. These two kinds, which belong to Lactobacillaceae and Bifidobacteriaceae, compete with intestinal pathogens like *Escherichia coli* and *C. perfringens*. Consuming probiotics containing these particular strains of bacteria has been shown to

significantly boost their numbers, which occurs in tandem with a decrease in harmful intestinal microbes [29].

To help maintain the microbiota eubiosis, protection against gastrointestinal pathogens, boost immunity, maintain normal serum cholesterol levels, control blood pressure, prevent the development of certain cancerous conditions, improve nutrient processing and food nutritional value, promote vitamin synthesis, improve protein digestion, stimulate the production of antimicrobial agents, and fight infections, probiotics must be consumed in sufficient amounts through functional foods [30]. Several research studies support the idea that prebiotics can be used to restore human health, support the makeup of a healthy gut microbiota, and increase the proliferation of particular probiotic species, as we have discussed. Prebiotic fermentation products have significant positive health impacts on people, such as preventing colitis and colon cancer and having anti-inflammatory and anti-apoptotic properties [31]. The human health benefits of probiotic strains are mentioned in **Figure 3**.

Implementing “-omic” techniques could clarify the fundamental mechanisms of gut microbiota interaction, including selectivity and specificity on fermentable carbohydrates and other components and cross-feeding occurrences. Because prebiotics aim to maintain a healthy microbiome or reverse microbial dysbiosis, their use attracts a lot of interest. By controlling food molecules at the nanoscale, food bioactives can be encapsulated in micro- and nanoparticles, which could alter and improve desirable properties to create functional foods. The literature has already used encapsulation techniques to create synbiotics [32].

However, creating synbiotics suggests a promising strategy for creating functional foods that will eventually help alter gut flora and transmit health benefits. To compete with the natural microbiota, one of the goals is to boost and preserve cell viability following transit through the stomach and small intestine. The choice of a prebiotic candidate that will improve the probiotic strain’s capacity to endure in the gastrointestinal

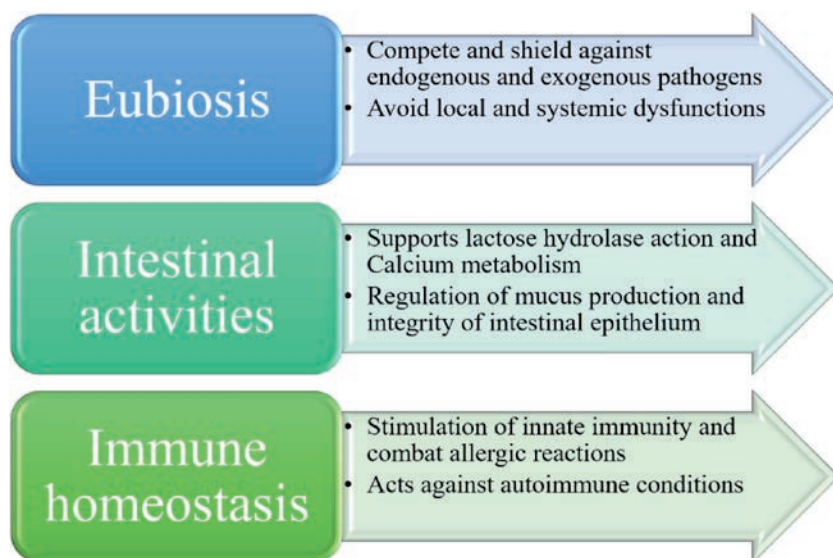


Figure 3.
Health benefits of probiotic strains.

tract will provide another significant obstacle. According to this perspective, looking into the selective fermentation of possible prebiotic chemicals and creating innovative, sustainable formulations is essential. Renewable resources may be assessed as starting materials for the extraction of potential prebiotics [33, 34].

4. Food processing techniques influencing the gut microbiome

In the last several years, the subject of gut microbiota and the microbiota-gut-brain (MGB) axis has taken center stage in studies and publications. In addition to preserving regular physiological metabolism, the gut microbiota serves as a dynamic interface between the host, diet, and environment. Large amounts of trans and saturated fat, added sugar, salt, and food additives are included in modern ultra-processed foods (UPF), which have a negative impact on both physical and intestinal health. Furthermore, these detrimental elements directly alter the metabolism of microorganisms and the functions of the gut microbiota, which may then affect the neuronal network [35].

The detrimental effects of trans fat, added sugar, and salt on gut and brain functioning have been extensively studied; however, the effect of food additives on the MGB axis has received comparatively less attention. According to data from several research, food additives may be connected to inflammation and metabolic disorders. Additionally, they might change the microbial metabolites and composition of the gut microbiota, which could impact behavior and cognition. Thus, based on the most recent studies, we stress that food additives such as emulsifiers, artificial sweeteners, colorants, and preservatives interact with the gut flora and may impact changing the brain and behavior. Future research should examine if gut dysbiosis mediates the impact of UPF on behavior and cognitive disorders [9]. The importance of balance between the microflora is explained in **Figure 4**.

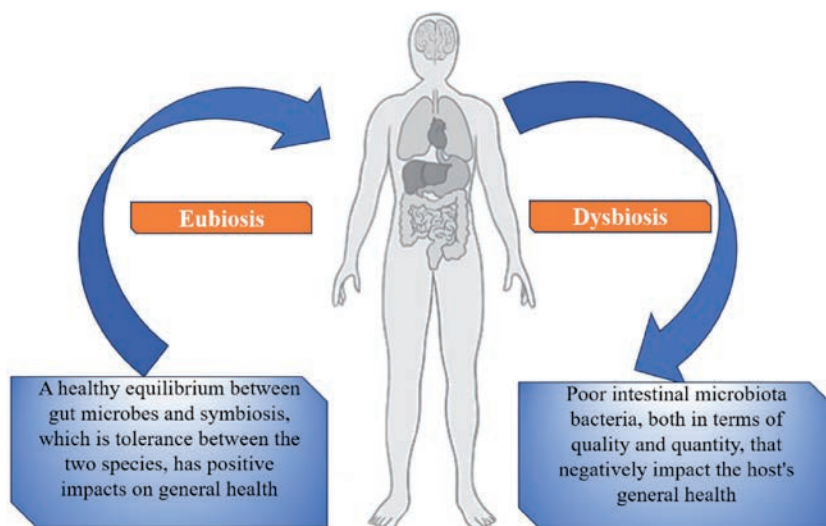


Figure 4.

The importance of gut microbiota-host axis that depends on a satisfactory balance between the group of microorganisms.

4.1 Thermal techniques to increase nutrient bioavailability

Food undergoes significant changes due to industrial and domestic cooking, which raises the bioavailability of macro- and micronutrients generally. The most significant effect is starch gelatinization, which occurs when heat treatment causes physical changes in starch granules that make them difficult for humans to digest. Gelatinized starch quickly turns into glucose and serves as a good substrate for human amylases. Additionally, heat-induced protein denaturation typically makes them easier to digest, particularly for plant proteins [36]. In certain situations, however, this impact can be lessened or even reversed by thermal protein aggregation or thermally induced protein cross-linking. The plant food matrix swells as a result of thermal treatment, which is necessary for small molecule bioaccessibility. There is strong evidence that cooking at home, particularly with steaming and a microwave, improves phytochemical bioaccessibility. The gold standard in this regard is the impact of heat treatment on carotenoid bioavailability: processed tomatoes, particularly those that contain oil, offer three times as much bioavailable lycopene as their raw counterparts [37, 38]. Overall, a cooked food diet provides less phytochemicals to the microbiota than a matching raw food diet. Furthermore, the gut biotransformation of every food component is more noticeable when the vegetable food matrix opens. There is some evidence that blanching green leaves and boiling tubers results in considerable phytic acid losses (5–15%). By freeing them from entrapment in the plant matrix, thermal processing can also increase the bioavailability of carotenoids, thiamin, vitamin B-6, niacin, and folate. It is yet unknown, though, if these increases in bioavailability offset the declines in the activity of water-soluble and heat-labile vitamins (such as thiamin, riboflavin, vitamin C, and folate). Shorter cooking periods and steaming rather than boiling are advised to reduce the oxidation of carotenoids and loss in cooking water [39].

4.2 Drying

Drying is a technique that lowers a product's water content to a point where it prevents microbiological growth and reproduction, extending its shelf life and avoiding spoiling. Freeze-drying, vacuum drying, solar drying, and air drying are some of the several drying techniques. While high-temperature drying is typically linked to higher losses of these compounds, freeze-drying is the most successful technique for maintaining the polyphenol content in products. However, the length of the drying process also affects polyphenol retention, in addition to temperature. The particular types of polyphenols present substantially impact the final polyphenol level in a product [40].

Furthermore, the time of harvest can affect antioxidant activity and polyphenol levels. Higher quantities of polyphenols have been found in extracts from olive leaves gathered in the summer and fall; this pattern holds even after the leaves are dried at high temperatures. Higher exposure to sunlight during these seasons is probably linked to this rise in polyphenol concentration. Polyphenols in food can be preserved by drying, but the right temperature, time, and processing technique must be used. Since lower temperatures and freeze-drying are linked to decreased polyphenol losses or even an increase in their concentration in the finished product, they seem to be useful techniques [41].

4.3 Fermentation

During fermentation, microorganisms may break down the glycosidic bonds of high-molecular-weight polyphenols, which could affect how intestinal microbes

directly use them. Furthermore, polyphenol-related enzymes such as glycosidases, phenolic acid decarboxylases, esterases, and tannases may be produced during fermentation. These enzymes can increase the bioavailability and bioactivity of polyphenols by releasing those that were previously bound within the dietary matrix. Moreover, high-molecular-weight polyphenols can change into low-molecular-weight forms by fermentation. The enzymatic activity of the microorganisms involved in the fermentation process frequently causes this change. For example, ellagic tannins may be converted to intermediary compounds like gallagic acid and punicalin during pomegranate fermentation, producing ellagic acid [42].

High-molecular-weight polyphenols are usually broken down into smaller molecular forms through fermentation, and these smaller molecular forms are typically linked to enhanced antioxidant activity. Increased polyphenol bioactivity and bioavailability are frequently observed in fermented foodstuffs. Consuming fermented soy, for example, changed the composition of isoflavones, improving their absorption and raising the bioavailability of particular plasma metabolites, according to a study conducted on humans [43]. Also, the polyphenol content of the product can have a favorable effect on fermentation by encouraging the growth of good bacteria and inhibiting the growth of harmful ones. Foods that undergo fermentation can have higher levels of polyphenols and have improved bioavailability and bioactivity. Because enzymes break down high-molecular-weight polyphenols during this process, higher amounts of polyphenols are linked to it. Furthermore, the growth of harmful microbes might be inhibited by polyphenols during fermentation [44].

Additionally, the type of raw material, the bacterial strains utilized, and the duration of fermentation are important variables that can greatly affect the amount of polyphenols in products. The right fermentation time must be chosen to optimize the advantages of polyphenols while reducing their breakdown. Because certain raw materials have larger levels of polyphenols that might be released or augmented during fermentation, the kind of raw material is also crucial. Furthermore, the bioavailability of polyphenols can be improved by selecting bacterial strains such as lactic acid bacteria. Furthermore, whether the fermentation process is regulated is a crucial factor to consider because regulated circumstances offer consistency that can assist in maintaining or even raising the amount of polyphenols [45].

4.4 Cold processing

Freezing is a cold food processing technique used to prolong product shelf life by slowing down physicochemical and biological activities. In general, this method has little effect on the amount of polyphenols. For example, the amounts of polyphenols in fresh raspberries were unaffected by freezing them at -30°C . Furthermore, freezing has been identified as a very promising first processing technique for enhancing black garlic's functional qualities. In a similar vein, freezing organic butternut squash was linked to an increase in bioaccessible polyphenols rather than a decrease in polyphenol content. A product's polyphenol concentration may vary depending on how quickly it is frozen [46, 47].

Rapid freezing produces smaller ice crystals and may result in less cellular damage than slow freezing, which tends to produce larger ice crystals that can harm cell structures more. There is not much research on this subject, though, and what is known suggests that freezing may have a negative impact on the amount and bioactivity of polyphenols. Apples frozen at -50°C , for instance, have lower antioxidant activity

and polyphenol levels. Therefore, more investigation is required to determine the ideal freezing temperatures and processing techniques in order to optimize the final product's polyphenol concentration, bioavailability, and bioactivity [48, 49].

5. Microbial enzymes in food processing

Food preparation has long involved the use of microbes or enzymes. Novel enzymes with a broad range of uses and specificity have been created due to technological advancements, and new application areas are constantly being investigated [50]. Because they are more stable than plant and animal enzymes, microbial enzymes are important in the food industry. Their great consistency makes process adjustment and optimization simple, and they may be manufactured economically and with less time and space needed through fermentation processes. Several of these enzymes are used in many industrial sectors; for example, amylolytic enzymes are used in the food, detergent, paper, and textile industries [51]. They manufacture high fructose corn syrups, maltose syrups, crystalline glucose, and glucose syrups, among other products. They are used as detergents to get rid of stains that are made of starch. They are employed in the paper industry to lower the viscosity of starch so that paper can be coated appropriately. Amylases are used in the textile industry to size the warp of textile fibers. Likewise, there are several uses for enzymes such as lipases, xylanases, and proteases in the food industry [52]. The use of several enzymes in the food industry is mentioned in **Figure 5**.

Only roughly 5% of the more than 3000 enzymes that have been discovered are used in industry. Many industries now require far less energy as a result of the industrial use of enzymes, and the waste products produced by these applications are environmentally benign, biodegradable, and non-toxic. Additionally, using industrial

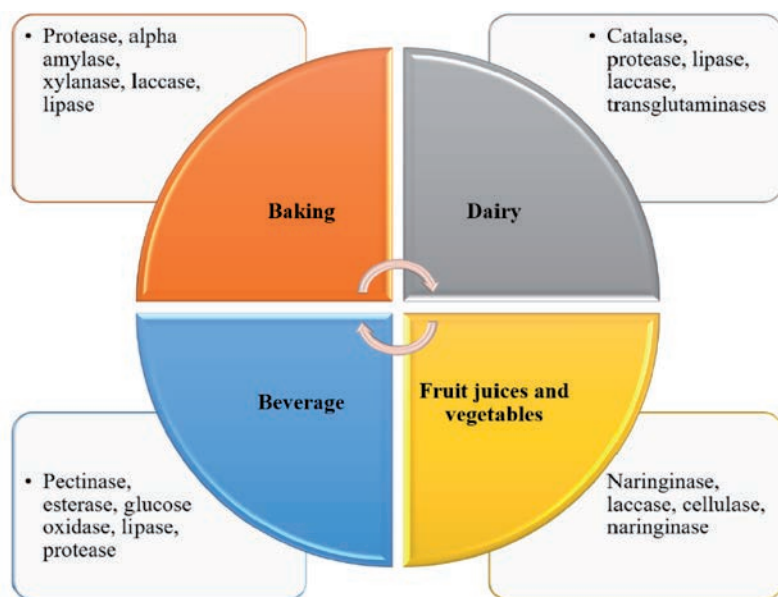


Figure 5.
Role of microbial enzymes in the food industry.

enzymes is more economical, and it is possible to genetically modify microorganisms to create better and more stable enzymes on a large scale. Because of this, several industries have adopted the usage of enzymes in place of production systems that rely on chemicals confirming once more the necessity of industrial enzyme manufacturing for a range of industrial uses [53]. The fact that some production conditions can be extremely harsh for the best enzyme activity is a disadvantage of using enzymes in industries. The enzymatic activity of enzymes may be impacted by the production's pH, pressure, temperature, and the presence of any inhibitors. For example, most enzymes function best at a neutral pH, about 37°C, and without inhibitors. To overcome this difficulty, industrial enzymes are produced from microbial sources rather than plant and animal sources. The microorganisms are easily accessible and can be easily cultivated in inexpensive growth media [54]. They have a very rapid rate of growth, and more significantly, the microorganisms' genomes may be altered using recombinant DNA technology to create enzymes that function best under various industrial production settings. Thus, thermophilic and hyperthermophilic microorganisms have created thermoactive and thermostable enzymes. Additionally, genetically modified microorganisms cultivated in selected growth conditions can create extracellular enzymes that can function best in an acidic or alkaline environment. The demand for industrial enzymes has increased due in large part to the fact that they are an environmentally friendly substitute for conventional and synthetic chemicals in many industrial processes, as opposed to the use of chemicals, which produces a lot of greenhouse gases. About 700 million kg of CO₂ are kept out of the atmosphere annually when enzymes are used in place of chemicals in industrial operations. Numerous enzyme-producing businesses have expanded as a result of the growing need for enzymes across a wide range of industries [55, 56].

6. Future directions on the understanding of gut microbiome and food processing technologies

Our understanding of how diet affects host microbial composition has improved because to the quick identification and quantification of gut bacterial taxa. Research involving the consumption of a certain food item shows how some bacteria typically react to the challenge of a particular nutrient. Probiotics, polyphenols, digestible and non-digestible carbs, protein, and lipids all cause changes in the microbiome that have a knock-on effect on the host's metabolic and immunologic indicators. For example, consumption of animal protein increases the number of bile-tolerant organisms like *Bacteroides*, *Alistipes*, and *Bilophila*, decreases the prevalence of the *Roseburia*/*E. rectale* group, and has a favorable correlation with overall microbial diversity [57].

Total anaerobic microflora counts and the relative abundance of *Bacteroides* and *Bilophila* appear to rise with a high-saturated-fat diet. A high-unsaturated-fat diet has not been shown to significantly change the gut bacterial profile in human studies; however, studies on mice have shown increases in *Verrucomicrobia* (*Akkermansia muciniphila*), lactic acid bacteria (*Lactobacillus* and *Streptococcus*), and Actinobacteria (*Bifidobacterium* and *Adlercreutzia*). Only non-digestible carbohydrates are observed to additionally enrich *Lactobacillus*, *Ruminococcus*, *Eubacterium rectale*, and *Roseburia*. Still, both digestible and non-digestible carbohydrates are frequently reported in the literature to enrich *Bifidobacterium* and decrease *Clostridia*. Finally, while lowering enteropathogenic *Clostridium* species, probiotics and polyphenols improve lactic acid bacteria and *Bifidobacterium* [58, 59].

Recent developments in the study of the microbiome present intriguing new resources that could improve human health. Using 16S rRNA amplicon sequencing, which uses the hypervariable sections of the bacterial 16S rRNA gene to identify bacteria present in biological materials, the majority of the studies examined in this publication surveyed the microbiome. Because 16S rRNA sequencing is inexpensive and very simple for sample preparation and bioinformatic analysis, it is the most often utilized technique for medical researchers to investigate the makeup of microorganisms. However, rather than function, 16S rRNA amplicon sequencing mainly offers information regarding microbial identity. Many researchers have used a shotgun metagenomic technique, which involves sequencing the entire bacterial genome, to look into the activities of the microbiome. Shotgun metagenomics offers information on both microbial identity and gene composition, but it is more expensive and requires more complex bioinformatics. Researchers can gain a better understanding of the functions of bacteria in human health by identifying the genes that they encode. This method will be an effective way to investigate the functioning of the microbiome since next-generation sequencing is becoming less expensive, sample preparation procedures have been improved, and metagenomic analysis has access to more bioinformatic tools. Another fascinating approach to examining the relationships between humans and bacteria is to do meta-analyses to correlate the microbiome with host genomes, transcriptomes, and immunophenotypes [17, 59, 60].

Another appealing, cutting-edge treatment strategy for numerous illnesses with significant genetic correlations is precision medicine. Notably, the microbiome is shaped by the host genotype as well, and the host-microbe relationship is essential to preserving human health. Consequently, a deeper comprehension of the interactions among genes, phenotypes, and the microbiome will offer crucial information about the potential applications of precision medicine. The finding that host-microbe interactions can be influenced by diet portends a viable new therapeutic strategy. It has already been discovered that the gut microbiota affects how well cancer immunotherapy works [61].

7. Conclusion

We are entering a time where we can use food to alter health in more ways and track the results using our metabolites or microorganisms. A vital component for a healthy microbiome, fiber has been neglected as discussions about fat and sugar have raged. It is no longer possible to overlook the detrimental effects that medications and processed food items have on the microbiome. Given the existing gaps in knowledge, we require clinical evidence that can be applied in clinical practice. Ideally, this will be achieved through randomized controlled studies that evaluate changes in gut microbiota composition and health outcomes using fecal microbiota transplantation or consistent matrices of probiotics or prebiotics.

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Conflict of interest

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References

- [1] Hou K, Wu ZX, Chen XY, Wang JQ, Zhang D, Xiao C, et al. Microbiota in health and diseases. *Signal Transduction and Targeted Therapy*. 2022;**7**(1):1-28
- [2] Gomaa EZ. Human gut microbiota/microbiome in health and diseases: A review. *Antonie Van Leeuwenhoek*. 2020;**113**(12):2019-2040
- [3] Iacomino G, Rufián Henares JÁ, Lauria F. Personalized nutrition and gut microbiota: Current and future directions. *Frontiers in Nutrition*. 2024;**11**:1375157
- [4] Lares-Michel M, Reyes-Castillo Z, Housni FE. Towards the characterisation of sustainable diet's gut microbiota composition and functions: A narrative review. *Gut Microbiome*. 2023;**4**:e15
- [5] David LA, Maurice CF, Carmody RN, Gootenberg DB, Button JE, Wolfe BE, et al. Diet rapidly and reproducibly alters the human gut microbiome. *Nature*. 2014;**505**(7484):559-563
- [6] Miclotte L, Van de Wiele T. Food processing, gut microbiota and the globesity problem. *Critical Reviews in Food Science and Nutrition*. 2020;**60**(11):1769-1782
- [7] Brewer MS. Natural antioxidants: Sources, compounds, mechanisms of action, and potential applications. *Comprehensive Reviews in Food Science and Food Safety*. 2011;**10**(4):221-247
- [8] Monteiro CA. Nutrition and health. The issue is not food, nor nutrients, so much as processing. *Public Health Nutrition*. 2009;**12**(5):729-731
- [9] Elechi JO, Sirianni R, Conforti FL, Cione E, Pellegrino M. Food system transformation and gut microbiota transition: Evidence on advancing obesity, cardiovascular diseases, and cancers—A narrative review. *Food*. 2023;**12**(12):2286
- [10] Moreno FJ, Garrido-Romero M, Pazos F, Benito C, Borrego-Yaniz G, Bowes C, et al. Relevance of gut microbiome research in food safety assessment. *Authorea Preprints*. 2023;**16**:264-289
- [11] Merten C, Schoonjans R, Di Gioia D, Peláez C, Sanz Y, Maurici D, et al. Exploring the need to include microbiomes into EFSA's scientific assessments. *EFSA Journal*. 2020;**18**(6):e18061
- [12] Thursby E, Juge N. Introduction to the human gut microbiota. *Biochemical Journal*. 2017;**474**(11):1823-1836
- [13] Li J, Jia H, Cai X, Zhong H, Feng Q, Sunagawa S, et al. An integrated catalog of reference genes in the human gut microbiome. *Nature Biotechnology*. 2014;**32**(8):834-841
- [14] Portune KJ, Beaumont M, Davila AM, Tomé D, Blachier F, Sanz Y. Gut microbiota role in dietary protein metabolism and health-related outcomes: The two sides of the coin. *Trends in Food Science and Technology*. 2016;**57**:213-232
- [15] Wong JM, Jenkins DJ. Carbohydrate digestibility and metabolic effects. *The Journal of nutrition*. 2007;**137**(11):2539S-2546S
- [16] Roager HM, Hansen L, Bahl MI, Frandsen HL, Carvalho V, Gøbel RJ, et al. Colonic transit time is related to bacterial metabolism and mucosal turnover in the gut. *Nature Microbiology*. 2016;**1**(9):1-9

- [17] Singh RK, Chang HW, Yan DI, Lee KM, Ucmak D, Wong K, et al. Influence of diet on the gut microbiome and implications for human health. *Journal of Translational Medicine*. 2017;**15**:1-7
- [18] Vergnolle N. Protease inhibition as new therapeutic strategy for GI diseases. *Gut*. 2016;**65**(7):1215-1224
- [19] Lin R, Liu W, Piao M, Zhu H. A review of the relationship between the gut microbiota and amino acid metabolism. *Amino Acids*. 2017;**49**:2083-2090
- [20] Oliphant K, Allen-Vercoe E. Macronutrient metabolism by the human gut microbiome: Major fermentation by-products and their impact on host health. *Microbiome*. 2019;**7**:1-5
- [21] Lv Z, Wang Y, Yang T, Zhan X, Li Z, Hu H, et al. Vitamin a deficiency impacts the structural segregation of gut microbiota in children with persistent diarrhea. *Journal of Clinical Biochemistry and Nutrition*. 2016;**59**(2):113-121
- [22] Li L, Somerset S. Associations between flavonoid intakes and gut microbiota in a group of adults with cystic fibrosis. *Nutrients*. 2018;**10**(9):1264
- [23] González A, Gálvez N, Martín J, Reyes F, Pérez-Victoria I, Dominguez-Vera JM. Identification of the key excreted molecule by lactobacillus fermentum related to host iron absorption. *Food Chemistry*. 2017;**228**:374-380
- [24] Engevik MA, Morra CN, Röth D, Engevik K, Spinler JK, Devaraj S, et al. Microbial metabolic capacity for intestinal folate production and modulation of host folate receptors. *Frontiers in Microbiology*. 2019;**10**:2305
- [25] Scheers N, Rossander-Hulthen L, Torsdottir I, Sandberg AS. Increased iron bioavailability from lactic-fermented vegetables is likely an effect of promoting the formation of ferric iron (Fe 3+). *European Journal of Nutrition*. 2016;**55**:373-382
- [26] Sewell AK, Han M, Qi B. An unexpected benefit from *E. Coli*: How enterobactin benefits host health. *Microbial Cell*. 2018;**5**(10):469
- [27] Qi B, Han M. Microbial siderophore enterobactin promotes mitochondrial iron uptake and development of the host via interaction with ATP synthase. *Cell*. 2018;**175**(2):571-582
- [28] Ho N, Prasad V. Probiotics, prebiotics, synbiotics and naturally fermented foods: Why more may be more. *Annals of Gastroenterology: Quarterly Publication of the Hellenic Society of Gastroenterology*. 2013;**26**(3):277
- [29] Charitos IA, Topi S, Castellaneta F, D'Agostino D. Current issues and perspectives in patients with possible sepsis at emergency departments. *Antibiotics*. 2019;**8**(2):56
- [30] Yang SY, Yoon KS. Effect of probiotic lactic acid bacteria (LAB) on the quality and safety of Greek yogurt. *Food*. 2022;**11**(23):3799
- [31] Ballini A, Charitos IA, Cantore S, Topi S, Bottalico L, Santacroce L. About functional foods: The probiotics and prebiotics state of art. *Antibiotics*. 2023;**12**(4):635
- [32] Sathyabama S, Vijayabharathi R. Co-encapsulation of probiotics with prebiotics on alginate matrix and its effect on viability in simulated gastric environment. *LWT-Food Science and Technology*. 2014;**57**(1):419-425

- [33] Kolida S, Gibson GR. Synbiotics in health and disease. Annual Review of Food Science and Technology. 2011;2(1):373-393
- [34] Delgado GT, Tamashiro WM. Role of prebiotics in regulation of microbiota and prevention of obesity. Food Research International. 2018;113:183-188
- [35] Song Z, Song R, Liu Y, Wu Z, Zhang X. Effects of ultra-processed foods on the microbiota-gut-brain axis: The bread-and-butter issue. Food Research International. 2023;167:112730
- [36] Rao AV. Processed tomato products as a source of dietary lycopene: Bioavailability and antioxidant properties. Canadian Journal of Dietetic Practice and Research. 2004;65(4):161-165
- [37] Juárez I, Ludwig IA, Bresciani L, Dall'Asta M, Mena P, Del Rio D, et al. Bioaccessibility of (poly) phenolic compounds of raw and cooked cardoon (*Cynara cardunculus* L.) after simulated gastrointestinal digestion and fermentation by human colonic microbiota. Journal of Functional Foods. 2017;32:195-207
- [38] Yadav SK, Sehgal S. Effect of domestic processing and cooking methods on total, HCl extractable iron and in vitro availability of iron in spinach and amaranth leaves. Nutrition and Health. 2002;16(2):113-120
- [39] Palermo M, Pellegrini N, Fogliano V. The effect of cooking on the phytochemical content of vegetables. Journal of the Science of Food and Agriculture. 2014;94(6):1057-1070
- [40] Arfaoui L. Dietary plant polyphenols: Effects of food processing on their content and bioavailability. Molecules. 2021;26(10):2959
- [41] Losada-Echeberría M, Naranjo G, Malouche D, Taamalli A, Barrajón-Catalán E, Micol V. Influence of drying temperature and harvesting season on phenolic content and antioxidant and antiproliferative activities of olive (*Olea europaea*) leaf extracts. International Journal of Molecular Sciences. 2022;24(1):54
- [42] Yang F, Chen C, Ni D, Yang Y, Tian J, Li Y, et al. Effects of fermentation on bioactivity and the composition of polyphenols contained in polyphenol-rich foods: A review. Food. 2023;12(17):3315
- [43] Ahmed IA, Babiker EE, Al-Juhaimi FY, Bekhit AE. Clove polyphenolic compounds improve the microbiological status, lipid stability, and sensory attributes of beef burgers during cold storage. Antioxidants. 2022;11(7):1354
- [44] Heo SJ, Kim AJ, Park MJ, Kang K, Soung DY. Nutritional and functional properties of fermented mixed grains by solid-state fermentation with *Bacillus amyloliquefaciens* 245. Food. 2020;9(11):1693
- [45] Sejbuk M, Mironczuk-Chodakowska I, Karav S, Witkowska AM. Dietary polyphenols, food processing and gut microbiome: Recent findings on bioavailability, bioactivity, and gut microbiome interplay. Antioxidants. 2024;13(10):1220
- [46] Salazar-Orbea GL, García-Villalba R, Bernal MJ, Hernández A, Egea JA, Tomás Barberán F, et al. Supplementary materials. Effect of Storage Conditions on the Stability of Polyphenols of Apple and Strawberry Purees Produced at Industrial Scale by Different Processing Techniques. 2023;71:2541-2553
- [47] Dalmau ME, Bornhorst GM, Eim V, Rosselló C, Simal S. Effects of freezing,

freeze drying and convective drying on in vitro gastric digestion of apples. Food Chemistry. 2017;**215**:7-16

[48] Chan KH, Chang CK, Gavahian M, Yudhistira B, Santoso SP, Cheng KC, et al. The impact of different pretreatment processes (freezing, ultrasound and high pressure) on the sensory and functional properties of black garlic (*Allium sativum* L.). Molecules. 2022;**27**(20):6992

[49] Kamiloglu S, Koc Alibasoglu E, Acoglu Celik B, Celik MA, Bekar E, Unal TT, et al. Bioaccessibility of carotenoids and polyphenols in organic butternut squash (*Cucurbita moschata*): Impact of industrial freezing process. Food. 2024;**13**(2):239

[50] Gurung N, Ray S, Bose S, Rai V. A broader view: Microbial enzymes and their relevance in industries, medicine, and beyond. BioMed Research International. 2013;**2013**(1):329121

[51] Pandey A, Nigam P, Soccol CR, Soccol VT, Singh D, Mohan R. Advances in microbial amylases. Biotechnology and Applied Biochemistry. 2000;**31**(2):135-152

[52] Souza PM. Application of microbial α -amylase in industry-a review. Brazilian Journal of Microbiology. 2010;**41**:850-861

[53] Patel AK, Dong CD, Chen CW, Pandey A, Singhania RR. Production, purification, and application of microbial enzymes. In: Biotechnology of Microbial Enzymes. India: Academic Press; 2023. pp. 25-57

[54] Singh S, Bajaj BK. Bioprocess optimization for production of thermoalkali-stable protease from *Bacillus subtilis* K-1 under solid-state fermentation. Preparative Biochemistry and Biotechnology. 2016;**46**(7):717-724

[55] Littlechild JA. Enzymes from extreme environments and their industrial applications. Frontiers in Bioengineering and Biotechnology. 2015;**3**:161

[56] Okpara MO. Microbial enzymes and their applications in food industry: A mini-review. Advances in Enzyme Research. 2022;**10**(1):23-47

[57] Goodrich JK, Waters JL, Poole AC, Sutter JL, Koren O, Blekman R, et al. Human genetics shape the gut microbiome. Cell. 2014;**159**(4):789-799

[58] von Schwartzenberg RJ, Turnbaugh PJ. Siri, what should I eat? Cell. 2015;**163**(5):1051-1052

[59] Wexler HM. Bacteroides: The good, the bad, and the nitty-gritty. Clinical Microbiology Reviews. 2007;**20**(4):593-621

[60] Kamada N, Seo SU, Chen GY, Núñez G. Role of the gut microbiota in immunity and inflammatory disease. Nature Reviews Immunology. 2013;**13**(5):321-335

[61] Vétizou M, Pitt JM, Daillère R, Lepage P, Waldschmitt N, Flament C, et al. Anticancer immunotherapy by CTLA-4 blockade relies on the gut microbiota. Science. 2015;**350**(6264):1079-1084

Novel Food Packaging: Insights and Trends

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and Shankar Lal*

Abstract

By shielding food from chemical, microbiological, and physical harm, proper packaging helps ensure that customers receive secure and clean food. A vital relationship between manufacturers and their customers is packaging; if done incorrectly, the items lose quality and consumers become less trusting. The food sector is highly aware of customer expectations due to recent trends in lifestyle change; as a result, the packaging industry must either evolve or remain stagnant. This circumstance has made it extremely difficult for the food packaging industry to develop novel food packaging methods. These days, the most promising topics for technical development are innovative packaging for food methods including aseptic, nano, active, bioactive, and intelligent packaging that are purposefully connected to food items. Technological developments in packaging may help keep food from spoiling by delaying ripening, oxygenation, water penetration, and ultraviolet interactions. By doing this, it supports people's personalized lifestyles and helps meet their demands across the food supply chain. This chapter reviews different innovative techniques and the role of nanotechnology in the development of food packaging.

Keywords: novel packaging, nanotechnology, nanofiber, bio-composite film, biodegradable, nano-spun fibers, active packaging, intelligent packaging, antimicrobial, nanoparticle

1. Introduction

Packaging is a socio-scientific field that works in society to deliver products to the final customer in the best possible condition for their intended purpose. Food packaging serves several different purposes, including preventing contamination and spoiling, facilitating food storage and transportation, and ensuring consistent measuring of ingredients. Mass commerce, extensive distribution, and relevant advertising are made feasible by enabling the creation and standardization of brands [1]. Food packaging is used to shield food from elements that might cause deterioration, such as light, heat, and humidity [2]. According to Grönman et al. [3], there are three different levels of packaging: primary, secondary, and tertiary.

The coating or film that immediately encloses and interacts with the food is known as primary packaging. Because it comes into close touch with the materials, primary packaging is the layer that has the biggest impact on food quality. Products that are packed in primary packaging are covered by secondary packaging. The outer packing used for storage, distribution, and bulk handling is known as tertiary packaging. Food safety may not always be ensured even with these three layers of packaging [4].

Since the phenomena of globalization have made it possible to access a vast array of foods from all over the world, it is becoming more and more important to preserve their original organoleptic qualities. In order to meet customer demands, the food sector was compelled to create new methods and technology. Accordingly, a number of packing methods have been developed [5]. The food sector commonly uses metals, glass, and synthetics as packaging materials. These materials have been employed in a variety of food packaging applications after being manufactured using standard processing techniques. Petroleum-based polyethylene is the most often used polymer in the food packaging industry.

It is difficult for PE and other synthetic polymers to break down biologically after being disposed of in land or water bodies, which can lead to dangerous levels of pollution [6]. In order to manufacture synthetic polymers, which take millions of years to refill, people worldwide are concerned about the loss of naturally occurring resources, such as fossils [7]. Although plastics are widely used because they are inexpensive, transparent, lightweight, and impermeable to gases and moisture, their use has a number of disadvantages, such as poor heat resistance, non-biodegradability, and the presence of toxic softeners, which contribute to environmental pollution and related harms [8]. In order to meet the demands of effective food protection against oxidation and microorganism attacks, research and development on novel packaging materials have advanced significantly. Food qualities and immediate freshness can be shown by clever food packaging materials with integrated or embellished sensory aspects [9]. Beyond their fundamental ability to act as a barrier against moisture and oxygen, food packaging materials can be made more active by adding active ingredients like antimicrobial nanoparticles, which keep bacteria away from food [6, 10]. Pathogenic bacteria growing on food can be killed or inhibited by such active packaging materials [11]. To increase the shelf life of both treated and raw food, the electrospinning process has also been used in the past 10 years to prepare packaging materials [12]. An examination of many sustainable solutions, ranging from broad examples to cutting-edge technologies like bio-nanocomposites and antimicrobial packaging, follows a historical history that places the development of food packaging materials in context. Innovative techniques such as hybrid nanoparticle coatings and multifunctional bio-nanocomposite films are showcased, along with more environmentally friendly manufacturing techniques and current developments in sustainable materials [13]. This chapter also covers the necessity for sustainable and creative packaging methods to meet the food industry's present packaging needs.

2. Conditions for an effective food packaging system

Figure 1 lists the essential needs for the food packaging system.



Figure 1.
 Important feature required for food packaging system.

3. Shelf life

Shelf life, according to the American Institute of Food Technologists, is “The period between a food product’s manufacture and retail purchase, during which time the product is in a state of satisfactory quality in terms of nutritional value, taste, texture, and appearance” [14]. Shelf life, according to the UK’s Institute of Food Science and Technology, is “The period of time that the food product will remain safe; be certain to retain desired sensory, chemical, physical, microbiological, and functional characteristics; and comply with any label declaration of nutritional data when stored under the recommended conditions” [14]. Shelf life is influenced by a number of factors, including extrinsic factors like temperature, humidity, light, and enzymatic, chemical, and non-enzymatic reactions, as well as intrinsic factors like water activity, pH, microflora, oxygen availability, and reduction potential. Food quality decline is caused by a variety of chemical, biological, and physical interactions. The physical and chemical makeup of food can be altered by enzymatic and non-enzymatic browning, fat oxidation, hydrolysis, lipolysis, and proteolysis [15].

4. Active and intelligent food packaging system

Conventional food packaging serves as a passive barrier to postpone the negative environmental impacts on the food item. However, food preservation is dynamically influenced by active packaging by enabling packages to interact with food and the environment [16, 17]. **Figure 2** describes how smart packaging has been led by different technologies and recent demands. Developments in active packaging have helped a variety of disciplines, including microbial growth, moisture migration, delayed oxidation, and controlled respiration rate. Aroma emitters, ethylene removers,

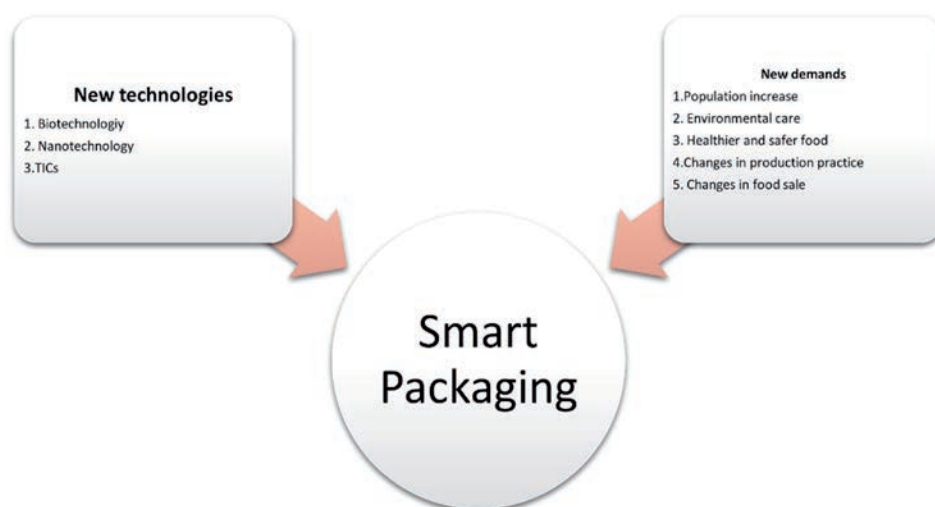


Figure 2.
Driving forces for the development of smart packaging.

odor absorbers, and carbon dioxide absorbers/emitters are further active packaging technologies. Although oxygen removal, moisture control, and purge have all been important aspects of active packaging, purge control has been the most profitable. The poultry industry's usage of drip-absorbing pads serves as one illustration [18].

Additionally, perm selectivity—the selective penetration of package components to different gases—can be controlled using active packaging technology. Through coating, lamination, micro-perforation, coextrusion, or polymer mixing, permeability can be changed to modify the ambient concentration of gaseous chemicals within a package in connection to the respiration kinetics or oxidation of meals. Some nanocomposite materials may also be used as active packaging by actively blocking the entry of moisture, carbon dioxide, and oxygen into food. Oxygen scavengers, ethylene scavengers, carbon dioxide scavengers/emitters, preservative releasers, moisture absorbers, ethanol emitters, flavor/odor absorbers, and temperature-regulating packaging are a few examples of popular active packaging applications utilized in the food business. The American Heritage Dictionary defines “intelligent” as “having certain data storage and processing capabilities” and “showing sound judgment and rationality” [19]. Advances in time and technology, including ripeness monitors, temperature regulators, biosensors, and radio frequency indicators, have led to intelligent packaging [20]. It senses, detects, records, and communicates in order to make decisions, increase storage time, and improve quality and safety. Food quality is monitored and communicated using intelligent or smart packaging [16, 19]. Biosensors, radio frequency identification, ripeness indicators, and time-temperature indicators (TTIs) are a few examples. These smart gadgets can be affixed to the exterior or inside of a package, or they can be integrated into packaging materials. **Figure 3** classifies smart packaging system into active and intelligent packaging.

4.1 Time-temperature indicator

It is described as a basic tool that provides information on a food product's time-temperature change. Irreversible changes that manifest as physical deformation, including color changes, might be chemical, biological, or physical [21].

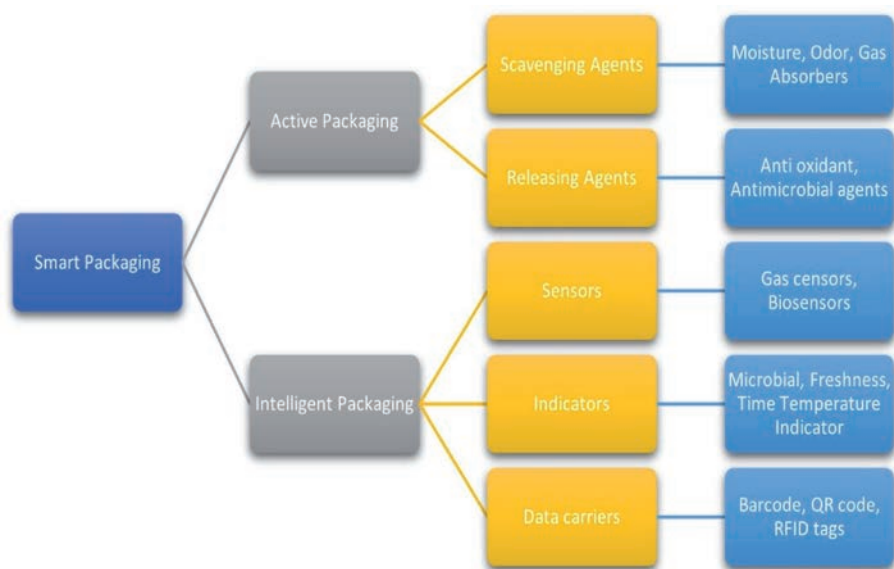


Figure 3.
 Classification of food packaging systems.

4.2 Freshness indicators

Two kinds of modifications can occur in fresh food products, including:

- i) Microbiological alterations, including the production of harmful substances, disagreeable odors, and pH shifts.
- ii) Oxidation of lipids and pigments results in discoloration, unpleasant chemical and biological interactions, and tastes and aromas. A food product's quality can be immediately shown via a freshness indicator. The response between the indicator and the metabolites created during the development of bacteria in the product allows for the indication of microbiological quality. An indication that particularly indicates spoiling (lack of freshness) of a product would be perfect for quality control of packaged items, in addition to temperature abuse or packaging leakage. Consequently, regardless of the “use-by” date, customers are urged not to utilize such items [22]. The purpose of this package indicator is to guarantee product freshness both during purchase and consumption. Perishable goods including milk, fruits, vegetables, cakes, and other cold items can be packaged with it [23].

4.3 Pathogen indicators

Through the detection of immobilized antibodies, this aids in determining the presence of harmful microorganisms. One material used to create polyethylene-based packing materials with this kind of indication is Toxin Guard TM, which is sold commercially. This occurs when the material comes into contact with the analyte (toxin, bacterium), which first binds to an antibody that has been precisely tagged and then to a trapping antibody that is printed in a particular pattern.

4.4 Indicators of leaks

Food quality may be tracked using leak indicators based on carbon dioxide and oxygen. When these gases are present or absent, a chemical or enzymatic reaction causes these indicators to change color. The development of non-toxic and irreversible O₂ sensors to ensure O₂ absence in oxygen-free food packaging techniques, like packing under nitrogen or vacuum, has gained more attention. Lee [24] created a UV-activated colorimetric O₂ indicator by employing TiO₂ nanoparticles by using UVA light to photo-sensitize the reduction of methylene blue (MB) by triethanolamine in a polymer encapsulating. When exposed to UV radiation, the sensor bleaches and remains colorless until it comes into touch with oxygen, which causes it to return to its former blue hue. The pace of color recovery is closely correlated with the amount of oxygen exposure.

5. Modified atmosphere packaging

A technology known as modified atmosphere packaging (MAP) uses a prepared gas combination to create air within the package before it is sealed. The composition of the in-package atmosphere cannot be changed after the package is sealed [25]. The respiration of the product's contents and/or solution of some of its gases, however, may cause its composition to alter while it is being stored. In contrast, vacuum packing removes air from the product prior to closing without adding any more gases.

In modified atmosphere packaging, gases including oxygen, carbon dioxide, and nitrogen are used commercially. The food's pH is lowered by carbonic acid, which is a byproduct of carbon dioxide and water. It also prevents the growth of molds and certain aerobic bacteria [16]. Because they can withstand the gas, lactic acid bacteria may take the place of aerobic spoilage bacteria in meat that has been packed in a changed environment. Additionally, the majority of yeasts are carbon dioxide resistant. Carbon dioxide has minimal effect on anaerobic bacteria, such as those that cause food poisoning. As a result, MAP products made from these microbes may pose a health risk. Carbon dioxide concentrations between 5% and 50% suppress molds and some aerobic Gram-negative bacteria [26]. Generally speaking, a gas's inhibitory power increases with concentration. As the temperature drops, carbon dioxide's ability to suppress bacteria rises. By replacing oxygen, nitrogen, on the other hand, only works to stop lipids from oxidizing. It is a bulking ingredient that keeps MAP packets from collapsing when the carbon dioxide dissolves in the meal because of its poor water solubility [25, 27]. Sulfur dioxide has been used to prevent the formation of mold and germs in some soft fruits and fruit juices due to its antibacterial qualities. Moreover, argon, helium, xenon, and neon have been utilized in the MAP of various foods [16]. MAP packaging is available as thermoformed trays or pouches with heat-sealed closures. These trays and pouches must be made of materials that have low gas permeability (CO₂, N₂, and O₂), with the exception of fresh product packaging. Polyvinylidene chloride (PVDC), polyamides, polyester (PET), and polyethylene are used in different combinations to create laminates.

6. Nanotechnology

Nanotechnology is a novel system that employs materials or devices with lengths ranging from 1 to 100 nm [28]. Nanomaterials and nanotechnology are extremely

tiny, measuring fewer than 100 nm. Nanotechnology is now being used by more than 400 enterprises worldwide for the processing of food and packaging [27, 29]. Researchers are currently concentrating on packaging materials with antibacterial and biodegradable qualities in the food industry. The use of polysaccharides such as cellulose, pullulan, agarose, starch, and chitosan improves the food packaging materials' biodegradable qualities, whereas the addition of metal nanoparticles improves their antibacterial qualities.

Nanofibers, nanorods, cellulose, nanotubes, nanoclays, and other materials can be used in packaging materials and are believed to provide them with physical strength and stiffness [30]. The barrier qualities of the packing material are improved by addition of nanoparticles to the conventional polymer layer, such as the vacuum-deposited Al coating on polyethylene sheets [30]. Nanotechnology provides food safety in terms of packaging to provide a longer shelf life for food products by reducing nutrient loss [31]. In the context of intelligent packaging, food packaging materials, such as nanoparticles, not only extend food's shelf life but also prevent food spoilage, ensure food safety, and provide insight into the food's history.

Ag nanoparticles and PP (polypropylene) are components of a newer, longer TM nanocomposite that aids in pathogen suppression. Montmorillonite, a naturally occurring clay that may be created from volcanic ash or other minerals, is used to create the nanoparticles in the highly advanced packing approach [32]. The use of Ag, Cu, Zn, and TiO₂ nanoparticles in the production of food packaging materials was also covered. These materials included meat products (fresh-cut beef), fruit (apples, apple slices, oranges, kiwi, and strawberries), and fruit juice (apples, oranges, and pineapples). Nanotechnology has lately revolutionized the food industry because of its many applications in nutrition, food science, agriculture, food processing and packaging, and nutraceuticals [33]. Consequently, this new food packaging technique reduces packaging waste, improves food quality and safety, and extends storage time [27].

6.1 Improved packaging system

The addition of nanoparticles to the polymer in this packaging method improves its gas, temperature, and humidity barrier qualities [34, 35]. Nanocomposites may significantly improve the mechanical strength, weight, heat resistance, and barrier properties (against carbon dioxide, moisture, oxygen, and volatiles present in food) of the food packaging material [35]. Numerous investigations have been carried out to ascertain how the nanoparticles interact with foodborne bacteria. ZnO nanoparticles integrated into the polymeric matrix allow food to interact with the nanoparticles inside the nanocomposites, eventually protecting the food against infections [36]. Commercially, metal and metal oxide nanoparticles are used extensively in the food system, for example. Baby bottles contain silver nanoparticles, many breweries use nanoclays to make beer bottles, food packaging materials use carbon nanotubes because they give the package mechanical strength and exhibit antimicrobial properties, and food packaging and wrapping materials contain ZnO nanoparticles embedded in them [36].

6.2 Biopolymer nanocomposites

A novel approach to conventional techniques for improving the properties of polymers is provided by nanocomposites. Compared to plain polymers and traditional composites, nanocomposites exhibit superior mechanical strength, barrier attributes,

and heat resistance [37]. The application of nanoscale montmorillonite clay to enhance the mechanical and thermal characteristics of nylon is a well-known example [38]. Nanocomposites are more resilient to the stresses of thermal food processing, storage, and transportation when utilized in food packaging [39]. Carbon nanotubes, graphene nanosheets, and nanoclays montmorillonite (MMT) and kaolinite are examples of particle fillers that have been used and suggested in the literature.

Magnesium aluminum silicate platelets at the nanometer scale make up MMT clays. Platelets with a high aspect ratio are produced by their dimensions, which are 1 nm thick and 100–500 nm in diameter [40]. Hundreds of layered platelets are piled into particles, or tactoids, that are 8–10 μm in size to produce the clay structure. Since interfacial forces control polymer-filler interactions, nanoclays' high surface-to-volume ratio primarily affects polymer characteristics. To fully use the potential large surface area, clay particles should be exfoliated as individual platelets and evenly distributed throughout the polymer matrix [41]. The gas barrier qualities of polymeric materials can be effectively enhanced by exfoliated nanoclays. When incorporated into polymers, they form a labyrinthine structure that slows down the rate of penetration of flowing gases by providing a convoluted route [42]. Large amounts of filler (about 60%vol) are used in traditional composite constructions, however, at extremely modest loads (<2%vol), nanocomposites can exhibit substantial changes in characteristics. Graphene nanoplates (GNPs) based on carbon can create high-barrier, heat-resistant nanocomposites that show promise for use in food packaging. According to recent reports, GNPs dispersed in poly(methyl methacrylate) (PMMA) with dimensions of 20–60 nm in thickness and 0.5–25 μm in diameter raise the glass transition temperature for PMMA by 30°C at 1–5 weight percent loading [41]. High-speed shearing techniques were used to distribute GNPs. Another carbon-based nanofiller that has garnered a lot of interest is carbon nanotubes (CNTs), which have inherent mechanical and electrical characteristics. **Figure 4** presents various substrates of biopolymer production and **Figure 5** describes different sources of biopolymeric packaging material.

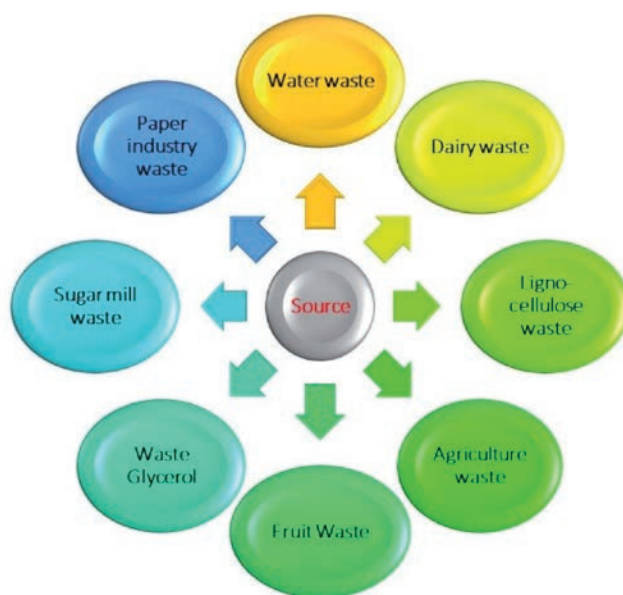


Figure 4.
Substrate sources for biopolymer production.

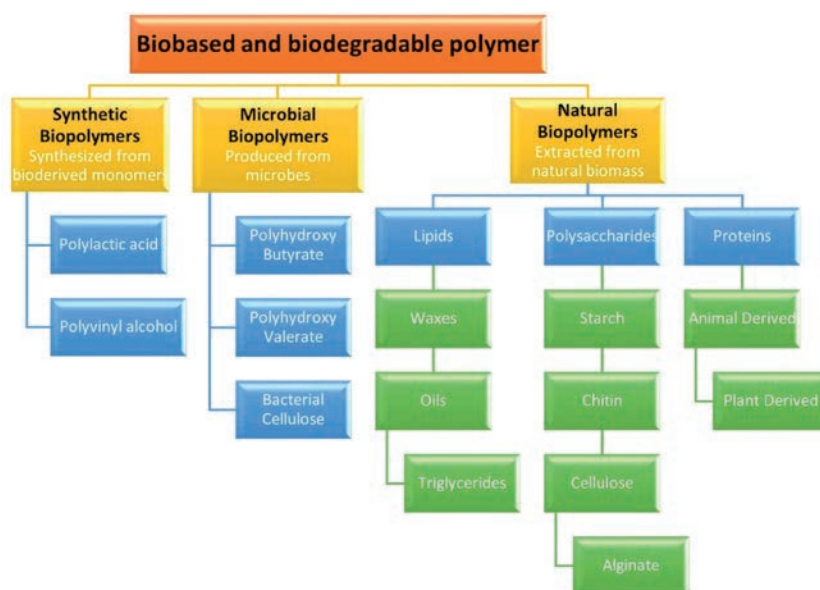


Figure 5.
 Sources of biopolymers.

6.2.1 Manufacturing techniques

A variety of techniques, such as melt intercalation, solution exfoliation, and in-situ polymerization, can be used to create bio-nanocomposites. The in-situ polymerization process involves adding monomers to layered clays, which are then polymerized by heat, radiation, or a catalyst. Using a solvent, layered clays are exfoliated into individual platelets in solution exfoliation. The clay suspension is then mixed with the platelets to adsorb the polymer onto them. Layered clays are mixed with the molten polymer matrix during melt intercalation [43]. It is possible to create flexible bio-nanocomposite films with modified properties by adding suitable filler materials, such as MMT, to the SPI-plasticizer system.

Few studies on SPI-MMT bio-nanocomposites have been reported in the literature [44–46]. According to these findings, bio-nanocomposite films made of SPI and MMT may resemble plastics in terms of their mechanical and barrier qualities. Because of its adaptability and simplicity of use, melt intercalation in an extruder is one of the most promising methods for creating nanocomposites. High shear mixing in the extruder shears and peels off layered clays (6–13 nm) into platelets (1–10 nm). The polymer that has melted is then mixed with these platelets to create exfoliations.

The same technique may be used to make biopolymer-based nanocomposites in an extruder. Extrusion is one of the most crucial processing techniques for producing plastics on a wide scale. Consequently, the commercialization potential of these films will be enhanced by extrusion-based biopolymer nanocomposite films. Extrusion processing has been demonstrated to be viable for the production of biopolymers and bio-composites [47, 48]. The structure and characteristics of nanocomposites are greatly impacted by extrusion processing factors such as barrel temperature distribution and screw speed [49, 50]. **Table 1** presents previously studied various biopolymeric materials along with barrier properties.

Material	Film preparation	Oxygen barrier ^b	Moisture barrier ^a	Mechanical properties (TS) ^c	References
Chitosan	Aqueous	Good	Poor	Moderate	[43, 51]
Soy protein	Aqueous	Good	Poor	Poor	[52, 53]
Whey protein	Aqueous	Good	Poor	Poor	[53, 54]
Starch/PCL	Extrusion	Moderate	Moderate	Moderate	[52]
Starch	Aqueous	Moderate	Poor	Moderate	[53, 55]
Gluten	Aqueous-EtOH	Good	Moderate	Moderate	[53]
Zein	EtOH	Moderate	Moderate	Moderate	[53]
PLA	Extrusion	Moderate	Moderate	Good	[56, 57]
Starch nanocomposite	Extrusion/aqueous	N/A	Moderate	Moderate	[55]

Note: ^a Test condition: 38°C, 90/0%RH, Poor = 10-100 g.mm/m².d.kPa, Moderate = 0.1-10 g.mm/m².d.kPa, Good = 0.01-0.1 g.mm/m².d.kPa, (LDPE: 0.08 g.mm/m².d.kPa); ^b Test conditions: 25°C, 0-50%RH, Poor = 100-1000 cm³.mm/m².d.kPa, Moderate = 10-100 cm³.mm/m².d.kPa, Good = 1-10 cm³.mm/m².d.kPa; ^c Test conditions: 25°C, 50%RH, Moderate TS = 10-100 MPa, Moderate E = 10-50%, (LDPE: TS = 13 Mpa, E = 500%).

Table 1.

Showing various materials for film formation with its barrier properties.

6.3 Electrospun nanofibers

Using a high-voltage electric field, electrospinning is a straightforward, affordable, and promising method for creating continuous nanoscale threads from a variety of polymer materials. The electrospinning process for many applications was recently summarized in a few review publications. Electrospun nanostructures were examined by Torres-Giner et al. [58] as cutting-edge bioactive platforms for functional coatings, drug delivery, tissue engineering, and food packaging. It was suggested to functionalize the electrospun surfaces by adding bioactive materials, and the electrospinning of bioactive polymers including synthetic, natural, and blends of polymers was thoroughly examined. The encapsulation of bioactive chemicals in electrospun nanofibers for possible culinary applications was reviewed by Wen et al. [59].

Proteins and polysaccharides are examples of natural biopolymers, which are food-grade polymers utilized as functional additives in meals to alter their mouthfeel, texture, and flavor through their aggregation or gelation characteristics. The utilization of electrospun fibers in food packaging systems is negatively impacted by the hydrophilicity and weak mechanical qualities of natural biopolymers, but they typically have good biodegradation and several binding sites for loading bioactive chemicals. Conversely, natural biopolymers can be combined with biocompatible polymers dissolved in solvents such as acetic acids, alcohols, and water that are authorized for use in food applications to create food-grade electrospun mats. This is due to the fact that biocompatible polymers such as PVA, PCL, and PEO are hydrophobic and have high mechanical properties [60].

The structural benefits of the electrospun fiber mats made using this nonmechanical method include high porosity, high surface-to-volume ratio, ultrafine structures, and customized shapes [61]. High encapsulation effectiveness of bioactive substances can be attained based on these benefits. Encapsulating thermosensitive chemicals using the nonthermal method of electrospinning is crucial for maintaining the

structure and improving stability and functioning throughout food processing and storage [59]. Furthermore, the quantity of organic solvents left in food systems is decreased by the quick evaporation of solvents [61].

Because of its structural and functional benefits, electrospinning is a preferred method for creating active food packaging. One of the drawbacks of electrospinning, despite its enormous promise in the food packaging industry, is the poor productivity of electrospun fibers, which still prevents them from being widely used [62]. Although there has been increasing interest in using natural biopolymers (like proteins and polysaccharides) in the electrospinning process for food packaging, most of these materials are hydrophilic, meaning they lack adequate mechanical properties and good moisture and oxygen barrier properties, and their high rigidity makes them difficult to process in conventional equipment [63]. Furthermore, little research has been done so far on these materials' long-term stability or resilience to thermal and UV damage. **Figure 6** shows different electrospinning techniques acquired for nano-spun fibers.

Table 2 presents previously studied data on electrospun fibers, including processing parameters, solvent, polymer concentration, and the electrospinning method.

6.4 Nanocoating

High-barrier coatings that stop gases from leaking through, hydrophobic coatings that allow for self-cleaning, and antimicrobial coatings for hygienic areas are examples of coatings based on nanosilica, nanotitanium, and nanoaluminum. Edible films made of polysaccharides are cheap, water-soluble, and less resistant to moisture than those made of proteins, which have good mechanical qualities and good oxygen barrier qualities but less resistance to moisture, and lipid-based films, which have good moisture

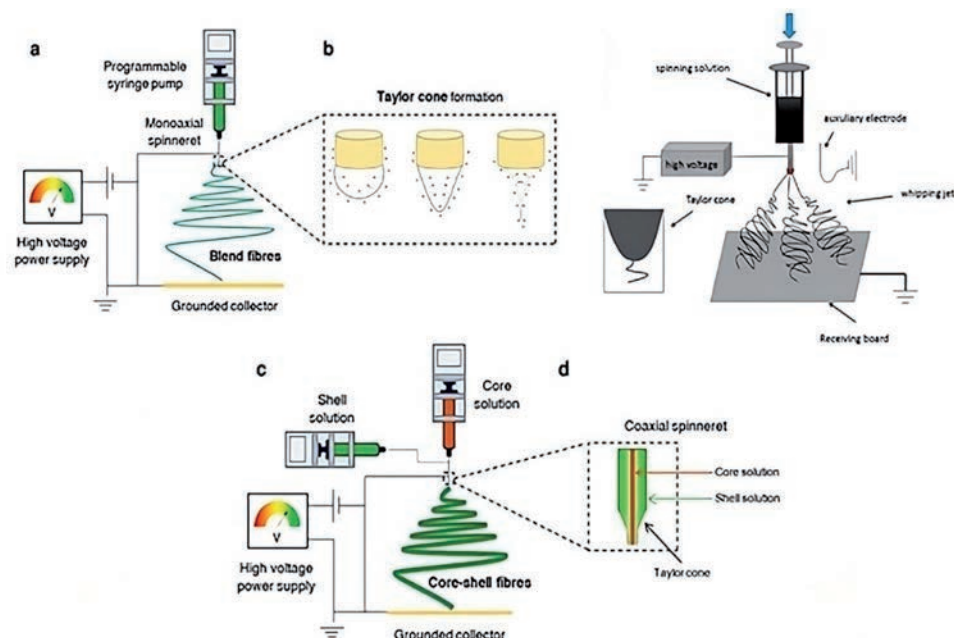


Figure 6.
 (a) Traditional electrospinning setup, (b) multijet electrospinning setup, (c) coaxial electrospinning setup, (d) coaxial spinneret (figure was adapted from [70]).

Polymer	Electro-spinning methods	Solvent	Polymer concentration	Processing parameter	Refs.
SPI and PVA	Emulsion electrospinning	Distilled water	11% and 11%	7 cm, 15 kV, 0.15 mL h ⁻¹	[64]
Acyclovir hydroxypropyl-beta-cyclodextrin	Blend electrospinning	Water	7% and 180%	15 kV, 0.5 mL h ⁻¹	[65]
EVOH44 (core) and 2-propanol (sheath solvent)	Coaxial electrospinning	2-Propanol/water 7:3	6% (core) and solvent (sheath)	17 cm, 6 mL h ⁻¹ (core), 250 µL h ⁻¹ (sheath), 24 kV	[66]
Gum Arabic and pullulan	Blend electrospinning	Deionized water	Blend solution 20%	10 cm, 0.4 mL h ⁻¹ , 16 kV	[67]
PLA	Suspension electrospinning	Dichloromethane (DCM) and TFE	13%wt	15 cm, 1 mL h ⁻¹ , 20 kV	[68, 69]
PVP (core), PCL (intermediate) and CA (sheath)	Triaxial electrospinning	TFE	19% (core), 11% (intermediate) and 12% (sheath)	0.6 mL h ⁻¹ (core), 12–14 kV (inter), 1.2 mL h ⁻¹ (sheath), 0.25 mL h ⁻¹ (sheath), 20 cm	[69]

Table 2.

Examples of polymers and electrospinning techniques along with processing parameters.

resistance and poor oxygen barrier qualities. Lactic acid is produced by fermenting maize starch to create polylactide (PLA), a thermoplastic polyester. This polymer is transparent, brittle, well-processed, expensive, recyclable, and compostable. It also has a high molecular weight. A potentially non-toxic, biodegradable, and biocompatible substance known as a “green nanocomposite” is created when biopolymers, such as proteins and carbohydrates, are mixed with nanoclay. Metal nanoparticles, including those of silver, gold, zinc, iron, nickel, titanium, palladium, iridium, and platinum, are sometimes used as catalysts. The most inert metals are being explored for possible medicinal uses, such as the heat treatment of malignancies [71]. Inorganic nanoparticles of metal oxides ZnO, TiO₂, ZnS, and carbon nanotubes have improved barrier and mechanical properties that enable thermal and electrical conductivity in addition to other functional properties like UV and antimicrobial protection (already present in sunscreen and cosmetic products) and photocatalytic capabilities [43].

6.5 Nanoscale enzyme immobilization systems

The food business uses enzymes extensively for a variety of purposes. Enzymes' sensitivity to processing conditions and/or substances that might hinder their activity, leading to a limited operating life or inactivation, can sometimes limit their direct

usage. Improved stability to temperature and pH, resistance to proteases and other denaturing agents, and a suitable environment for repeated use or controlled release are all possible when the enzymes are immobilized in various specially designed carriers [72]. Enzyme immobilization has also been explored for packaging applications in recent decades.

Enzymes such as lactase or cholesterol reductase could be added to the packaging to increase the food product's value and suit the requests of customers who have health difficulties associated with enzymes [73]. Nanoscale immobilization systems would work much better since they would change mass transfer and increase the available surface contact area, which may be the most important factors affecting such systems' effectiveness [55]. To support biomolecules, a variety of materials have been developed. Since inorganic supports, such as clays, have been demonstrated to be efficient enzyme carriers with a high affinity for protein adsorption [74], new techniques addressing enzyme adsorption into clays mixed into polymers may help control the release of enzyme molecules [75].

Sharma et al. [76] demonstrated that CPs may be used as immobilizing matrices for biomolecules by immobilizing glucose oxidase onto films of poly(aniline-co-fluoroaniline) [77]. Silica nanoparticle modification has made glutamate dehydrogenase and lactate dehydrogenase immobile [78]. The immobilized enzymes' remarkable activity makes the modified silica nanoparticles suitable for biosensing applications. A multitude of techniques may be used to create enzyme immobilization films. Using LbL assembly, Rudra et al. [79] produced a polypeptide multilayer antimicrobial nanofilm made up of positively charged layers of egg white lysozyme, a chicken enzyme that is frequently employed as a food preservative, and negatively charged layers of poly(L-glutamic acid).

The growth of *Micrococcus luteus* was effectively inhibited by the nanofilms. By varying the number of film layers, the scientists showed how to easily control the lysozyme's rate of release. In LbL films, Caseli et al. [80] used chitosan to effectively immobilize glucose oxidase (GO). The enzyme activity was nearly identical to that in a homogeneous solution, indicating that the LbL approach was appropriate for immobilizing GO. This technique might be used in a variety of systems that include this enzyme's catalysis, including biosensors. A rapid and easy method for creating nanofibers from a variety of materials is electrospinning. It exhales a jet of a viscous polymer solution from a capillary using a high electric field. A fiber-based structure that facilitates the trapping of bioactive chemicals is formed when the jet hardens by solvent evaporation or cooling [81]. A-chymotrypsin glucose oxidase and cellulase have all been shown to significantly boost the immobilized enzymes' capacity to catalyze because of the electrospun nanofibers' fine porous structure and huge specific surface area [82].

7. Combining cutting-edge food processing methods with creative packaging techniques to increase shelf life

The mechanistic/operational understanding and competitive benefits of advanced processing technologies toward microbiological food safety and quality have been demonstrated in a substantial and rapidly expanding body of research over the past 10 years. Several comprehensive state-of-the-art evaluations serve as the foundation for this study [61, 83]. This section's goal is to evaluate their possible effects on material performance and following interactions with food counterparts during in-pack processing and/or storage for better packaging material fabrication and functioning.

In addition to influencing the section outline, these intervention criteria have significantly reduced the number of pertinent technologies (CP, HP, MW, and US) that were chosen for additional assessment. Only a small number of review publications [84] thoroughly discuss the packaging implications of new food processing technologies, as far as the authors are aware. Furthermore, there has not been much research done on bio-based packaging solutions in connection with developing technologies; thus, traditional polymers, biomaterials, and composites will all be explored together in a technology-dependent fashion. **Table 3** depicts various innovative technologies involved during the processing of polymeric packaging material.

7.1 Packaging of fresh-cut fruits and vegetables

When fresh-cut fruits and vegetables are processed, mechanical damage typically causes wounding stressors in the cut tissues, which raises the respiration rate of the tissues. During respiration, complex substrate molecules such as starch, sugars,

Technology	Composition of the material or substrate	Conditions of processing	Influence on the properties of the material	Refs.
Microwave	Soy protein isolate and zein blended film, respectively	350 W and 60°C for 2 minutes	Glass transition temperature by 50%, breaking strength by 5–25%, and melting temperature by 3.5%	[85]
	Waxy maize starch	1600 W (160 W/g) for 5 minutes; 2450 MHz frequency and seven repetitions	Molecular weights range from 21×10^7 to 1.82×10^7 g/mol, relative crystallinity from 19.58% to 2.91%, onset temperatures from 69.90°C to 75°C, DH values between 13.40 and 10.20 J/g, and viscosities	[86]
High-pressure processing	PVA and chitosan solution in a 1:1 combination with 0.10% (w/v) TiO ₂ nanoparticles	Water serves as the pressure medium at room temperature ($23 \pm 2^\circ\text{C}$) for 15 minutes at 200, 400, and 600 MPa.	Up to 6% density and 38% film thickness (particularly at 400 MPa). Water vapor permeability of up to 20%; up to 7% permeability of oxygen 4.78–5.6% elongation upon break, up to around 100% tensile strength After 11 hours, the TiO ₂ nanoparticle migration ratio can reach up to 28%.	[87]
Ultrasound	US processing of edible films containing whey protein	Power 820 W (50% power setting); 20.8 W ultrasonic wave; 60 minutes; 35 kHz ultrasonic bath	Mold and yeast for control, US 5 minutes, US 10 minutes, and US 15 minutes were 4.77, 4.17, 3.85, and 3.69 log CFU/g; the overall amount of colonies for control, US 5 minutes, US 10 minutes, and US 15 minutes was 6.72, 5.98, 5.28, and 5.14 log CFU/g; the ascorbic acid content rose by 49.55% for control, 41.14% for US 5 minutes, 32.83% for US 10 minutes, and 44.24% for US 15 minutes. Water vapor permeability ($0.1\text{--}0.75 \text{ gmmMPa}^{-1} \text{ h}^{-1} \text{ m}^2$), piercing strength (0.5–1.2 MPa), and tensile strength (0.7–0.9 MPa)	[88]

Technology	Composition of the material or substrate	Conditions of processing	Influence on the properties of the material	Refs.
Cold plasma	Grafting CP-activated cellulose/chitin blend fiber with eugenol and rosehip/grape seed oil	CP: 50 Pa vacuum glass reactor; air or N ₂ (10 cm ³ /min); 1.3 MHz; 30 W; 15 minutes γ -irradiation dosage: 5, 10, 20 k Gy	Compared to γ -irradiation (9.7–22.8% grafting), air CP (31.1–58.7% grafting) is more effective. Greater degree of grafting for vegetable oils.	[89]
	High methoxyl apple pectin and crosslinked by Ca ²⁺ plasticizer: glycerol and polyethylene glycol (PEG) 400	170–230 V (15 minutes)	Cross-linking and increasing voltage work together to reduce oxygen and carbon dioxide transmission rates in films. Higher voltage treatments increase the moisture sorption rate and capacity of the films.	[90]

Table 3.
 Selected examples on the implementation of innovative technologies toward enhanced bio-materials.

and organic acids that are often found in plant cells undergo oxidative breakdown to produce simpler molecules, which release water, carbon dioxide, and energy. Since O₂ is involved in the conversion of 1-amino-cycloprane-1-carboxylic acid to ethylene, environments with low O₂ (1–5%) and high CO₂ (5–10%) have been utilized to increase the shelf life of fresh-cut fruits and vegetables by lowering respiration, product transpiration, and ethylene production [91].

Fruit and vegetable respiration rates and postharvest shelf life have generally been shown to be inversely correlated. Fresh-cut fruits and vegetables' enzymatic browning, hardness, and decay have also been shown to be successfully controlled by low O₂ and high CO₂ levels. Furthermore, lower O₂ levels can significantly slow the growth of aerobic spoilage microbes. On the other hand, some anaerobic psychrotrophic infections may be permitted or even encouraged to develop under specific circumstances [92]. Because too low or too high concentrations of O₂ and CO₂ can cause the production of unwanted metabolites and the release of various physiological disorders, it is necessary to have a sufficient amount of O₂ inside packages in order to limit aerobic respiration without causing anaerobic processes [92].

In recent years, elevated O₂ atmospheres have been proposed as an alternative to low O₂ atmospheres to prevent undesirable anoxic respirative processes, inhibit the growth of naturally occurring spoilage microorganisms, and preserve the fresh-cut produce's fresh-like quality [93]. However, edible coatings can be used either in addition to or instead of modified atmospheric packaging (MAP) to extend the shelf life of fresh-cut fruits, due to their inherent biocide activity or by adding antimicrobial compounds, edible films and coatings may help to lessen the negative effects associated with minimal processing, improving food safety while also delaying deterioration and improving quality [94]. The use of edible coatings to transfer active chemicals is actually one of the most important advancements done to date to increase the shelf life of fresh-cut vegetables.

8. Conclusion

In a worldwide supply chain, creative food packaging has become essential for tackling the twin issues of ecological sustainability and food safety. Although conventional resources have offered useful solutions, the shift to alternatives that are sustainable is required due to their ecological disadvantages. The packaging industry has undergone a transformation because of developments in active and intelligent packaging made possible by nanotechnology. Intelligent systems employ sensors to give immediate time quality surveillance, while active packaging integrates features like oxygen scavengers and antibacterial agents. Longer shelf life, less waste, and more consumer confidence are all guaranteed by these technologies. By enhancing the material's strength, barrier qualities, and biodegradability, nanotechnology further improves packaging. By providing effective and environmentally beneficial methods of food preservation, the incorporation of bio-based composites and nanomaterials supports international initiatives to lessen footprints on the environment. These developments are essential for striking a balance between sustainability and food security as the sector develops. Future food packaging will be shaped by the joint efforts of researchers, producers, and legislators, guaranteeing solutions that are efficient, long-lasting, and in line with customer demands. However, these advances continue to confront obstacles such as limited customer adoption, high prices, inconsistent quality, and safety issues. Sustainability is a crucial component as packaging needs to be practical and reasonably priced while also reducing waste and the ecological imprint. To create secure, productive, and affordable solutions that emphasize the use of biodegradable materials, sustainable resources, and efficiency in terms of energy procedures, thorough study is necessary. It takes a multidisciplinary approach that includes disciplines like sociology, marketing, and psychology to comprehend consumer preferences and promote the adoption of sustainable packaging solutions. The food packing sector can guarantee that potential remedies are not only technologically sophisticated but also environmentally sustainable, morally sound, and widely accepted by addressing both the technical and social dimensions. This will open the door for significant and responsible advancement that benefits both consumers and the environment.

Conflict of interest

The authors declare no conflict of interest.

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References

- [1] Altaf U, Kanojia V, Rouf A. Novel packaging technology for food industry. *Journal of Pharmacognosy and Phytochemistry*. 2018;7(1):1618-1625
- [2] Carocho M, Morales P, Ferreira ICFR. Natural food additives: Quo vadis? *Trends in Food Science & Technology*. 2015;45:284-295. DOI: 10.1016/j.tifs.2015.06.007
- [3] Grönman K, Soukka R, Järvi-Kääriäinen T, Katajajuuri JM, Kuisma M, Koivupuro HK, et al. Framework for sustainable food packaging design. *Packaging Technology and Science*. 2013;26(4):187-200
- [4] Muncke J, Myers JP, Scheringer M, Porta M. Food packaging and migration of food contact materials: Will epidemiologists rise to the neotoxic challenge. *Journal of Epidemiology and Community Health*. 2014;68(7):592-594
- [5] Ribeiro-Santos R, Andrade M, de Melo NR, Sanches-Silva A. Use of essential oils in active food packaging: Recent advances and future trends. *Trends in Food Science and Technology*. 2017;61:132-140
- [6] Zhong T, Oporto GS, Jaczynski J. Antimicrobial food packaging with cellulose-copper nanoparticles embedded in thermoplastic resins. In: *Food Preservation*. Morgantown, WV, United States: Academic Press; 2017. pp. 671-702
- [7] Al-Tayyar NA, Youssef AM, Al-Hindi R. Antimicrobial food packaging based on sustainable bio-based materials for reducing foodborne pathogens: A review. *Food Chemistry*. 2020;310:125915
- [8] Ramos ÓL, Pereira RN, Cerqueira MA, Martins JR, Teixeira JA, Malcata FX, et al. Bio-based nanocomposites for food packaging and their effect in food quality and safety. In: *Food Packaging and Preservation*. Portugal: Academic Press; 2018. pp. 271-306
- [9] Müller P, Schmid M. Intelligent packaging in the food sector: A brief overview. *Food*. 2019;8(1):16
- [10] Yildirim S, Röcker B, Pettersen MK, Nilsen-Nygaard J, Ayhan Z, Rutkaite R, et al. Active packaging applications for food. *Comprehensive Reviews in Food Science and Food Safety*. 2018;17(1):165-199
- [11] Malhotra B, Keshwani A, Kharkwal H. Antimicrobial food packaging: Potential and pitfalls. *Frontiers in Microbiology*. 2015;6:611
- [12] Moreira JB, de Moraes MG, de Moraes EG, da Silva VB, Costa JA. Electrospun polymeric nanofibers in food packaging. In: *Impact of Nanoscience in the Food Industry*. Rio Grande do Sul, Brazil: Academic Press; 2018. pp. 387-417
- [13] Hussain S, Akhter R, Maktedar SS. Advancements in sustainable food packaging: From eco-friendly materials to innovative technologies. *Sustainable Food Technology*. 2024;2(5):1297-1364
- [14] Potter NN, Hotchkiss JH. Principles of food packaging. In: *Food Science: Fifth Edition*. Boston, MA: Springer US; 1995. pp. 478-513
- [15] Robertson GL. Food packaging and shelf life. In: *Food Packaging and Shelf Life, A Practical Guide*. CRC Press; 2012. pp. 1-6

- [16] Brody AL, Strupinsky EP, Kline LR. Active Packaging for Food Applications. Florida: CRC Press; 2001
- [17] Lopez-Rubio A, Almenar E, Hernandez-Muñoz P, Lagarón JM, Catalá R, Gavara R. Overview of active polymer-based packaging technologies for food applications. *Food Reviews International*. 2004;**20**(4):357-387
- [18] Suppakul P, Miltz J, Sonneveld K, Bigger SW. Active packaging technologies with an emphasis on antimicrobial packaging and its applications. *Journal of Food Science*. 2003;**68**(2):408-420
- [19] Kerry JP, O'Grady MN, Hogan SA. Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: A review. *Meat Science*. 2006;**74**(1):113-130
- [20] Peltzer M, Wagner J, Jiménez A. Migration study of carvacrol as a natural antioxidant in high-density polyethylene for active packaging. *Food Additives and Contaminants*. 2009;**26**(6):938-946
- [21] Pavelková A. Time temperature indicators as devices intelligent packaging. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*. 2013;**61**(1):245-251
- [22] Gontard N, Guillaume C. 16 packaging and the shelf life of fruits and vegetables. *Food Packaging and Shelf Life*. 2010:297-310
- [23] Wilson CL. Intelligent and Active Packaging for Fruits and Vegetables. Boca Raton: CRC Press; 2008
- [24] Lee DS. Carbon dioxide absorbers for food packaging applications. *Trends in Food Science and Technology*. 2016;**57**:146-155
- [25] Wyrwa J, Barska A. Innovations in the food packaging market: Active packaging. *European Food Research and Technology*. 2017;**243**:1681-1692
- [26] Brennan L, Langley S, Verghese K, Lockrey S, Ryder M, Francis C, et al. The role of packaging in fighting food waste: A systematised review of consumer perceptions of packaging. *Journal of Cleaner Production*. 25 Jan 2021;**281**:125276
- [27] Pal M. Nanotechnology: A new approach in food packaging. *Journal of Food: Microbiology, Safety & Hygiene*. 2017;**2**:2
- [28] Duncan TV. Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *Journal of Colloid and Interface Science*. 2011;**363**(1):1-24
- [29] Neethirajan S, Jayas DS. Nanotechnology for the food and bioprocessing industries. *Food and Bioprocess Technology*. 2011;**4**:39-47
- [30] Bradley EL, Castle L, Chaudhry Q. Applications of nanomaterials in food packaging with a consideration of opportunities for developing countries. *Trends in Food Science and Technology*. 2011;**22**(11):604-610
- [31] Pathakoti K, Manubolu M, Hwang HM. Nanostructures: Current uses and future applications in food science. *Journal of Food and Drug Analysis*. 2017;**25**(2):245-253
- [32] Huang JY, Li X, Zhou W. Safety assessment of nanocomposite for food packaging application. *Trends in Food Science and Technology*. 2015;**45**(2):187-199
- [33] Wesley SJ, Raja P, Raj AA, Tirouchelvamae D. Review

- on-nanotechnology applications in food packaging and safety. *International Journal of Engineering Research*. 2014;**3**(11):645-651
- [34] Gokularaman S, Cruz SA, Pragalyaashree MM, Nishadh A. Nanotechnology approach in food packaging-review. *Journal of Pharmaceutical Sciences and Research*. 2017;**9**(10):1743-1749
- [35] Zanetti M, Carniel TK, Dalcanton F, dos Anjos RS, Riella HG, de Araújo PH, et al. Use of encapsulated natural compounds as antimicrobial additives in food packaging: A brief review. *Trends in Food Science and Technology*. 2018;**81**:51-60
- [36] Haq ANU et al. Synthesis approaches of zinc oxide nanoparticles: The dilemma of ecotoxicity. *Journal of Nanomaterials*. 2017;**2017**:1-4
- [37] Sorrentino A, Gorrasi G, Vittoria V. Potential perspectives of bio-nanocomposites for food packaging applications. *Trends in Food Science & Technology*. 2007;**18**(2):84-95
- [38] Cho JW, Paul DR. Nylon 6 nanocomposites by melt compounding. *Polymer*. 2001;**42**(3):1083-1094
- [39] Thostenson ET, Chou TW. Carbon nanotube-based health monitoring of mechanically fastened composite joints. *Composites Science and Technology*. 2008;**68**(12):2557-2561
- [40] Arora A, Padua GW. Nanocomposites in food packaging. *Journal of Food Science*. 2010;**75**(1):R43-R49
- [41] Sumit G. Nanotechnology in food packaging a critical review. *Russian Journal of Agricultural and Socio-Economic Sciences*. 2012;**10**(10):14-24
- [42] Singh E, Osmani RA, Jhadav S, Kazi H, Vaghela R. Bionanocomposites in food packaging applications and their risk assessment for public health. In: *Bionanocomposites for Food Packaging Applications*. Maharashtra, Karnataka, India: Woodhead Publishing; 2022. pp. 453-477
- [43] Zheng H, Du Y, Yu J, Huang R, Zhang L. Preparation and characterization of chitosan/poly(vinyl alcohol) blend fibers. *Journal of Applied Polymer Science*. 2001;**80**(13):2558-2565
- [44] Dean KM, Petinakis E, Yu L. Biodegradable thermoplastic starch/ poly(vinyl alcohol) nanocomposites with layered silicates. In: *Nanocomposites with Biodegradable Polymers: Synthesis, Properties, and Future Perspectives*. Vol. 68. New York, U.S: Oxford University Press; 2011. p. 58
- [45] Rhim JW, Kim YT. Biopolymer-based composite packaging materials with nanoparticles. In: *Innovations in Food Packaging*. Jeonnam, South Korea and Virginia, USA: Academic Press; 2014. pp. 413-442
- [46] Chen X, Lee DS, Zhu X, Yam KL. Release kinetics of tocopherol and quercetin from binary antioxidant controlled-release packaging films. *Journal of Agricultural and Food Chemistry*. 2012;**60**(13):3492-3497
- [47] Mohanty F, Swain SK. Bionanocomposites for food packaging applications. In: *Nanotechnology Applications in Food*. Sambalpur, India: Academic Press; 2017. pp. 363-379
- [48] Li H, Li F, Wang L, Sheng J, Xin Z, Zhao L, et al. Effect of nano-packing on preservation quality of Chinese

jujube (*Ziziphus jujuba* Mill. var. *inermis* (Bunge) Rehd). *Food Chemistry*. 2009;**114**(2):547-552

[49] Borse NK, Kamal MR. Melt processing effects on the structure and mechanical properties of PA-6/clay nanocomposites. *Polymer Engineering and Science*. 2006;**46**(8):1094-1103

[50] Lertwimolnun W, Vergnes B. Influence of screw profile and extrusion conditions on the microstructure of polypropylene/organoclay nanocomposites. *Polymer Engineering and Science*. 2007;**47**(12):2100-2109

[51] De Moura MR, Avena-Bustillos RJ, McHugh TH, Krochta JM, Mattoso LH. Properties of novel hydroxypropyl methylcellulose films containing chitosan nanoparticles. *Journal of Food Science*. 2008;**73**(7):N31-N37

[52] Zhao R, Torley P, Halley PJ. Emerging biodegradable materials: Starch-and protein-based bio-nanocomposites. *Journal of Materials Science*. 2008;**43**(9):3058-3071

[53] Charles AL, Kao HM, Huang TC. Physical investigations of surface membrane–water relationship of intact and gelatinized wheat–starch systems. *Carbohydrate Research*. 2003;**338**(22):2403-2408

[54] Ramos ÓL, Silva SI, Soares JC, Fernandes JC, Poças MF, Pintado ME, et al. Features and performance of edible films, obtained from whey protein isolate formulated with antimicrobial compounds. *Food Research International*. 2012;**45**(1):351-361

[55] Singh RP, Pandey JK, Rutot D, Degée P, Dubois P. Biodegradation of poly(ϵ -caprolactone)/starch

blends and composites in composting and culture environments: The effect of compatibilization on the inherent biodegradability of the host polymer. *Carbohydrate Research*. 2003;**338**(17):1759-1769

[56] Rhim JW, Hong SI, Ha CS. Tensile, water vapor barrier and antimicrobial properties of PLA/nanoclay composite films. *LWT- Food Science and Technology*. 2009;**42**(2):612-617

[57] Aloui H, Deshmukh AR, Khomlaem C, Kim BS. Novel composite films based on sodium alginate and gallnut extract with enhanced antioxidant, antimicrobial, barrier and mechanical properties. *Food Hydrocolloids*. 2021;**113**:106508

[58] Torres-Giner S, Pérez-Masiá R, Lagaron JM. A review on electrospun polymer nanostructures as advanced bioactive platforms. *Polymer Engineering and Science*. 2016;**56**(5):500-527

[59] Wen P, Zong MH, Linhardt RJ, Feng K, Wu H. Electrospinning: A novel nano-encapsulation approach for bioactive compounds. *Trends in Food Science and Technology*. 2017;**70**:56-68

[60] Zhang C, Feng F, Zhang H. Emulsion electrospinning: Fundamentals, food applications and prospects. *Trends in Food Science and Technology*. 2018;**80**:175-186

[61] Zhang ZH, Wang LH, Zeng XA, Han Z, Brennan CS. Non-thermal technologies and its current and future application in the food industry: A review. *International Journal of Food Science and Technology*. 2019;**54**(1):1-3

[62] Agarwal S, Greiner A. On the way to clean and safe electrospinning—Green electrospinning: Emulsion and suspension electrospinning.

Polymers for Advanced Technologies. 2011;**22**(3):372-378

[63] Mihindukulasuriya SD, Lim LT. Nanotechnology development in food packaging: A review. Trends in Food Science and Technology. 2014;**40**(2):149-167

[64] Bayrak E. Nanofibers: Production, characterization, and tissue engineering applications. In: 21st Century Nanostructured Materials—Physics, Chemistry, Classification, and Emerging Applications in Industry, Biomedicine, and Agriculture. Ankara, Turkey: Intech Open; 2022. p. 265

[65] Pinheiro Bruni G, de Oliveira JP, Gómez-Mascaraque LG, Fabra MJ, Guimarães Martins V, da Rosa Zavareze E, et al. Electrospun β -carotene-loaded SPI/PVA fiber mats produced by emulsion-electrospinning as bioactive coatings for food packaging. Food Packaging and Shelf Life. 2020;**23**:100426. DOI: 10.1016/j.fpsl.2019.100426

[66] Celebioglu A, Uyar T. Electrospun formulation of acyclovir/cyclodextrin nanofibers for fast-dissolving antiviral drug delivery. Materials Science and Engineering: C. 2021;**118**:111514

[67] Melendez-Rodriguez B, Torres-Giner S, Zavagna L, Sammon C, Cabedo L, Prieto C, et al. Development and characterization of electrospun fiber-based poly(ethylene-co-vinyl alcohol) films of application interest as high-gas-barrier interlayers in food packaging. Polymers. 2021;**13**(13):2061

[68] Ma J, Xu C, Yu H, Feng Z, Yu W, Gu L, et al. Electro-encapsulation of probiotics in gum Arabic-pullulan blend nanofibres using electrospinning technology. Food Hydrocolloids. 2021;**111**:106381

[69] Rokbani H, Ajji A. Rheological properties of poly(lactic acid) solutions added with metal oxide nanoparticles for electrospinning. Journal of Polymers and the Environment. 2018;**26**:2555-2565

[70] Han D, Sherman S, Filocamo S, Steckl AJ. Long-term antimicrobial effect of nisin released from electrospun triaxial fiber membranes. Acta Biomaterialia. 2017;**53**:242-249

[71] Özkar S, Finke RG. Iridium (0) nanocluster, acid-assisted catalysis of neat acetone hydrogenation at room temperature: Exceptional activity, catalyst lifetime, and selectivity at complete conversion. Journal of the American Chemical Society. 2005;**127**(13):4800-4808

[72] Lopez-Rubio A, Gavara R, Lagaron JM. Bioactive packaging: Turning foods into healthier foods through biomaterials. Trends in Food Science and Technology. 2006;**17**(10):567-575

[73] Fernández A, Cava D, Ocio MJ, Lagarón JM. Perspectives for biocatalysts in food packaging. Trends in Food Science and Technology. 2008;**19**(4):198-206

[74] Gopinath S, Sugunan S. Enzymes immobilized on montmorillonite K 10: Effect of adsorption and grafting on the surface properties and the enzyme activity. Applied Clay Science. 2007;**35**(1-2):67-75

[75] Rhim JW, Ng PK. Natural biopolymer-based nanocomposite films for packaging applications. Critical Reviews in Food Science and Nutrition. 2007;**47**(4):411-433

[76] Sharma R, Jafari SM, Sharma S. Antimicrobial bio-nanocomposites and their potential applications

in food packaging. *Food Control*. 2020;**112**:107086

[77] Ahuja A, Samyn P, Rastogi VK. Paper bottles: Potential to replace conventional packaging for liquid products. *Biomass Conversion and Biorefinery*. 2024;**14**(13):13779-13805

[78] Qhobosheane M, Santra S, Zhang P, Tan W. Biochemically functionalized silica nanoparticles. *The Analyst*. 2001;**126**(8):1274-1278

[79] Rudra JS, Dave K, Haynie DT. Antimicrobial polypeptide multilayer nanocoatings. *Journal of Biomaterials Science. Polymer Edition*. 2006;**17**(11):1301-1315

[80] Caseli L, dos Santos Jr DS, Foschini M, Gonçalves D, Oliveira ON Jr. Control of catalytic activity of glucose oxidase in layer-by-layer films of chitosan and glucose oxidase. *Materials Science and Engineering: C*. 2007;**27**(5-8):1108-1110

[81] Huang ZM, Zhang YZ, Kotaki M, Ramakrishna S. A review on polymer nanofibers by electrospinning and their applications in nanocomposites. *Composites Science and Technology*. 2003;**63**(15):2223-2253

[82] Wu L, Yuan X, Sheng J. Immobilization of cellulase in nanofibrous PVA membranes by electrospinning. *Journal of Membrane Science*. 2005;**250**(1-2):167-173

[83] Kourkoutas Y, Chorianopoulos N, Nisiotou A, Valdramidis VP, Karatzas KA. Application of innovative technologies for improved food quality and safety. *BioMed Research International*. 2016;**2016**:1-2

[84] Gontard N, Guillard V, Iglesias MM, Peyron S, Raouche S, Iannace S, et al.

Packaging challenges for novel processed food. *New Food*. 2010;**5**(1):71-78

[85] Wang N, Gao YZ, Wang P, Yang S, Xie TM, Xiao ZG. Effect of microwave modification on mechanical properties and structural characteristics of soy protein isolate and zein blended film. *Czech Journal of Food Sciences*. 2016;**34**(2):180

[86] Yang C, Tang H, Wang Y, Liu Y, Wang J, Shi W, et al. Development of PLA-PBSA based biodegradable active film and its application to salmon slices. *Food Packaging and Shelf Life*. 2019;**22**:100393

[87] Lian Z, Zhang Y, Zhao Y. Nano-TiO₂ particles and high hydrostatic pressure treatment for improving functionality of polyvinyl alcohol and chitosan composite films and nano-TiO₂ migration from film matrix in food simulants. *Innovative Food Science and Emerging Technologies*. 2016;**33**:145-153

[88] Cruz-Diaz K, Cobos Á, Fernández-Valle ME, Díaz O, Cambero MI. Characterization of edible films from whey proteins treated with heat, ultrasounds and/or transglutaminase. Application in cheese slices packaging. *Food Packaging and Shelf Life*. 2019;**22**:100397

[89] Irimia A, Ioanid GE, Zaharescu T, Coroabă A, Doroftei F, Safrany A, et al. Comparative study on gamma irradiation and cold plasma pretreatment for a cellulosic substrate modification with phenolic compounds. *Radiation Physics and Chemistry*. 2017;**130**:52-61

[90] Basak S, Annature US. Rheological performance of film-forming solutions and barrier properties of films fabricated from cold plasma-treated high methoxyl apple pectin and crosslinked by Ca²⁺: Impact of plasma treatment voltage.

International Journal of Biological
Macromolecules. 2023;227:938-951

[91] Nayik GA, Muzaffar K.
Developments in packaging of fresh
fruits-shelf life perspective: A review.
American Journal of Food Science and
Nutrition Research. 2014;1(5):34-39

[92] Predrag P, Danijela B. Fresh-cut
apples spoilage and predictive microbial
growth under modified atmosphere
packaging. In: Food Safety and
Protection. CRC Press; 2017. pp. 29-46

[93] Van der Steen C, Jacxsens L,
Devlieghere F, Debevere J. Combining
high oxygen atmospheres with
low oxygen modified atmosphere
packaging to improve the keeping
quality of strawberries and raspberries.
Postharvest Biology and Technology.
2002;26(1):49-58

[94] Rojas-Graü MA, Oms-Oliu G,
Soliva-Fortuny R, Martín-Belloso O.
The use of packaging techniques to
maintain freshness in fresh-cut fruits
and vegetables: A review. International
Journal of Food Science and Technology.
2009;44(5):875-889

The Application of Noble Gases in the Food Industry

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Abstract

Noble gases have revolutionised food packaging technology by providing a unique combination of safety and effectiveness in food preservation. These naturally occurring elements - neon (Ne), helium (He), argon (Ar), krypton (Kr), radon (Rn), and xenon (Xe) - are ideal for food storage due to their chemical inertness and lack of colour or odour. In an era where food safety and shelf-life extension are paramount, noble gases serve multiple critical functions: minimising foodborne illness risk, acting as natural preservatives, maintaining product freshness, and enhancing presentation. This chapter examines the applications of noble gases in food preservation and packaging systems, with a particular focus on their role in extending shelf-life while ensuring food safety.

Keywords: noble gases, food packaging, food preservation, food safety, shelf-life extension, inertness, MAP technology

1. Introduction

Food is a fundamental human necessity, and ensuring the safety of the global food supply is a critical human right. Worldwide, a significant portion of the population faces risks associated with consuming unsafe food. Every year, millions of people suffer from foodborne illnesses, many of which result in fatalities [1]. Maintaining food safety standards remains a global challenge that fundamentally impacts human health, societal welfare, and population-level health outcomes. Protecting consumers requires an understanding of how and where food contamination occurs during production and processing. Several factors can introduce risks, rendering food potentially dangerous and threatening public health. Addressing these challenges necessitates implementing strategies to prevent contamination from the moment crops are harvested to when food reaches consumers [2].

Food packaging is a vital preventive measure, providing a protective barrier against environmental contaminants, bacterial growth, and chemical hazards during storage and distribution. It extends shelf-life and facilitates product handling [3]. Modified atmospheric packaging (MAP) is a highly effective packaging method for prolonging the shelf-life of food products by employing specific gas mixtures. It is defined as “*the packaging of a perishable product in an atmosphere modified to differ from air.*” MAP is widely used in the food industry to maintain food quality and freshness [4, 5].

Emerging research has explored noble gases as supplementary or alternative atmospheric components in MAP. Noble gases, located in Group 18 of the periodic table, represent a distinct class of chemical elements, including helium, neon, argon, krypton, xenon, and radon. These elements exhibit exceptional chemical inertness and analogous physicochemical properties due to their electronic configuration. Their stability results from a complete outer valence shell, which significantly diminishes their reactivity under standard conditions [6, 7]. The initial discovery of noble gases dates back to 1784 when the British scientist Henry Cavendish observed an unexplained gaseous remnant after eliminating nitrogen and oxygen from air samples. Their formal identification followed the collaborative efforts of Rayleigh and Ramsay in the late nineteenth century, coinciding with milestones such as the detection of helium during the 1868 solar eclipse and the announcement of a new element in 1895 [7].

In the food industry, noble gases are strategically combined with MAP gases to optimise shelf-life and sensory characteristics [8, 9]. Their chemical inertness has demonstrated promise in food preservation, effectively extending the shelf-life of various perishable products, including meats, prepared meals, fruits, and vegetables [10]. This chapter discusses the fundamentals of food packaging preservation, the role of each noble gas in packaging, and the safety and environmental considerations of noble gases in the food industry.

2. Fundamentals of food packaging preservation

2.1 Different food preservation methods

Food preservation prevents spoilage by halting the growth of harmful microorganisms and preventing fat rancidity while maintaining the original taste, consistency, and nutrients [11]. The practice aims to amplify dietary diversity, produce value-added food products, and address issues related to poor agricultural planning [12].

Traditional and modern food preservation techniques focus on preventing bacterial growth and fat degradation, allowing foods to maintain stability and safety without refrigeration while retaining nutritional benefits and sensory qualities. Food deterioration can occur through environmental factors, enzyme activity, or microbial growth [13]. Traditional practices, dating back hundreds of years, include salt preservation, canning, curing, drying, fermentation, dehydration, pickling, freezing, refrigeration, smoking, and adding sugar to jams and jellies [13–15]. Recent scientific advancements have improved traditional methods and developed novel techniques, including MAP, irradiation, pasteurisation, high-pressure processing, nanotechnology, hydrolysis, electric pulse, antimicrobial agents, and microwave heating technology [13, 15].

2.2 Mechanisms of food spoilage

Food spoilage is a natural degradation process that renders food unsuitable for consumption, often resulting in sensory changes and potential toxicity [16]. Spoilage is driven by intrinsic factors, such as oxygen content, water activity, pH levels, enzyme activity, and extrinsic factors, including temperature, humidity,

and microorganisms. Spoilage manifests through microbial, chemical, and physical mechanisms, with bacteria, moulds, and yeasts playing a central role. Understanding these mechanisms is critical for maintaining food safety and quality [15, 17–19].

2.3 Importance of food packaging and MAP

Food packaging is essential for protecting food products, simplifying handling and transportation, and extending shelf-life, benefiting consumers. The primary goal is to safeguard food quality and safety by protecting against potential physical, chemical, microbiological, and other hazards [3]. The type of packaging material affects the sensory qualities (flavour and aroma) of food and is crucial for optimising food quality and safety. While various materials like plastics, glass, metal, and paper composites are used, growing consumer health concerns highlight the importance of preventing harmful substances from migrating from packaging into food [3, 20, 21].

Evolving consumer preferences have led to the development of innovative technologies, such as active and intelligent packaging, which interact with the food environment by releasing enhancing substances or scavenging harmful gases [20].

MAP employs altered gaseous compositions of oxygen (O_2), carbon dioxide (CO_2), and nitrogen (N_2) to retard food deterioration processes (**Figure 1**). When integrated with complementary preservation methods like anti-browning agents, it effectively preserves fresh-cut produce. The challenge lies in maintaining optimal atmospheric conditions, as fresh produce continues to respire after packaging, consuming oxygen, and releasing carbon dioxide. The selective permeability of packaging films regulates gas exchange, preventing elevated respiration rates and anaerobic metabolism [22–25]. Noble gases, when used alongside CO_2 , O_2 , and N_2 , have demonstrated significant efficacy in extending the storage life of various foods, including fresh produce, meats, prepared meals, fruits, and vegetables [10].

Carbon dioxide (CO_2)	Oxygen (O_2)	Nitrogen (N_2)
• It is a colourless gas with a slight pungent odour at high concentrations. • An increase in CO_2 concentration eliminates the growth of moulds and bacteria.	• It is a odourless and colourless gas that is highly reactive and can result in combustion. • A reduction in O_2 concentration results in the reduction of fat/oil oxidation. • O_2 allows for the survival of molds and aerobic bacteria.	• N_2 is an inert, nonflammable gas with taste, odour, colour, featuring low water solubility and density lower than air. • Prevents packaging collapse during CO_2 concentrations while maintaining atmospheric balance in MAP.

Figure 1.
 Characteristics and functions of CO_2 , O_2 , and N_2 in Modified Atmosphere Packaging (MAP): CO_2 for antimicrobial control, O_2 for oxidation regulation, and N_2 for structural integrity. Information by Refs. [4, 10].

2.4 Methods of applying MAP gases to extend the shelf-life of various food types

The gas composition of O₂ and CO₂ plays a key role in MAP systems for fresh-cut produce. Research has shown that different fruits and vegetables require varying optimal gas concentrations. According to a review by Caleb et al. [26], optimal O₂ levels range from 3 to 19% and CO₂ from 1 to 23.28%. Other research focusing on MAP has suggested using a gas composition of 5% O₂ with 0–5% CO₂, or 3–5% O₂ with 5–10% CO₂, both at 5°C. A study on ready-to-eat pomegranate arils found that 10% of O₂ combined with 15% of CO₂ was most effective [27]. Research by Rokalla et al. [28] shows that active MAP successfully preserved pomegranate arils for 5 days at ambient temperature, while maintaining a safe microbial load of five logs colony-forming unit (CFU)/g and preserving the fruit's chemical and quality attributes.

MAP systems typically use gas compositions of 20–30% CO₂ and 70–80% O₂ in raw red meat, increasing storage time from 2–4 days to 5–8 days. Non-processed white fish utilise 30% O₂, 40% CO₂, and 30% N₂, while fatty fish require 40% CO₂ and 60% N₂ [10]. Fish products must be stored at ≤3°C with a maximum 10–14 days storage period under MAP conditions. Historical studies demonstrated that 100% CO₂ doubled refrigerated pork and lamb storage duration [10]. The gas compositions in MAP are tailored to the specific needs of different food types, balancing microbial inhibition and quality preservation.

3. Argon gas in food preservation

Argon is colourless, odourless, tasteless, and chemically inert. It is the third most abundant atmospheric gas and one of the most common noble gases. At standard atmospheric pressure, argon exists as a gas and has low thermal conductivity. Argon's chemical inertness precludes reactivity with other elements, rendering it invaluable for applications requiring atmospheric isolation [29].

Recent research shows an increased interest in argon gas applications in food preservation. This gas outperforms nitrogen due to its superior solubility in both aqueous and oil-based substances, allowing it to better remove trapped and dissolved oxygen from food materials. Beyond its physicochemical properties, argon exhibits significant enzyme-suppressing capabilities, specifically in the inhibition of respiratory enzymes such as oxidases. Studies have demonstrated that noble gases influence both the speed and output of enzyme reactions. Notably, argon can inhibit oxidases even in oxygen-rich environments, a capability that nitrogen lacks [30–32].

Comparative analysis of argon-based versus nitrogen-based MAP demonstrated argon's superior oxygen displacement and oxidation prevention across multiple food categories. Integration of organoleptic evaluation, microbial assessment, and double-blind sensory testing revealed that argon-based MAP yielded 25% higher quality metrics and extended shelf-life across diverse products, including nuts, wine, snacks like potato chips, cheese, prepared foods, poultry, processed meats, orange juice, and produce. Results showed enhanced preservation of organoleptic properties and chemical flavour components compared to conventional MAP methods [31].

Figure 2 shows how inert gases (Ar, N₂, and CO₂) enhance food preservation through oxygen displacement in food packaging. When food is packaged with these inert gases, the oxygen concentration is reduced, creating an anaerobic environment that inhibits pathogenic growth and spoilage processes while maintaining food quality and safety [33].

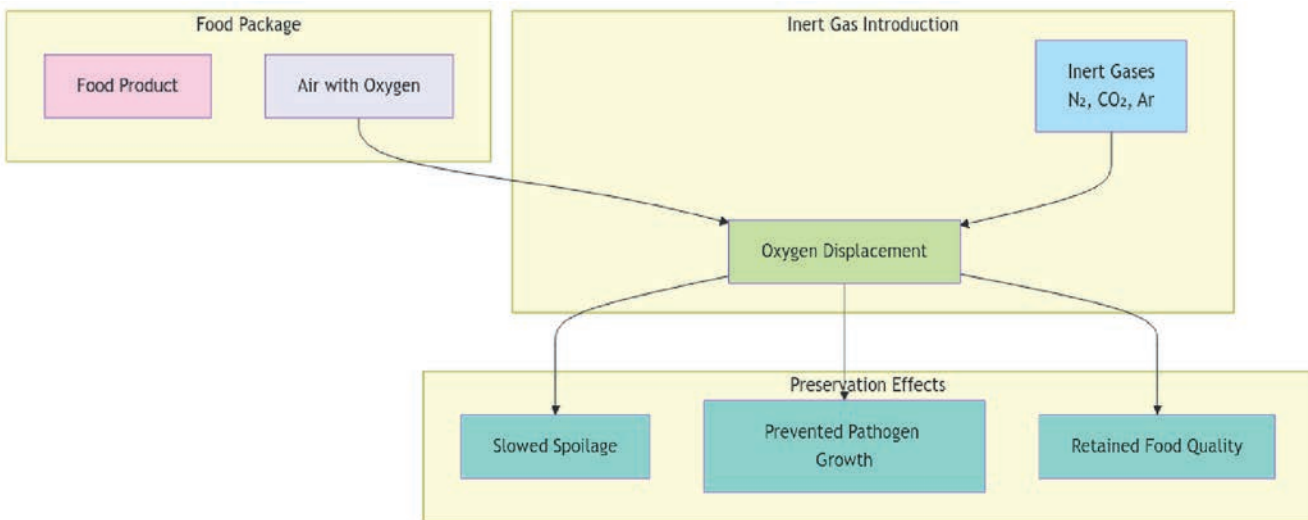


Figure 2.
Diagram illustrating how inert gases prevent foodborne illnesses and preserve food safety.

4. Helium gas in food preservation

Helium is the first element in the noble gas family and is an inert gas that cannot be detected by human senses. It is odourless, colourless, tasteless, and non-toxic. Of all the noble gases, helium has the lowest boiling and melting points, and it remains in gaseous form unless subjected to extreme conditions [34]. Food manufacturers employ helium in their packaging processes to ensure airtight seals. Thanks to its exceptionally small molecules, helium can penetrate tiny openings, making it an ideal gas for detecting leaks in food packaging [35, 36].

5. Neon gas in food preservation

Neon is one of the lightest of noble gases and is grouped together with the other unreactive to moderately reactive noble gases [37]. It is chemically inert, has a high density, and is non-toxic. Although not directly used in food packaging or preservation, it is used as an economical cryogenic refrigerant [38].

6. Krypton gas in food preservation

Krypton rarely reacts with other elements and does not readily form chemical compounds due to its inertness. It is an odourless, tasteless, and colourless gas that makes up a tiny fraction of Earth's air [39]. When fresh-cut produce is pressurised with inert gases such as krypton and argon under specific conditions, gas hydrates form within the tissue. This process reduces intracellular water activity and enzyme function, thereby decreasing metabolic rates [40, 41]. Research on extending the shelf-life and maintaining the quality of certain vegetables, such as white mushrooms, indicates that a mixture of pressurised krypton and argon gas can preserve them for up to 9 days when stored at 4°C [42].

7. Radon gas in food preservation

Radon is an invisible, flavourless, and odourless gas that is radioactive by nature. It is produced through the natural decay of uranium and releases ionising radiation as it degrades. This gas is present throughout the atmosphere and can bind to airborne particles [43]. The radioactive properties of radon pose health risks, including cancer and infections, therefore its use in food preservation is extremely limited [44]. However, its ionising radiation can be utilised in food packaging through two methods: sterilising materials for aseptic packaging, and radiation processing of already-packaged foods. Aseptic packaging involves sterile product filling in controlled environments, while prepackaged food irradiation treats both food and packaging simultaneously [45]. The radiation resistance of packaging materials is crucial for the successful implementation of either method.

8. Xenon gas in food preservation

Xenon is a noble gas characterised by being colourless, odourless, and safe for both humans and the environment. While generally non-reactive like other noble gases,

it uniquely forms compounds with water and certain organic substances like hydroquinone and phenol. Despite its useful properties, xenon's industrial applications are restricted due to its excessive cost [46].

Xenon has several beneficial applications in food preservation: it can form gas hydrates that may help preserve proteins and enzymes, it provides inherent preservation properties that help maintain product stability, and its non-toxic nature makes it a safe choice for food preservation with no risks to consumer health [47].

9. Methods of applying MAP technology and noble gases in food preservation

The following innovative approaches highlight the effectiveness of noble gases in enhancing food preservation techniques, contributing to food safety and quality.

MAP in combination with argon gas has attracted attention for its effects on vegetable preservation. Argon's high water solubility and atomic size similarity to oxygen enables it to compete for enzymatic oxygen receptor sites, thereby reducing metabolic activity and extending product shelf life [48]. A study by Liguori et al. [49] compared two argon-enriched atmospheres (MAP 1: 90% Ar, 10% O₂ and MAP 2: 80% Ar, 10% CO₂, 10% O₂) against 36 samples of air-packaged fresh-cut broccoli rabe storage at 6°C. Samples were evaluated over 9 days, with MAP 1 showing superior preservation of sensory attributes. Results indicated that high-argon atmospheres effectively extend the shelf life of minimally processed leafy vegetables. Other studies show that a pressurised argon-krypton gas mixture (2 MPa for 2 hours at room temperature) before cold storage (5°C for 15 days) improved preservation. The treatment resulted in reduced mass loss, cell membrane permeability, CO₂ concentration, and vitamin C loss compared to untreated peppers [50].

Another method of using noble gases, such as xenon, is in the form of gas hydrates as a preservation method for enzyme activity, comparing it with room temperature and liquid nitrogen storage. Gas hydrates are crystalline structures where water molecules form hydrogen-bonded lattices that encapsulate small gas molecules like methane, ethane, or CO₂ [51]. Three enzymes were tested in a study by Shin et al. [47]: catalase, L-lactate dehydrogenase, and carbonic anhydrase, using xenon and natural gas hydrates. The enzyme solutions were subjected to gas hydrate formation by cooling them from 30 to 5°C under pressures of 20 bar for xenon and 55 bar for simulated natural gas. The method proved effective for preserving catalase and L-lactate dehydrogenase activity. The findings suggest gas hydrate storage could be superior to freeze-drying for certain enzymes, as it avoids mechanical protein damage.

The application of radon as ionising radiation in the food industry can process packaging material – which chemical treatments are unable to accomplish. Ionising radiation affects polymeric materials (such as plastic) in two ways: it can either increase molecular weight through cross-linking or decrease it through chain scission degradation [52]. The predominant reaction during irradiation in most plastics used for food packaging, such as polyethylene (PE), polypropylene (PP), and polystyrene (PS), is generally cross-linking. Cross-linking could decrease elongation, crystallinity, and solubility and increase the mechanical strength of polymers. Packaging materials are commonly irradiated prior to being filled with products by dairy, beverage, and processed food companies [52].

Research shows that the noble gas helium has applications in detecting leaks in canned foods. Helium leak detection, a highly sensitive method capable of finding

microscopic holes (as small as 1 micrometre) in canned foods, uses gas chromatography to measure helium forced through can holes. A study modified this test, using pressures of 570 mm Hg and a vacuum of 725 mm Hg, deviating from standard procedures. While the 725 mm Hg vacuum test showed lower effectiveness (39% detection in spoiled cans), the helium leak test remains a reliable method for ensuring food safety by detecting small leaks [53].

The evidence presented demonstrates that argon-enriched atmospheres excel at preserving minimally processed leafy vegetables, while helium's utility in leak detection enhances quality control in canned foods. The novel application of xenon gas hydrates shows promise in enzyme preservation, potentially revolutionising current preservation techniques. Current food preservation and packaging technologies, especially MAP and noble gases, effectively extend food shelf life but have room for improvement in the following areas:

Gas mixture optimisation: Better tailoring of argon, CO₂, and oxygen concentrations for specific foods, plus real-time monitoring capabilities.

Packaging materials: Development of more sustainable materials that balance structural integrity with biodegradability while maintaining preservation effectiveness.

Gas hydrate preservation: Refinement of temperature and pressure parameters for better enzyme stability, with potential applications for preserving sensitive compounds.

Leak detection: Enhancement of current helium-based methods for greater sensitivity and efficiency in quality control processes.

Consumer awareness: Improved education about food preservation technologies' benefits and safety features to increase public acceptance and adoption. These improvements would help the food industry to meet evolving market demands while maintaining food safety and quality.

10. Safety considerations and environmental implications

The implementation of noble gases in food packaging necessitates several critical safety considerations to maintain preservation efficacy. Primary requirements include ensuring an environment devoid of reactive gases, maintaining package integrity through proper sealing techniques, and verifying the purity of noble gases used. Personnel must receive appropriate training in gas handling protocols, while packaging materials must demonstrate compatibility with noble gases to prevent permeation or reactivity. Furthermore, the maintenance of precise atmospheric conditions through continuous monitoring of gas concentrations is essential for optimal food preservation and prevention of product degradation [54]. The use of noble gases in food applications is regulated through a combination of European Union (EU) laws, purity criteria, and general food safety regulations, ensuring that they are safe for consumers when used appropriately [55].

Noble gases represent an environmentally advantageous solution in packaging applications due to their chemical inertness, which prevents harmful chemical reactions and environmental contamination [56]. Notable examples include helium (939) and argon (E938) food additives, which have been deemed safe for food applications without toxicological evaluation by regulatory bodies, including the Scientific Committee for Food (SCF) and the Joint FAO/WHO Expert Committee on Food Additives (JECFA). Based on their physicochemical properties, the panel does require

that a minimum purity of 99.0% is used to comply with existing guidelines [57]. While these gases offer significant benefits in agricultural applications, including potential improvements in crop yields and soil health, their implementation presents environmental considerations regarding storage, cost-effectiveness, and broader ecological impact. This necessitates careful management strategies to ensure environmental sustainability in their industrial application [58].

11. Conclusion

The integration of noble gases into MAP presents a promising frontier in food preservation technology. Future research should focus on exploring innovative gas combinations that leverage the unique properties of noble gases, such as argon, helium, and xenon, to enhance their efficacy in extending shelf life and maintaining nutritional quality. Investigating the optimisation of packaging materials to synergise with these gases will be crucial in maximising their benefits.

Moreover, understanding the long-term health implications of using noble gases in food storage is essential for ensuring consumer safety and confidence. Research could also delve into the environmental impacts of these gases, assessing their sustainability in the context of global food systems.

Additionally, developing advanced monitoring systems for real-time analysis of gas composition within packaging could further enhance food safety and quality control. As the food industry faces increasing challenges related to waste reduction and food safety, the potential applications of noble gases in MAP could lead to groundbreaking solutions that promote sustainable practices and improved public health outcomes. The future of food preservation lies in the innovative application of these inert gases, paving the way for a more efficient and safe food supply chain.

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Conflict of interest

The author declares no conflict of interest.

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References

- [1] Fung F, Wang HS, Menon S. Food safety in the 21st century. *Biomedical Journal*. 2018;**41**(2):88-95. DOI: 10.1016/j.bj.2018.03.003
- [2] Dugassa, Fufa D. Food safety. In: Sajid Arshad MS, Khalid W, editors. *Health Risks of Food Additives—Recent Developments and Trends in Food Sector*. London, UK: IntechOpen; 2024. DOI: 10.5772/intechopen.109075
- [3] Alamri MS, Qasem AAA, Mohamed AA, Hussain S, Ibraheem MA, Shamlan G, et al. Food packaging's materials: A food safety perspective. *Saudi Journal of Biological Sciences*. 2021;**28**(8):4490-4499. DOI: 10.1016/j.sjbs.2021.04.047
- [4] Khan MY, Mittal A. Modified atmosphere packaging technique: An overview. In: *International Conference on Recent Advances in Engineering and Science*, 2020. Aligarh, India: University Polytechnic, AMU; 2020
- [5] Hintlian CB, Hotchkiss JH. The safety of modified atmosphere packaging: A review. *Food Technology*. 1986;**40**(12):70-76
- [6] Mendeleev D. *Osnovy Khimii (the Principles of Chemistry)* (in Russian). 7th ed. New York: Crowell-Collier; 1903
- [7] Ozima M, Podosek FA. *Noble gas geochemistry*. Cambridge, England: Cambridge University Press; 2001. DOI: 10.1017/CBO9780511545986
- [8] Farber JN, Harris LJ, Parish ME, Beuchat LR, Suslow TV, Gorney JR, et al. Microbiological safety of controlled and modified atmosphere packaging of fresh and fresh-cut produce. *Comprehensive Reviews in Food Science and Food Safety*. 2003;**2**(s1):142-160. DOI: 10.1111/j.1541-4337.2003.tb00032.x
- [9] Sandhya S. Modified atmosphere packaging of fresh produce: Current status and future needs. *LWT – Food Science and Technology*. 2010;**43**(3):381-392. DOI: 10.1016/j.lwt.2009.05.018
- [10] Mullan M, McDowell D. Modified atmosphere packaging. In: Coles R, Kirwan M, editors. *Food and Beverage Packaging Technology*. New Jersey, USA: John Wiley & Sons; 2011. pp. 263-294. DOI: 10.1002/9781444392180.ch10
- [11] Amit SK, Uddin MM, Rahman R, Islam SMR, Khan MS. A review on mechanisms and commercial aspects of food preservation and processing. *Agriculture and Food Security*. 2017;**6**(1):51. DOI: 10.1186/s40066-017-0130-8
- [12] Sharma K. Food storage and preservation: An essential key in food economy. In: *Futuristic Trends in Agriculture Engineering & Food Sciences*. Vol. 3. Book 22. Chikkamagaluru, Karnataka, India: Iterative International Publisher, Selfypage Developers Pvt Ltd; 2024. pp. 135-142. DOI: 10.58532/V3BCAG22CH12
- [13] Ahmad J, Ali M, Arif M, Iftikhar S, Ramzan I, Hussain M, et al. Review Article on: Traditional and Modern Techniques for Food Preservation. *International Journal of Modern Agriculture*. 2021;**10**(3). ISSN: 2305-7246
- [14] Kumar A. Food preservation: Traditional and modern techniques. *Acta Scientific Nutritional Health*. 2019;**3**(12):45-49. DOI: 10.31080/ASNH.2019.03.0529

- [15] Dweh TJ, Nayak J, Rout P, Parween A. Food storage and preservation. In: Futuristic Trends in Agriculture Engineering & Food Sciences Vol. 3 Book 24. Chikkamagaluru, Karnataka, India: Iterative International Publishers, Selfpage Developers Pvt Ltd; 2024. pp. 102-115. DOI: 10.58532/V3BCAG24CH9
- [16] Rana D, Pancheshwar D, Singh Y, Ansari F. Food Spoilage and it's Management. India: Integrated Publications; 2021. pp. 87-107. DOI: 10.22271/int.book.46
- [17] Jay JM, editor. Modern Food Microbiology. US: Springer; 2000. DOI: 10.1007/978-1-4615-4427-2
- [18] Steele R, editor. Understanding and Measuring the Shelf-Life of Food. Sawston, UK: Woodhead Publishing; 2004. DOI: 10.1533/9781855739024
- [19] Sperber WH, Doyle MP, editors. Compendium of the Microbiological Spoilage of Foods and Beverages. New York: Springer; 2009. DOI: 10.1007/978-1-4419-0826-1
- [20] Robertson GL. Food Packaging Principles and Practice. Florida, USA: CRC Press; 2006
- [21] Brody AL, Bugusu B, Han JH, Sand CK, McHugh TH. Scientific status summary. Innovative food packaging solutions: Innovative food packaging solutions. Journal of Food Science. 2008;73(8):R107-R116. DOI: 10.1111/j.1750-3841.2008.00933.x
- [22] Nath A, Deka BC, Singh A, Patel RK, Paul D, Misra LK, et al. Extension of shelf-life of pear fruits using different packaging materials. Journal of Food Science and Technology. 2012;49(5):556-563. DOI: 10.1007/s13197-011-0305-4
- [23] Singh R, Giri SK, Kotwaliwale N. Shelf-life enhancement of green bell pepper (*Capsicum annuum* L.) under active modified atmosphere storage. Food Packaging and Shelf-Life. 2014;1(2):101-112. DOI: 10.1016/j.fpsl.2014.03.001
- [24] Oliveira M, Abadias M, Usall J, Torres R, Teixidó N, Viñas I. Application of modified atmosphere packaging as a safety approach to fresh-cut fruits and vegetables—a review. Trends in Food Science and Technology. 2015;46(1):13-26. DOI: 10.1016/j.tifs.2015.07.017
- [25] Belay ZA, Caleb OJ, Opara UL. Modelling approaches for designing and evaluating the performance of modified atmosphere packaging (MAP) systems for fresh produce: A review. Food Packaging and Shelf-Life. 2016;10:1-15. DOI: 10.1016/j.fpsl.2016.08.001
- [26] Caleb OJ, Opara UL, Witthuhn CR. Modified atmosphere packaging of pomegranate fruit and arils: A review. Food and Bioprocess Technology. 2012;5(1):15-30. DOI: 10.1007/s11947-011-0525-7
- [27] Tavasoli Talarposhti S, Barzegar M, Hamidi-Esfahani Z. Effect of modified atmosphere packaging on aril physico-chemical and microbial properties of two pomegranate cultivars (*Punica granatum* L.) grown in Iran. Nutrition and Food Sciences Research. 2016;3(4):29-40. DOI: 10.18869/acadpub.nfsr.3.4.29
- [28] Rokalla P, Inbaraj BS, Dikkala PK, Sridhar K, Dasi DS, Koka L, et al. Active-modified atmosphere packaging of ready-to-eat pomegranate (*Punica granatum* L.) arils at ambient temperature for extending shelf-life. Agriculture. 2022;12(2):155. DOI: 10.3390/agriculture12020155

- [29] Sismanoglu BN, editor. Argon: Production, Characteristics, and Applications. New York, USA: Nova Science Publishers, Inc; 2013
- [30] Spencer KC. The use of argon and other noble gases for the MAP of foods. In: Modified Atmosphere Packaging (MAP) and Related Technologies. UK: Campden & Chorleywood Research Association, Chipping Campden; 1995. pp. 6-7
- [31] Spencer KC, Humphreys DJ. Argon packaging and processing preserves and enhances flavor, freshness, and shelf-life of foods. In: Cadwallader KR, Weenen H, editors. ACS Symposium Series. Vol. 836. Washington, D.C.: Freshness and Shelf-life of Foods; 2002. pp. 270-291. DOI: 10.1021/bk-2003-0836.ch020
- [32] Spencer KC. Modified atmosphere packaging of ready-to-eat foods. In: Jung HH, editor. Innovations in Food Packaging. Vol. 13. Amsterdam, Netherlands: Elsevier Academic Press; 2005. pp. 185-203. DOI: 10.1016/B978-012311632-1/50044-9
- [33] Shirke A. In: Shirke A, editor. Dynamic Role of Inert Gases in Food Storage. Maharashtra, India: Abhijeet Shirke; 2024. Available from: <https://www.abhijeetshirke.in/role-of-inert-gases-in-food-storage/>
- [34] Park J, Choi J, Kim K. A study on temperature and pressure characteristics in a vessel as charging time of helium gas changes. *Applied Sciences*. 2023;**13**(20). Article 11348. DOI: 10.3390/app132011348
- [35] Cryospain. What Are Food Gases and Which Are the Main Ones? Cryospain. Madrid, Spain; 2022. Available from: <https://cryospain.com/main-food-gases>
- [36] Serra Leal JS, Incer-Valverde J, Morosuk T. Helium: Sources, applications, supply, and demand. *Gases*. 2023;**3**(4):181-183. DOI: 10.3390/gases3040013
- [37] Grochala W. On the position of helium and neon in the periodic table of elements. *Foundations of Chemistry*. 2018;**20**(3):191-207. DOI: 10.1007/s10698-017-9302-7
- [38] Dalakov P, Neuber E, Klier J, Herzog R. Innovative neon refrigeration unit operating down to 30 K. *MATEC Web of Conferences*. 2020;**324**:01003. DOI: 10.1051/mateconf/202032401003
- [39] Schrobilgen GJ, Lozinšek M. The world of krypton revisited. *Nature Chemistry*. 2016;**8**(7):732. DOI: 10.1038/nchem.2538
- [40] Oshita S, Seo Y, Kawagoe Y. Relaxation time of protons in intracellular water of broccoli. In: Proceedings of the CIGR International Symposium. Kyoto, Japan: Proceedings of the CIGR International Symposium; 2000. pp. 77-82
- [41] Zhang M, Zhan ZG, Wang SJ, Tang JM. Extending the shelf-life of asparagus spears with a compressed mix of argon and xenon gases. *LWT – Food Science and Technology*. 2008;**41**(4):686-691. DOI: 10.1016/j.lwt.2007.04.011
- [42] Lagnika C, Zhang M, Bashari M, Tounkara F. Effects of pressurised argon and krypton treatments on the quality of fresh white mushroom (*Agaricus bisporus*). *Food and Nutrition Sciences*. 2013;**4**(12):1191-1200. DOI: 10.4236/fns.2013.412153
- [43] Degu Belete G, Alemu Anteneh Y. General overview of radon studies in health hazard perspectives. *Journal of*

Oncology. 2021;**2021**:6659795. DOI: 10.1155/2021/6659795

[44] Al-Naggar IT, Shabaan HD. Radon in foods. In: Recent Techniques and Applications in Ionizing Radiation Research. London, UK: IntechOpen; 2020. DOI: 10.5772/intechopen.93123

[45] Chuaqui-Offermans N. Food packaging materials and radiation processing of food: A brief review. International Journal of Radiation Applications and Instrumentation Part C. 1989;**34**(6):1005-1007. DOI: 10.1016/1359-0197(89)90343-3

[46] Bajaj T, Cascella M, Bongor J. Xenon. Treasure Island (FL): StatPearls Publishing; 2020

[47] Shin J, Han S, Kang SP. Investigation of xenon and natural gas hydrate as a storage medium to maintain the enzymatic activity of the model proteins. Korean Journal of Chemical Engineering. 2016;**33**(4):1345-1351. DOI: 10.1007/s11814-015-0266-9

[48] Ghidelli C, Perez-Gago MB. Recent advances in modified atmosphere packaging and edible coatings to maintain quality of fresh-cut fruits and vegetables. Food Science and Nutrition. 2017;**58**:662-679

[49] Liguori L, Malvano F, Fratianni F, Nazzaro F, Orilio P, Albanese D. Effect of argon-enriched modified atmosphere on the over quality and bioactive compounds of ready-to-use broccoli rabe (*Brassica rapa sylvestris* L. var. esculenta) during the storage. Food Science and Technology International. 2023;**29**(1):84-94. DOI: 10.1177/10820132211062696

[50] Raymond LV, Zhang M, Karangwa E, Chesereka MJ. Mixed noble gas effect on cut green peppers. International

Agrophysics. 2013;**27**(1):75-79. DOI: 10.2478/v10247-012-0070-2

[51] Sloan ED Jr, Koh CA, Koh CA. Clathrate Hydrates of Natural Gases. 3rd ed. Florida, USA: CRC Press; 2007. DOI: 10.1201/9781420008494

[52] Haji-Saeid M, Sampa MHO, Chmielewski AG. Radiation treatment for sterilization of packaging materials. Radiation Physics and Chemistry (Oxford, England: 1993). 2007;**76**(8-9):1535-1541. DOI: 10.1016/j.radphyschem.2007.02.068

[53] Gilchrist JE, Rhea US, Dickerson RW, Campbell JE. Helium leak test for micron-sized holes in canned foods. Journal of Food Protection. 1985;**48**(10):856-860. DOI: 10.4315/0362-028X-48.10.856

[54] Compendium Packaging. Food safety and standards (packaging). Regulations, 2018. 2024. Available from: https://fssai.gov.in/upload/uploadfiles/files/Compendium_Packaging_01_02_2022.pdf

[55] Home – EIGA. European Industrial Gases Association. EIGA: European Industrial Gases Association. Brussels, Belgium: EIGA; 2021. Available from: <http://www.eiga.eu/>

[56] Venturepak. Why Are Noble Gases Used in Food Packaging in 2023? Venturepak. Merseyside, England; 2023. Available from: <https://www.venturepak.co.uk/why-are-noble-gases-used-in-food-packaging/>

[57] EFSA FAF Panel (EFSA Panel on Food Additives and Flavourings), Castle L, Andreassen M, Aquilina G, Bastos M, Boon P, et al. Re-evaluation of argon (E 938) and helium (E 939) as food additives. EFSA Journal.

2024;22(10):e9048. DOI: 10.2903/j.
efsa.2024.9048

[58] Mozhyako A, Dudkin V,
Kosolapov V, Savchenko I, Zhuchenko A,
Diuldin M. On the possibility of
using noble gases in the liquid phase
in agriculture. IOP Conference
Series. Earth and Environmental
Science. 2020;578(1):012025. DOI:
10.1088/1755-1315/578/1/012025

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Based on the fact that food processing plays an essential role in the constantly changing global food system, shaped by technological innovation, sustainability, and evolving consumer demands, *Food Processing – Novel Technologies and Practices* offers an integrated perspective on the latest advancements in the field, highlighting the transformative potential of non-thermal technologies, intelligent processing systems, digitalization, and circular economy strategies. With this volume, we aimed to highlight how these solutions can improve food safety and quality, extend shelf life, and contribute to more efficient resource use, in line with environmental and regulatory requirements. Additionally, through its interdisciplinary approach, the volume provides valuable insights for researchers, industry professionals, and policymakers, supporting the development of sustainable and resilient food systems. *Food Processing – Novel Technologies and Practices* is a reference resource for those involved in the future of food processing.

*Maria Rosário Bronze,
Food Science and Nutrition Series Editor*

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