Novel Foods and SUSTAINABILITY in Food Science

Editor
AYŞE SEVGILI

BIDGE

BIDGE Publications

NOVEL FOODS AND SUSTAINABILITY IN FOOD SCIENCE

Editor: AYŞE SEVGILI

ISBN: 978-625-372-876-2

1st Edition

Page Layout By: Gozde YUCEL

Publication Date: 18.12.2025

BIDGE Publications

Certificate No: 71374

www.bidgeyayinlari.com.tr - bidgeyayinlari@gmail.com
Krc Bilişim Ticaret ve Organizasyon Ltd. Şti.
Güzeltepe Mahallesi Abidin Daver Sokak Sefer Apartmanı No: 7/9 Çankaya / Ankara

Contents

GREEN CHEMISTRY PRINCIPLES IN SUSTAINABLE FOOD ENGINEERING

GÜLTEN ŞEKEROĞLU[1]
AHMET KAYA[2]

Introduction

Food production is critical to sustainability due to its substantial use of land and water resources, its contribution to greenhouse gas emissions, and the generation of waste and contaminants (Bhandari & Kasana, 2018; Poore & Nemecek, 2018). Furthermore, food safety is paramount because foodborne pathogens and toxic substances can pose severe health risks. Sustainability and safety are interrelated because food spoilage can compromise food safety, resulting in increased food waste. Likewise, contamination from chemicals, biological agents, or particles can compromise food safety. Where chemical approaches can mitigate spoilage, achieving them more sustainably is desirable. Various institutions have delineated the degree of sustainability achieved by food processes.

[1] Assist. Prof. Dr., Gaziantep University, Naci Topçuoğlu Vocational School, Food Processing Department Orcid: 0000-0002-5499-1028, sekeroglu@gantep.edu.tr
[2] Prof. Dr., Gaziantep University, Engineering Faculty, Food Engineering Department, Orcid: 0000-0001-6960-3780, kaya@gantep.edu.tr

The food processing industry is one of the top five spenders on pollution abatement. Sustainable food engineering seeks to adopt greener production methods while maintaining food safety and quality. The principles of green chemistry provide a framework for identifying the most effective means to sustainably engineer. The food engineering sector focuses on critical attributes, materials, and processes for sustainable food systems, and opportunities for incorporating green chemistry into food engineering follow through already-established green engineering initiatives (Nevárez-Moorillón et al., 2022). As a widely implemented concept in the chemical industry, green chemistry can help food engineers devise safer, more sustainable designs and practices for food processes than conventional approaches, enabling the safe and sustainable provision of engineered products.

The Food-Environment Nexus: Challenges and Impacts

The contemporary global environmental landscape is increasingly strained by various issues that directly impact food engineering and science. The following summarizes the most notable environmental challenges, along with their ramifications for the food industry, with a primary focus on sustainability, food security, and biodiversity.

First and foremost, climate change is a significant issue that impacts agricultural output by causing extreme weather events and altering climate patterns. Reports indicate that climate changes lead to reduced crop yields, impacting food availability and, consequently, global food security (Oriekhoe et al., 2024; Ziervogel & Ericksen, 2010). Furthermore, the increased prices of agricultural inputs, such as fertilizers and water, exacerbated by climate-related stresses, pose a threat to the livelihoods of smallholder farmers (Souissi et al., 2024). The reliance on traditional agricultural methods, which include the use of chemical fertilizers, exacerbates environmental damage and biodiversity loss (Sousa et al., 2024; Gwiazdowska et al., 2024).

Green Chemistry

Green chemistry is a fundamental approach in the field of chemistry that aims to conduct processes in accordance with the principles of sustainable development. It is an interdisciplinary field that involves the application of a wide range of principles to minimize the environmental impact of both chemical processes and products (Yuan, 2024). Green chemistry focuses on devising sustainable alternatives to conventional approaches by utilizing renewable raw materials, thereby reducing waste and strictly avoiding the use of toxic and potentially hazardous reagents and solvents in the production and application of chemical products.

The goal of green chemistry is to develop chemicals and processes that minimize or eliminate the production or use of hazardous materials. Twelve guiding principles form the foundation of this field, shaping the discipline and directing efforts toward these goals (Figure 1). In the realm of sustainable food engineering, the goal is to develop food products and bioprocesses that are safe, nutritious, and economically viable, while also preserving biodiversity and the natural environment. This approach seeks to reduce the regulatory complexities associated with the production, distribution, processing, and sale of food and related products. Therefore, the principles of green chemistry are particularly applicable to food engineering, highlighting the relevance of innovative process and product design within that specific context (Amoneit et al., 2024; Sajid & Płotka-Wasylka, 2022).

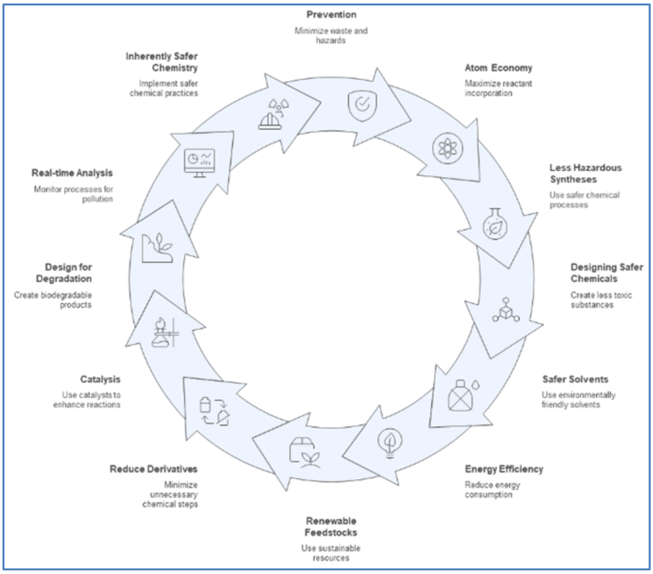

Figure 1 Principles of Green Chemistry

Prevention

It is better to prevent waste than to treat or clean up waste after it has been formed. In food systems, waste generated during food processing is responsible for substantial economic losses and has a significant environmental impact. Depending on the equipment and processing time, the generation of wastewater during the processing of specific food matrices, such as fruits, cereals, and vegetables, may account for more than 90% of the total mass balance; thus, pollution is often unavoidable (Bhandari & Kasana, 2018). The application of green processing principles enables the minimization or even complete avoidance of hazardous and toxic waste generation. In food processing, innovative methods are available to process food in an entirely aqueous environment, thereby eliminating the use of dangerous and harmful solvents. The developed processes also enable the intensive processing of food matrices, resulting in reduced overall processing time and water usage. Thus, the environmental-related impact associated with water consumption and wastewater generation is reduced to the lowest level (Rashid & Shahzad, 2021).

Atom economy

The subsequent procedures required to separate and purify a product are simplified when fewer materials are used in the process. Food is processed in various ways to ensure its quality and safety, as well as to provide value-added goods that meet customer needs. One of the crucial unit processes for preserving the nutrients and bioactive substances found in the food matrix is food extraction. Solid-liquid extraction is currently the most widely used method due to its ease of use, despite its disadvantages as a conventional approach. In a contemporary solid-liquid extraction process, less than 10% of the elements that enter end up in the finished product (Shrivastav, et al, 2024).

Less hazardous chemicals

Solvent use during food processing poses significant safety and environmental challenges. Solvents can be hazardous, generating air pollution, water contamination, and exposure risks (Capello et al., 2007). To address these challenges, solvent use can be eliminated through the application of several innovative alternatives. The alternative(s) chosen depend on the process and could include simply switching to a safe and non-toxic solvent or residue stripping that removes solvents completely and guarantees zero contamination of food products (Chemat et al., 2012).

By replacing solvents, other potential hazards can also arise, such as exposure to volatile organic compounds (VOCs). Because of that, attention during food processing is drawn to their physicochemical properties and environmental and sanitary impact. An ideal alternative presents a combination of non-toxicity, biodegradability, eco-compatibility, availability from renewable resources, and economic feasibility (Clarke et al., 2018); petroleum-based solvents such as methyl ethyl ketone, ethanol, isopropanol, and acetone should be discarded since they fail to meet these criteria. Vegetable oils provide a good alternative, being non-polar, biodegradable, non-toxic, and environmentally friendly. They are applied in food and cosmetic formulations and used in the extraction of bioactive feedstock (Yara-Varón et al., 2017).

Numerous non-toxic green solvents have emerged recently, together with technologies to process those (Viñas-Ospino et al., 2023). Supercritical fluids, limonene, ionic liquids, natural deep eutectic solvents (NADES), and vegetable oils are promising candidates for extracting carotenoids from fruit and vegetable by-products, with the best alternative dependent upon target bioactive characteristics and associated extraction parameters (Chemat et al., 2019). Green solvents feature low toxicity and relevant properties that allow addressing several industrial processes. For the food sector, and despite promising results, much work remains to confirm their suitability.

The food industry relies heavily on organic solvents and other chemical substances for diverse processing operations such as extraction, concentration, and food packaging. Many of these substances are postulated today as potentially detrimental to food quality and consumer safety. Additionally, some food-processing applications exhibit high-temperature and long-storage potential and cause undesirable changes such as hydrolysis, polymerization, oxidation, browning, or off-flavor development in unprocessed food (Luning, P., & Sanny, M. (2016). Hence, determining a good alternative to conventional solvents and other chemical substances while preserving food quality and extending the lifetime and safety of the end-product is nowadays essential in food engineering. Several strategies reported include avoiding the use of such substances, shortening processing time, and maintaining unprocessed foods unchanged (Viñas-Ospino et al., 2023). Attributes such as dissolving power, ease of removal, remaining content in the final product, eco-friendliness, health safety, the absence of by-products under specified process conditions, availability, and low cost must be considered. Minimal chemical composition, negligible health risk, compliance with regulation, no indirect contribution to food establishment pollution, and maintaining required levels must be met (Kerton & Marriott, 2013). Bio-based natural and ecological substances—vegetable oils—substitute organic solvents entirely and are bio-based, non-toxic, biodegradable, and environmentally friendly.

Food waste valorization and reduction

Recent evaluations of the global food supply system highlight a significant disparity between resource availability and demand. Food insecurity continues to rise, despite the fact that 1.05 billion tonnes of food are wasted annually. This is true in both wealthy and developing countries (UNEP, 2024). In fact, approximately 1 in 11 people worldwide (up to 757 million) are undernourished, and 2.8 billion can't afford healthy food (FAO et al., 2024). This troubling trend is also happening in wealthy countries. For example, USDA data shows that 47.4 million Americans were recently food insecure (Rabbitt et al., 2024). These findings suggest that simply increasing production is insufficient; comprehensive strategies targeting waste reduction and distribution equity are essential to mitigating global hunger. While consumer behavior plays a role, substantial wastes originate from food-processing operations or raw materials added during processing. These operations consume a significant amount of both environmental resources and process expenditures, creating unavoidable environmental emissions. Moreover, effective resource recovery at an early stage of food processing, e.g., from raw materials or semifinished products before they enter the final formulation stage, minimizes the risk of contamination or deterioration. The development and implementation of next-generation food-processing technology, food raw materials with tailored properties, food microbial systems with tailored characteristics, and food packaging with appropriate barrier properties will help mitigate waste generation at multiple levels (Kumar et al., 2022; Sarker et al., 2024).

Catalysis and process intensification in food production

The use of catalytic processes can significantly enhance the sustainability of food production. Enzymatic catalysis is one of the most sustainable forms of catalysis, as it facilitates reactions under mild conditions and usually with minimal byproduct formation. The use of enzymes as reactants in high-throughput reaction screening can also expedite the development of new food products. (Bhandari & Kasana, 2018). Intensifying food processes while minimising energy and material use is increasingly feasible with developments such as co rotatory kneading of dough, continuous processing, and multi-step processes using a single piece of equipment

Life cycle assessment and environmental impact

Food systems consume more than 30% of the world's energy and are responsible for around 23% of total greenhouse gas emissions. However, assessing the environmental impact of food systems using conventional chemical and environmental methods such as the demand, dilution, and emission factors often displays significant regional dependence due to the widespread distribution of food and our preference for fresh food. As a result, it is not always easy to evaluate overall food system performance. Food engineering typically involves raw material selection, processing, and conversion activities as an integrated whole from the viewpoint of resource efficiency (Fantin, 2019). For example, the LCA methodology applied to potato crisps as a food product in Canada has been developed to evaluate food-specific chemical emission mechanisms and their regional dependence quantitatively. In addition, a systematic theoretical framework that explicitly considers food destinations and essential physical-chemical interaction mechanisms for chemical contaminant transfer during food processing is proposed to support the quantitative evaluation of food contribution within food systems universally.

Sustainable Process Design for Food Safety and Quality

According to the UN's Food and Agriculture Organization, up to 1.3 billion tons of food are wasted each year. Much of this waste happens during post-harvesting and food processing, including storage, distribution, and marketing. Food loss has an environmental, social, and economic impact in terms of water, energy, land, and nutrients wasted in vain. Thus, food supply systems must be efficient, safe, and capable of delivering high-quality food without deterioration of nutrients and substances, and non-desirable changes in humidity, flavor, or odor. The challenge is to develop alternatives to conventional processes that generate targets for sustainable food safety and quality. Low-impact food engineering facilitates the design of alternative sustainable processes. Food safety and quality cannot be compromised, and new concepts have to introduce parameters such as length of shelf-life, desired food attributes, bioprocess monitoring, and control of undesirable reactions/minimisation of un-desired by-products (Rosenberg, 2021; Coudard et al., 2021; Abbade, 2023; Gatto & Chepeliev, 2024).

Food safety and quality can be improved through the application of one or a combination of the following concepts: green extraction technologies that employ edible solvents that at worst are colorless, tasteless, and odorless (water, ethanol) and potentially provide safe food; prohibiting food-contact materials containing toxic substances normally detected in food-linked odors and flavors; and water stewardship that maintains the maximum distance between the kitchen sink and food processing and encourages valorization approaches that convert food susceptible to spoilage into high-value products

Green extraction technologies

The application of green chemistry principles in food engineering offers opportunities to contribute to sustainability by optimizing the design of food processes for safety and quality. Green extraction encompasses extraction processes for the recovery of nutraceuticals, pharmaceuticals, and cosmetics. The selection of environmentally friendly solvents is crucial to the sustainability of extraction processes (Morón-Ortiz et al., 2024). Non-toxic solvents, such as water, bio-based solvents, supercritical fluids, and solvents derived from food industry by-products, are especially suitable for the green extraction of nutraceuticals from food resources (Viñas-Ospino et al., 2023). Such solvents can be integrated into the process design of extraction operations, considered safe.

Biodegradable materials in packaging

As the environmental damage caused by traditional petroleum-based plastics continues to increase, research into the use of bio-based and biodegradable packaging materials in the food packaging industry has grown. (Kepekçi et al., 2024). For example, food and beverage packaging designs are being created using materials such as compostable paper and cardboard. Another example is the use of bioplastics, a type of polymer usually obtained from plant-based biological sources, unlike traditional plastics. Examples of bioplastics include polyhydroxyalkanoates obtained from corn starch, starch-based plastics, and polylactic acid. In addition, the applications of biodegradable films in the food and beverage industry are also increasing. Again, edible films applied to preserve the freshness of foods, extend their shelf life, and reduce waste are other important applications. These films are usually made from natural components such as starch, protein, and fruit and vegetable extracts to cover the surface of foods.

These new-generation packaging materials are highly advantageous for the circular economy due to their minimal carbon footprint and natural biodegradability at the end of their life cycle. These new materials are produced in an environmentally conscious manner (Kepekçi et al., 2024).

Emerging Technologies and Future Prospects

The integration of green chemistry principles and sustainable practices into industrial food production faces complex hurdles related to process efficiency, resource optimization, and supply chain transparency. To approach these challenges, urgently needed transformations will be driven by emerging technologies within the electronic, digital, and data-based economies. The Internet of Things (IoT), Artificial Intelligence (AI), Big Data, Robotics, and Remote Sensing will revolutionize food/health products and nutritional services throughout the supply chain (Aguilar et al., 2019). Further details on these technologies are as follows.

Current shifts in consumer lifestyles, such as limited time, health concerns, preferences for omnivore diets, and a growing desire for food safety, authenticity, and transparency, amplify the call for an agile, adaptable, integrated food industry that promotes the mass customization of food products (Hassoun et al., 2022). The demand for short life cycle, convenient, and safe products warrants rapid, effective cleaning between work activities. Such demand makes workforce adaptation or re-training critical, as managing food-grade biotechnology processes becomes imperative. The technology set should thus provide highly trained staff with process control, safety, and telemetry management options, considering that such systems advocate personnel-change management and simplify compliance documentation. Investment in wider interoperability between sensors, networks, controllers, instruments, and automation across hygienic and non-hygienic areas enables the further infusion of food safety, traceability, and authenticity into the development, production, and testing of food solutions from building design to delivery (Bouzembrak et al., 2019).

Integration of process control with modern vision-camera-based systems accelerates root-cause identification in food-permitted areas and should complement existing advanced vision systems. Faster readings on demanding geometries and surface conditions such as blurring, glare, and rapid motion can allow many machine-vision applications to enter the food sector or expand into material handling, conveyance, or packaging areas—growth severely limited by legacy architectures (Kakani et al., 2020). Operating over clear, predictable, bulk, dense products and tightly specified geometries at non-accelerated speeds permits entry into secondary packaging. Systems capable of achieving a quality index aligned with advanced technological offerings, using general-purpose computing engines such as Graphics Processing Units (GPUs), rapidly indent channels with sufficient market volume to justify entry—and import additional safety due to routine access to sanitation records.

Advances in the biosciences, biotechnology, and materials science sectors, alongside changing consumer preferences, will profoundly alter methods, locations, and systems of food production. Sensor-enhanced equipment capable of measuring environmental variables, soil composition, or crop maturity and development will increasingly automate decision-making and reduce reliance on personal effort and time in outdoor farming, particularly given limits on expertise and the increasing difficulty in assembling, recruiting, and retaining manpower (Wolfert et al., 2017). Sensor-embedded electronic components integrated into traditional elements of fishing vessels, equipment, cages, nets, traps, pots, crates, and anchors will alert operators to delays, blockages, or disruptions, or directly manage equipment, enabling real-time supply-chain or route-to-market optimization—an opportunity being currently explored.

With rapidly growing consumer demand for enhanced convenience, freshness, health, safety, and shorter food value chains, industry and academia have started rethinking food processing on the principles and foundations of the Fourth Industrial Revolution. New process steps in a hygiene-aware and food-compatible manner instead of via the associated batch transport, storage, and conversion adopted in the past will open large, cost-effective opportunities. To increase food productivity, non-thermal technologies, process intelligence, cyber-physical system (CPS), and accelerated digital transformation are mentioned as development opportunities alongside continuous processing.

Food-Engineering processes have to comply with the same principles that are being followed in the chemical, petrochemical, fine-chemical and pharmaceutical industries: apply alternative raw materials, avoid ultra-conditions of temperature, pressure, stoichiometry or phase equilibria, valorise byproducts, waste or co-products to avoid even more waste. Hence principles and priority should be given to study the non-thermal technologies applicable to food processing (Picart-Palmade et al., 2019). These non-thermal technologies are mainly applicable to the extraction, but in general have other applications in food processing that could be of great benefit. They have shown applicability at pilot scale, nevertheless for industry still represent more of an R&D approach. Focus should be given, to make changes, based on analytical knowledge investigation, to take high added-value compounds from by-products, co-products or wastes from food industries.

Emerging food processes will promote dialogue and practices anticipated by consumers and will lead to diversified modifications in food transformation and distribution. Food-safety authorities will emphasize highly selective binning to enhance stability and decrease discharges by implementing more compact techniques and thorough examination machinery in order to promote circular economy. Modern food process engineering necessitates dexterity to remain in tandem with sector evolution and to prioritize cleansing with affordable components, particularly in biotechnological procedures. Accelerated imaging-system assessments, self-diagnosis for upkeep, and broader architecture coupling will amplify food viability, traceability, and originality. The Industrial Internet of Things and information gathering will facilitate the proficient administration of production, assets, and upkeep. Within the next ten years, sensors, algorithms, data amalgamation, machine perception, and automation are projected to refine outdoor cultivation and mitigate restrictions associated with established methods. More compact, automatic depots close to urban areas and direct-current self-ruling conveyances for aliment distribution are set to become prevalent. Convergence in biological, biotechnological, and material sciences and variations in consumer predilections are likely to redefine food-formation venues and methodologies (Aguilar et al., 2019).

CONCLUSION

As a result, the discipline of food engineering has to maintain its core mission of protecting food safety, quality and nutritional value under increasing pressure of climate change, resource scarcity and biodiversity loss. Achieving this complex balance and overcoming global challenges requires going beyond traditional production models and fully integrating Green Chemistry principles into food processing. This integrated approach, which prevents waste at source, prioritizes non-toxic solvents and renewable raw materials, is the cornerstone of a new generation of 'Sustainable Food Engineering' paradigm that minimizes carbon footprint and is based on circularity. Ultimately, the combined application of innovative technologies and green chemistry principles will not only reduce industrial pollution, but also secure a safe and long-lasting food supply that respects the limits of the planet.

References

Abbade, E. B. (2023). Land footprint and GHG emissions from global food loss. Journal of the Science of Food and Agriculture. 103(9), 4430–4440. https://doi.org/10.1002/jsfa.12524

Amoneit, M., Weckowska, D., Spahr, S., Wagner, O., Adeli, M., Mai, I., & Haag, R. (2024). Green chemistry and responsible research and innovation: Moving beyond the 12 principles. Journal of Cleaner Production, 484, 144011. https://doi.org/10.1016/j.jclepro.2024.144011

Bhandari, S., & Kasana, V. (2018). Applications of Green Chemistry Principles in Agriculture. Green Chemistry & Technology Letters, 4(2), 10–12. https://doi.org/10.18510/gctl.2018.422

Bouzembrak, Y., Klüche, M., Gavai, A., & Marvin, H. J. P. (2019). Internet of Things in food safety: Literature review and a bibliometric analysis. Trends in Food Science Technology, 94, 54–64. https://doi.org/10.1016/j.tifs.2019.11.002

Bubalo, M. C., Vidović, S., Radojčić Redovniković, I., & Jokić, S. (2018). New perspective in extraction of plant biologically active compounds by green solvents. Food and Bioproducts Processing, 109, 52-73. https://doi.org/10.1016/j.fbp.2018.03.001

Capello, C., Fischer, U., & Hungerbühler, K. (2007). What is a green solvent? A comprehensive framework for the environmental assessment of solvents. Green Chemistry, 9(9), 927-934. http://dx.doi.org/10.1039/b617536h

Chemat, F., Abert-Vian, M., Fabiano-Tixier, A. S., Strube, J., Uhlenbrock, L., Gunjevic, V., & Cravotto, G. (2019). Green extraction of natural products. Origins, current status, and future challenges. TrAC Trends in Analytical Chemistry, 118, 248-263. https://doi.org/10.1016/j.trac.2019.05.037

Chemat, F., Vian, M. A., & Cravotto, G. (2012). Green extraction of natural products: concept and principles. International Journal of Molecular Sciences, 13(7), 8615-8627. https://doi.org/10.3390/ijms13078615

Clarke, C. J., Tu, W. C., Levers, O., Bröhl, A., & Hallett, J. P. (2018). Green and sustainable solvents in chemical processes. Chemical Reviews, 118(2), 747-800. DOI: 10.1021/acs.chemrev.7b00571

Coudard, A., Corbin, E., de Koning, J. I. J. C., Tukker, A., & Mogollón, J. M. (2021). Global water and energy losses from consumer avoidable food waste. Journal of Cleaner Production, 326, 129342. https://doi.org/10.1016/j.jclepro.2021.129342

Fantin, V. (2019). Environmental Life-Cycle based methods to support the transition towards Circular Economy in the Agri-food sector.Amsdottorato.https://doi.org/10.6092/UNIBO/AMSDOTTORATO/8799

FAO, IFAD, UNICEF, WFP, & WHO. (2024). The state of food security and nutrition in the world 2024: Financing to end hunger, food insecurity and malnutrition in all its forms. FAO. https://doi.org/10.4060/cd1254en

Gatto, A. & Chepeliev, M. (2024). Global food loss and waste estimates show increasing nutritional and environmental pressures. Nature Food. 5, 136–147. https://doi.org/10.1038/s43016-023-00915-6

Gwiazdowska, D., Marchwińska, K., & Juś, K. (2024). Sustainable food production and processing—sustainable agriculture and biotechnological approaches in food chain. Sustainable Food. Production and Consumption Perspectives, 13-28. https://doi.org/10.18559/978-83-8211-209-2/1

Hassoun, A., Aït-Kaddour, A., Abu-Mahfouz, A. M., Rathod, N. B., Bader, F., Barba, F. J., ... & Regenstein, J. (2022). The fourth industrial revolution in the food industry—Part I: Industry 4.0 technologies. Critical Reviews in Food Science and Nutrition, 63(23),6547–6563. https://doi.org/10.1080/10408398.2022.2034735

Kakani, V., Nguyen, V. H., Kumar, B. P., Kim, H., & Pasupuleti, V. R. (2020). A critical review on computer vision and artificial intelligence in food industry. Journal of Agriculture and Food Research, 2, 100033. https://doi.org/10.1016/j.jafr.2020.100033

Kepekci, R. A., Şekeroğlu, G., & Alhveis, I. (2024). Development of bioactive and environmentally friendly chitosan-based film using waste of pistachio dehulling process as a novel promising food packaging material. International Journal of Biological Macromolecules, 272, 132866. https://doi.org/10.1016/j.ijbiomac.2024.132866

Kerton, F. M., & Marriott, R. (2013). Alternative solvents for green chemistry. Royal Society of Chemistry. DOI: 10.1039/9781849736824

Kumar, R., Sharma, V., & Oruna-Concha, M. J. (2022). Waste Minimization and Management in Food Industry. In Smart and Sustainable Food Technologies (pp. 309–340). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-1746-2_11

Luning, P., & Sanny, M. (2016). Acrylamide in Fried Potato Products. In Acrylamide in Food (pp. 159–179). Elsevier. https://doi.org/10.1016/b978-0-12-802832-2.00008-5

Morón-Ortiz, Á., Mapelli-Brahm, P., & Meléndez-Martínez, A. J. (2024). Sustainable Green Extraction of Carotenoid Pigments:

Innovative Technologies and Bio-Based Solvents. Antioxidants, 13(2), 239. https://doi.org/10.3390/antiox13020239

Nevárez-Moorillón, G. V., Zakaria, Z. A., Prado-Barragán, L. A., & Aguilar, C. N. (2022). Editorial: New Trends in Food Processing: Reducing Food Loss, Waste, and the Environmental Impact. Frontiers in Sustainable Food Systems, 6. https://doi.org/10.3389/fsufs.2022.856361

Oriekhoe, O. I., Adisa, O., & Ilugbusi, B. S. (2024). Climate change and food supply chain economics: a comprehensive analysis of impacts, adaptations, and sustainability. International Journal of Applied Research in Social Sciences, 6(3), 267-278. https://doi.org/10.51594/ijarss.v6i3.885

Picart-Palmade, L., Cunault, C., Chevalier-Lucia, D., Belleville, M. P., & Marchesseau, S. (2019). Potentialities and Limits of Some Non-thermal Technologies to Improve Sustainability of Food Processing. Frontiers in Nutrition, 2019, 5, ff10.3389/fnut.2018.00130ff. ffhal-02048347f

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987–992. https://doi.org/10.1126/science.aaq0216

Rabbitt, M. P., Reed-Jones, M., Hales, L. J., & Burke, M. P. (2024). Household food security in the United States in 2023 (Report No. ERR-337). U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/publications/pub-details/?pubid=109895

Rashid, M. I., & Shahzad, K. (2021). Food waste recycling for compost production and its economic and environmental assessment as circular economy indicators of solid waste management. Journal of Cleaner Production, 317, 128467. https://doi.org/10.1016/j.jclepro.2021.128467

Rosenberg, M. (2021). Thoughts about food security, food loss and waste and what has to be done. AIMS Agriculture and Food, 6(3), 797–798. https://doi.org/10.3934/agrfood.2021048

Sajid, M., & Płotka-Wasylka, J. (2022). Green analytical chemistry metrics: A review. Talanta, 238, 123046. https://doi.org/10.1016/j.talanta.2021.123046

Sarker, A., Ahmmed, R., Ahsan, S. M., Rana, J., Ghosh, M. K., & Nandi, R. (2024). A comprehensive review of food waste valorization for the sustainable management of global food waste. Sustainable Food Technology, 2(1), 48–69. https://doi.org/10.1039/d3fb00156c

Shrivastav, G., Prava Jyoti, T., Chandel, S., & Singh, R. (2024). Eco-Friendly Extraction: Innovations, Principles, and Comparison with Traditional Methods. Separation & Purification Reviews, 54(3), 241–257. https://doi.org/10.1080/15422119.2024.2381605

Souissi, A., Dhehibi, B., Oumer, A. M., Mejri, R., Frija, A., Zlaoui, M., … & Dhraief, M. Z. (2024). Linking farmers' perceptions and management decision toward sustainable agroecological transition: evidence from rural tunisia. Frontiers in Nutrition, 11. https://doi.org/10.3389/fnut.2024.1389007

Sousa, R. d., Bragança, L., Silva, d., & Oliveira, R. S. (2024). Challenges and solutions for sustainable food systems: the potential of home hydroponics. Sustainability, 16(2), 817. https://doi.org/10.3390/su16020817

Tiwari, B. K. (2015). Ultrasound: A clean, green extraction technology. TrAC Trends in Analytical Chemistry, 71, 100-109. https://doi.org/10.1016/j.trac.2015.04.013

United Nations Environment Programme. (2024). Food waste index report 2024.

https://www.unep.org/resources/publication/food-waste-index-report-2024

Viñas-Ospino, A., López-Malo, D., Esteve, M. J., Frígola, A., & Blesa, J. (2023). Green Solvents: Emerging Alternatives for Carotenoid Extraction from Fruit and Vegetable By-Products. Foods, 12(4), 863. https://doi.org/10.3390/foods12040863

Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M.-J. (2017). Big Data in Smart Farming – A review. Agricultural Systems, 153, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023

Yara-Varón, E., Li, Y., Balcells, M., Canela-Garayoa, R., Fabiano-Tixier, A.-S., & Chemat, F. (2017). Vegetable Oils as Alternative Solvents for Green Oleo-Extraction, Purification and Formulation of Food and Natural Products. Molecules, 22(9), 1474. https://doi.org/10.3390/molecules22091474

Yuan, Y. (2024). Integrating green chemistry into sustainable agricultural practices: addressing global environmental challenges. Highlights in Science, Engineering and Technology, 121, 153-157. https://doi.org/10.54097/55ewrf20

Ziervogel, G. and Ericksen, P. (2010). Adapting to climate change to sustain food security. WIREs Climate Change, 1(4), 525-540. https://doi.org/10.1002/wcc.56

SUSTAINABLE FOOD WASTE ASSESSMENT

ZEYNEP ŞEBNEM YAKAR[1]

Introduction

Globally, a growing population, urbanization, and consumption habits lead to significant waste in the food production and consumption chain. According to the United Nations Food and Agriculture Organization (FAO), about one-third of all food produced worldwide is either wasted or lost (FAO, 2019). This not only causes economic losses but also environmental and social problems.

Understanding Food Waste and Its Types

Food waste refers to edible food that is lost or discarded at any stage of the food chain, from farm to table. Simply put, it means food that could have been eaten ends up in the trash (Gustavsson et al., 2011).

Food waste can be divided into two main categories:

[1] Lecturer Zeynep Şebnem Yakar., Gaziantep University, Naci Topçuoğlu Vocational School, Food Processing Department, Gaziantep/Turkey, Orcid: 0000-0001-7280-6829, syakar@gantep.edu.tr

- Household Food Waste: Organic waste from kitchens, generated by consumers.
- Industrial Food Waste: Production leftovers, by-products, or spoiled materials from food processing facilities.

Different definitions of food waste exist in literature:

1. Food waste is any food and its non-edible parts removed from the food supply chain for recovery or disposal (e.g., composting, plowed-under or unharvested crops) (Östergren ve ark., 2014).
2. Preventable food waste refers to materials that could have been eaten, without distinguishing between "likely preventable" or "preference loss" (e.g., peels, seeds). Food past its "best before" date is also considered preventable, as consumers could plan better (Östergren ve ark., 2014).
3. Unavoidable food waste refers to materials that are not typically edible, like bones and orange peels (Östergren ve ark., 2014).
4. Food waste prevention includes measures that reduce the amount of waste, the negative impacts on the environment and human health, or the harmful substances in materials and products, before they become waste [European Commission, 2008].

Stages Where Food Waste Occurs

Food waste happens at various stages of the food chain:

- Production: Harvest losses in agriculture, spoilage due to improper storage, or climate conditions.

- Processing and Packaging: Losses due to production errors, overproduction, or incorrect labeling.
- Distribution and Retail: Spoilage during transport or expired products.
- Consumption: Over-preparation of food in homes, restaurants, or hotels, poor storage, or thoughtless consumption FAO. (2022).

The Difference Between Food Waste and Food Loss

Food Loss: Occurs during the production, harvest, transport, or processing stages. Food Waste: Typically occurs at the consumer level in supermarkets, restaurants, or homes when edible food is thrown away (Kibler, K. M., et al. 2018).

In short, "loss" happens in production, while "waste" happens during consumption.

Reasons for Food Waste

- Overproduction and poor planning.
- Unconscious consumption habits.
- Not selling aesthetically imperfect products.
- Confusing "best before" dates with "expiration" dates.
- Inadequate cold chain and storage infrastructure.

Consequences of Food Waste and Ways to Reduce It

Food wastes are basically divided into three:

- Environmental: When food waste rots, it releases methane (CH_4) gas, contributing to the greenhouse effect.
- Economic: Resources used in production and distribution (water, energy, labor) are wasted (Sarker ve ark., 2022).

- Social: Millions of people worldwide suffer from hunger while large amounts of food are wasted.

Here are ways to reduce food waste:

- Buy only what you need and plan your shopping.
- Make use of leftovers (e.g., make soup or pastries).
- Understand "best before" dates correctly (they are not the same as "use by" dates).
- Compost organic waste.
- Support social projects like food banks (Mirabella et al., 2014).

Food Waste from a Sustainability Perspective

Food waste is directly linked to sustainable development goals. Specifically, the United Nations Sustainable Development Goal (SDG) 12.3 aims to halve per capita global food waste by 2030. A sustainable food system must consider not only production efficiency but also waste management, the circular economy, and resource use (United Nations. 2015).

Food sustainability is generally examined through three dimensions (UNEP. 2021):

1. Environmental Sustainability:

- Protecting soil, water, and biodiversity.
- Reducing carbon footprint.
- Preventing food waste.
- Using renewable energy.

2. Economic Sustainability (Kibler, K. M., et al. 2018:

- Efficiency in agricultural production.

- Income security for small-scale producers.
- Supporting fair trade and local economies.

3. Social Sustainability:

- Food security and the right to nutrition.
- Fair working conditions.
- Consumer awareness and education.

The goals of a sustainable food system are protecting natural resources in food production, reducing the impacts of climate change, preventing food waste, promoting healthy and balanced nutrition and supporting local production and supply chains (FAO. 2018).

Environmental and Economic Impacts of Food Waste

There are three important impacts:

1. Environmental Impacts: When food waste decays, it releases greenhouse gases like methane (CH_4), contributing to global warming. It also means wasting resources like water, energy, and land.
2. Economic Impacts: Food waste creates economic losses for both producers and consumers. According to the FAO, annual economic losses worldwide are in the trillions of dollars (UNEP. 2021).
3. Social Impacts: Food waste contradicts the global issues of hunger and malnutrition.

Methods for Utilizing Food Waste

1. Reuse and Redistribution Delivering edible food to those in need (e.g., through food banking) is one of the most direct ways to reduce waste (Papargyropoulou et al., 2014).

2. Animal Feed Production Using organic waste from the food industry as animal feed is a sustainable solution, both in terms of cost and resources.
3. Biogas and Energy Production Converting organic waste into biogas through anaerobic digestion holds significant potential for energy generation (Mirabella et al., 2014).
4. Compost and Fertilizer Production Composting kitchen and agricultural waste improves soil fertility in agricultural production and reduces the need for chemical fertilizers.
5. Innovative Technologies In recent years, innovative applications have been developed, such as producing protein, bioactive compounds, or bioplastics from food waste using biotechnological methods (e.g., microbial fermentation, enzymatic conversion) (Lin et al., 2013).

Modern Food Waste Valorization Technologies Based on Environmental and Economic Priority

Modern technologies used for valuing food waste have different priority levels based on their environmental impact and economic efficiency.

Hydrothermal carbonization (HTC) is a modern technology that converts food waste into a carbon-rich product called hydrochar (biochar) under high temperature (180–250 °C) and pressure. The products obtained can be used for soil improvement, energy storage, or as filtering materials. Since the HTC process is CO_2-neutral, it has low global warming potential. Hydrothermal carbonization is considered one of the highest-priority methods from both environmental and economic perspectives. (Zhang et al., 2021).

Fermentation is a biotechnological method that uses microorganisms to convert organic waste into products like organic acids, ethanol, or biogas. In modified fermentation processes, for example, for fumaric acid production, only 0.18 tons of CO_2 are released from one ton of food waste, increasing the method's environmental efficiency. This approach is considered an environmentally friendly alternative due to low carbon emissions and high product variety. (Papargyropoulou et al., 2014).

Ethanol production relies on converting food waste with high starch and sugar content (e.g., banana peels, fruit pulp, or grain residues) into biofuel. This method not only recovers energy but also reduces carbon emissions by decreasing fossil fuel consumption. Using food industry waste in ethanol production contributes to applying circular economy principles in the agriculture and energy sectors. (FAO, 2021).

Pyrolysis is a thermochemical process where food waste is heated at high temperatures (300–700 °C) in an oxygen-free environment to produce gas, liquid, and solid products (biogas, biofuel, biochar).

Anaerobic digestion is a biological method that uses microorganisms to break down organic waste in an oxygen-free environment to produce biogas (CH_4 + CO_2). Both methods are valuable for energy recovery, but due to their economic costs and infrastructure requirements, they are considered medium-priority technologies. (Zhang et al., 2021).

Composting is one of the simplest and most environmentally friendly methods, converting food waste into organic fertilizer through microbial decomposition. Animal feeding applications involve processing organic waste, especially fruit/vegetable and grain waste, for use as feed additives. Although these methods may have low economic returns, they are an important part of sustainable waste management strategies because they reduce waste storage and improve soil fertility. (FAO, 2019; T.C. Ministry of Agriculture and Forestry, 2023).

Food Waste Management in Turkey

Various public and private sector projects are being carried out in Turkey to reduce food waste.

- The "Protect Your Food – Protect Your Table" campaign by the Ministry of Agriculture and Forestry has been an important step in raising awareness.
- Municipalities and private initiatives are working on separate collection of organic waste and establishing composting facilities. However, a sustainable transformation requires stronger legislation, consumer education, and technology investments (Kibler, K. M., et al. 2018.

Globally, about one-third of food production is wasted. In high-income countries, waste is more consumer-driven, while in low/middle-income countries, it's due to harvest/transport/storage issues. Turkey, due to both structured policies and local dynamics, shows characteristics of both groups (T.C. Tarım ve Orman Bakanlığı, 2023).

General Trends in the World and Turkey

According to FAO data, 1/3 (approximately 1.3 billion tons) of produced food is lost or wasted; this has a significant environmental impact (global GHG emissions from food waste are reported to be around 8–10%). United Nations reports indicate the global average is around 70–80 kg per person per year, with household and service sectors being major sources of waste (28%). Official reports and academic studies in Turkey indicate high household waste, as well as losses in the agriculture and transport phases. Global trends show that in high-income countries, most waste occurs at the distribution and consumer level (appearance, over-buying, expiry dates). In low/middle-income countries, losses from production, harvest, storage, and transport are more dominant. Turkey experiences both "loss" (especially due to cold chain deficiencies, aesthetic culling) and "waste" (household, restaurants) problems due to its income and infrastructure heterogeneity (Tekiner ve ark., 2021).

Conclusion and Recommendations

Global literature and reports clearly show the scale and climate importance of food waste. Turkey faces similar problems but also has unique cultural, managerial, and infrastructural characteristics. Therefore, both global "best practices" should be adapted, and policies considering the local socio-cultural context should be developed. Sustainable food waste management is not just an environmental necessity but also an area that offers economic opportunities.

In the future, focus should be on using loss prevention technologies in the food production chain, increasing consumer awareness, strengthening legal regulations, and adopting a circular economy approach. Within this scope, strong collaboration among academia, industry, and public sectors will form the foundation of sustainable food systems.

Developing sustainable food waste management is crucial because it continues to be a major obstacle for society. Effective food waste management provides social, economic, and environmental benefits worldwide. Developing sustainable food waste management can be achieved by redistributing surplus production to those in need or social services. Also, educating the community on how to acquire necessities during a disaster will help reduce future food waste, ensuring food is accessible to everyone. Utilizing food waste as a raw material for energy production currently seems to be the most suitable option. Using biotechnological processes to convert food waste into value-added products is a very important strategy to reduce its impact on health and the environment through incineration and landfilling.

References

European Commission. Directive 2008/98/EC. Off. J. Eur. Union. 2008; 312: 3.

FAO. (2011). *Global food losses and food waste.* Food and Agriculture Organization of the United Nations.

FAO. (2018). *Sustainable food systems: Concept and framework.* Food and Agriculture Organization of the United Nations.
https://www.fao.org/3/ca2079en/CA2079EN.pdf

FAO. (2019). The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction. FAO.

FAO. (2021). *The State of Food and Agriculture 2021: Making agri-food systems more resilient to shocks and stresses.* Food and Agriculture Organization of the United Nations.

FAO. (2022). Food loss and waste database. Food and Agriculture Organization of the United Nations.

Fung L, Urriola PE, Baker L, Shurson GC. Estimated energy and nutrient composition of different sources of food waste and their potential for use in sustainable swine feeding programs. Transl Anim Sci, 2019; 3(1): 359-368

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., & Meybeck, A. (2011). Global food losses and food waste. FAO.

Kibler, K. M., et al. (2018). Food waste and the food-energy-water nexus: A review. Waste Management, 74, 52–62.

Lin, C. S. K., Pfaltzgraff, L. A., Herrero-Davila, L., Mubofu, E. B., Abderrahim, S., Clark, J. H., ... & Luque, R. (2013). Food waste as a valuable resource for the production of chemicals, materials and fuels. *Green Chemistry, 15*(2), 500–505.

Mamma D. Food wastes: feedstock for value-added products. Fermentation. 2020; 6(2): 47.

Mirabella, N., Castellani, V., & Sala, S. (2014). Current options for the valorization of food manufacturing waste: A review. Journal of Cleaner Production, 65, 28–41.

Östergren K, Gustavsson J, Hansen J, Møller H, Research O, Anderson G., Bellettato C, Canali M, Falasconi L, Gaiani S, Vittuari M, Salhofer S, Linzner R, Caspar B. (2014). FUSIONS definitional framework for food waste.

Papargyropoulou, E., et al. (2014). The food waste hierarchy as a framework. Journal of Cleaner Production, 76, 106–115.

Pleissner D, Lin CSK. Valorisation of food waste in biotechnological processes. Sustain Chem Process, 2013; 1: 21.

T.C. Tarım ve Orman Bakanlığı. (2023). Gıdanı Koru – Sofrana Sahip Çık Projesi Raporu. Ankara: Tarım ve Orman Bakanlığı Yayınları.

Tekiner, İ.H., Mrcan, N.N., Kahraman, A., & Özel, M. (2021). Dünya ve Türkiye'de gıda israfı ve kaybına genel bir bakış. *İstanbul Sabahattin Zaim Üniversitesi Fen Bilimleri Enstitüsü Dergisi.*

Sarker A, Ghosh MK, Islam T, Bilal M, Nandi R, Raihan ML, Hossain MN, Rana J, Barman SK, Kim JE. Sustainable food waste recycling for the circular economy in developing countries, with Special reference to Bangladesh. Sustainability, 2022; 14: 12035.

UNEP. (2021). Food Waste Index Report 2021. United Nations Environment Programme.

United Nations. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. United Nations.

Zhang, Y., Pan, Z., Zhu, Z., & Chen, H. (2021). Valorization of food waste via microbial fermentation: A review. Biotechnology Advances, 53, 107870.

ALTERNATIVE PROTEIN SOURCES: PLANT BASED PROTEINS

HİCRAN UZUN KARKA[1]
ANIL UZUN ÖZCAN[2]

Introduction

In the context of an unprecedented worldwide population surge, projected to reach approximately 9.7 billion by 2050, the quest for sustainable food sources is more urgent than ever. Traditional animal-derived protein sources, while they offer rich nutritional benefits, pose significant environmental challenges, such as high greenhouse gas emissions, extensive land utilization, and substantial water consumption (Nirmal et al., 2024). In this light, alternative protein sources, particularly plant-based proteins, have emerged as promising solutions to address both food security and environmental sustainability (Daniel & Kassa, 2021). Plant-based proteins offer a multitude of advantages, including greater digestibility and nutritional enhancement through processes such as germination and extrusion cooking (Yimam et al., 2025). Germination, a natural

[1] Assist. Prof. Dr., Gaziantep University, Food Processing Department, hicranuzun@gantep.edu.tr, ORCID ID: 0000-0003-1098-3197,
[2] Assist. Prof. Dr., Kilis 7 Aralık University, Nutrition and Dietetics Department, aniluzunozcan@kilis.edu.tr, ORCID ID: 0000-0003-4039-9389

growth process involving the sprouting of seeds, enhances the protein quality in legumes and other plant sources. This process improves their amino acid profiles and elevates digestibility, making them more competitive with traditional proteins (Trașcă et al., 2024). Additionally, extrusion cooking modifies the physical and chemical properties of legume proteins, further improving their nutritional profile while reducing preparation time (Bagarinao et al., 2024). Moreover, consumer acceptance and readiness to incorporate plant-based proteins into their diets is notably higher than for more avant-garde alternatives like insect proteins or lab-cultured meats (Pasqualone et al., 2020). Many households are willing to accept plant-based meat substitutes due to concerns about health, welfare of animals, sustainability in the environment, and nutrient content (Grasso et al., 2019). The rise in flexitarian diets—where meat consumption is significantly reduced while plant-based foods are emphasized—acts as a bridge towards more sustainable dietary habits in many cultures (Vliet et al., 2015). The economic implications of transitioning to a diet richer in plant-based proteins are also promising. Sustainable agricultural approaches aimed at developing plant-based proteins can lower the environmental imprint of food production, supporting a system that enhances public health while conserving natural resources (Boachie & Aluko, 2025). Indeed, studies reveal that even minor reductions in meat consumption can lead to substantial environmental benefits, underscoring the need for widespread adoption of plant-based foods (Marrone et al., 2025).

Types of Plant Based Protein Sources

Plant-based proteins are gaining popularity as sustainable, nutrient-dense alternatives to animal protein. These proteins come from a range of plant sources, each with their own nutritional profiles, functions, and applications. We categorise and explain the many forms of protein that come from plants based on their botanical origins, composition, and health advantages.

Legume Proteins

Legumes, such as soybeans, lentils, chickpeas, and peas, are among the richest sources of plant-based proteins. Soybeans are especially remarkable for their total amino acid profile, which includes all nine essential amino acids required for human health (Janssen et al., 2017). Research indicates that they can be used not only in traditional forms but also as derivatives like soy protein isolates and textured vegetable proteins, which serve as meat substitutes (Florença et al., 2021). Legumes also provide dietary fiber, vitamins, and minerals, contributing to overall health, especially in managing cardiovascular conditions (Janssen et al., 2017).

Grain Proteins

Grains like quinoa, amaranth, barley, and oats are excellent sources of plant proteins. Quinoa is unique among grains as it contains all essential amino acids, making it a complete protein (Janssen et al., 2017). Additionally, whole grains are high in fiber and various micronutrients, promoting digestive health and reducing the risk of chronic diseases (Wei, 2025). These grains can be used in various culinary applications, from whole food forms to protein powders and gluten-free baked goods.

Seed Proteins

Seeds, such as chia, flaxseeds, and hemp seeds, are gaining recognition for their high protein and healthy fat content. For example, hemp seeds contain roughly 25% protein and are rich in omega-3 and omega-6 fatty acids, which are crucial for heart health (Cavallo & Califano, 2024). They are often incorporated into smoothies, energy bars, and baked goods, providing both protein and essential fatty acids.

Nut Proteins

Nuts, including almonds, walnuts, and peanuts, provide significant protein alongside healthy fats, fiber, and antioxidants. Though higher in calories, nuts are linked to improved heart health and weight management when consumed in moderation (Sharma et al., 2014). Nut proteins can be utilized in various forms, such as nut butters and protein-rich snacks.

Pseudocereal Proteins

Pseudocereals like buckwheat and quinoa serve as excellent protein sources, frequently compared to traditional cereals. They are particularly advantageous for individuals following gluten-free diets. Buckwheat, for instance, contains high levels of protein, fiber, and antioxidants, playing a vital role in disease prevention (Janssen et al., 2017). These pseudocereals can be found in various forms, including flour and flakes, making them popular in health food products.

Algal Proteins

Algae, specifically blue-green algae and seaweeds, are emerging as innovative protein sources. Supplements such as spirulina contain up to 60% protein and offer additional health benefits, including anti-inflammatory properties (Cavallo & Califano, 2024). Algal proteins are an attractive choice for enhancing the nutritional value of smoothies, energy bars, and vegetarian dishes.

Insect Proteins

While not plants, edible insects are increasingly recognized for their protein content and sustainability. Representing a highly efficient protein source, insects require significantly less land and water compared to traditional livestock (Florença et al., 2021). Studies suggest they contain comparable protein levels to meat and fish, making them a potential supplement to plant proteins in the future food supply (Florença et al., 2021).

Extraction and Processing Methods of Plant-Based Proteins

The extraction and processing of plant-based proteins are critical steps toward harnessing their nutritional benefits while ensuring functional properties suited for food applications. Various methodologies have been developed and optimized to efficiently extract proteins from plant sources, each with specific advantages and challenges. This section delineates the predominant extraction and processing techniques utilized in obtaining plant-based proteins.

Conventional Extraction Methods

Conventional methods for extracting proteins from plants typically involve alkaline extraction, isoelectric precipitation, and TCA/acetone precipitation. The alkaline extraction method involves using sodium hydroxide or similar bases to dissolve proteins, followed by adjusting the pH to precipitate them at their isoelectric point (Yu et al., 2023). This technique is widely employed due to its simplicity and effectiveness in isolating proteins from diverse plant materials.

The TCA/acetone method, noted for its efficacy in precipitating proteins, involves using trichloroacetic acid and acetone to denature proteins and remove contaminants such as polysaccharides and phenolic compounds that can impede protein analysis (Hassan et al., 2018). While this method is effective in recovering proteins from various sources, it may pose challenges in terms of sample re-dissolution and purification of specific protein fractions.

Phenolic Extraction

In scenarios where high-quality protein extraction is desired, especially from tissues rich in polysaccharides, phenolic extraction methods may be employed. This technique often yields proteins with superior purity due to the efficiency of phenolic solvents in solubilizing proteins while minimizing co-extraction of non-protein compounds (Tan et al., 2015). For example, phenol-based extraction has been particularly beneficial for extracting proteins from high-carbohydrate sources like sugarcane, allowing for cleaner protein preparations suited for proteomic analyses (Amalraj et al., 2010).

Enzymatic and Assisted Extraction Techniques Enzymatic extraction methods involve using specific enzymes to break down cell walls and enhance protein release. This approach can increase protein yield and improve the functional properties of the extracted proteins (Akyüz et al., 2024). Techniques such as ultrasound-assisted extraction, microwave-assisted extraction, and high-pressure assisted extraction have also gained popularity, breaking down barriers in plant cells to facilitate easier protein solubilization (Yu et al., 2023; Akyüz et al., 2024). These methods are particularly valuable for increasing the extraction efficiency of proteins that are otherwise difficult to isolate.

Solvent and Chemical Fractionation

Solvent extraction techniques involve using various organic or inorganic solvents to partition proteins from other cellular constituents. These methodologies can be effective in removing lipids and other impurities, leading to higher purity protein isolates (Manzanilla-Valdez et al., 2024). The use of deep eutectic solvents is a novel approach that is being explored for simultaneous extraction of proteins and bioactive compounds, enhancing the sustainability and efficiency of the extraction process (Grudniewska & Pastyrczyk, 2023).

Physical Processing Techniques

Once proteins are extracted, physical processing methods such as extrusion and 3D printing are applied to modify their texture and functionality. Extrusion processing is particularly prominent in the production of plant-based meat alternatives, where it helps in texturizing proteins to mimic meat-like structures. These processing techniques not only enhance sensory attributes but also improve the digestibility and functional performance of plant proteins in food applications (Yu et al., 2023).

Separation and Purification Techniques

Following extraction, further purification is often required to achieve desired protein concentrations and specific functionalities. Techniques such as chromatography, gel electrophoresis, and centrifugation are employed for the separation of proteins based on size, charge, or affinity (Dyčka et al., 2011; Jin et al., 2019). These methods are essential for isolating specific proteins or protein fractions that meet the requirements of various applications in food science and nutrition.

Functional and Nutritional Properties of Plant-Based Proteins

Plant-based proteins are increasingly recognized as sustainable and nutritious alternatives to animal-based protein sources. Understanding their functional and nutritional properties is crucial for incorporating them into diets, especially in the context of growing concerns over environmental sustainability and health. This synthesis will explore the key attributes of plant-based proteins, including their amino acid profiles, digestibility, functional properties, and health benefits.

Amino Acid Composition

The nutritional value of a protein is largely determined by its amino acid composition, particularly the presence of essential amino acids (EAAs) necessary for human health. While animal proteins typically possess a balanced amino acid profile, many plant proteins lack one or more EAAs, which has historically limited their reputation as complete protein sources (Salles et al., 2021). However, certain plant proteins, such as those derived from soy, quinoa, and hemp, have demonstrated comprehensive profiles, making them viable options for meeting dietary protein needs (Axentii & Codină, 2024; Nemś et al., 2022). For instance, hemp protein is noted for its rich essential nutrients and complete amino acid profile, thus promoting balanced diets (Axentii & Codină, 2024).

Digestibility and Bioavailability

The digestibility of plant-based proteins can often be lower than that of animal proteins due to anti-nutritional factors present in plant materials, such as phytates and tannins (Sá et al., 2022). Various processing methods, such as germination and fermentation, have been employed to enhance the nutritional value by breaking down these compounds and improving amino acid bioavailability (Sá et al., 2022; Mohammed et al., 2017). Studies have shown that processing can significantly impact protein digestibility and absorption rates, indicating that food preparation methods are critical in maximizing the nutritional benefits of plant proteins (Sá et al., 2022).

Functional Properties

Plant proteins exhibit diverse functional properties, including solubility, emulsification, gelling, and foaming capabilities. These properties are influenced by the protein's structure, the presence of other food components, and processing conditions (Penchalaraju & Bosco, 2022; Justino et al., 2024). For example, pea proteins have shown promising emulsifying and gelling properties, making them suitable for meat analogues and various food formulations (Penchalaraju & Bosco, 2022; Yu et al., 2023). Advancements in processing technologies, such as ultrasound-assisted extraction and enzymatic modifications, have enhanced the functional applications of plant proteins in food systems (Justino et al., 2024; Yu et al., 2023).

Health Benefits

The consumption of plant-based proteins has been associated with numerous health benefits, including improved cardiovascular health, weight management, and reduced risk of chronic diseases. Plant proteins are typically lower in saturated fats and cholesterol and higher in dietary fiber compared to their animal counterparts (Bryant & Sanctorum, 2021; Ren et al., 2024). Research has indicated that protein from legumes, for example, can have anabolic effects comparable to that of milk proteins, reinforcing their role in muscle maintenance, particularly in older adults (Salles et al., 2021). Additionally, the bioactive compounds present in many plant proteins also confer antioxidant and anti-inflammatory properties, contributing to overall health (Axentii & Codină, 2024).

Market Acceptance and Consumer Attitudes

As dietary patterns continue to shift towards plant-based diets, consumer attitudes towards plant-based proteins are evolving. Marketing strategies that emphasize the health and environmental benefits of plant proteins are increasingly popular, appealing to a demographic that prioritizes sustainable and health-conscious food choices (Lacy-Nichols et al., 2021; Bryant & Sanctorum, 2021). The growth of plant-based meat analogues and fortified foods further reflects changing consumer preferences and an increasing recognition of the functional attributes of these proteins in mimicking traditional meat products (Yu et al., 2023).

Food Applications of Plant-Based Proteins

The growing interest in plant-based proteins has spurred innovation across various sectors of the food industry, leading to diverse applications ranging from meat alternatives to dairy substitutes and nutritional supplements. Plant proteins' functional and nutritional properties are being leveraged to produce foods that appeal to health-conscious consumers and those seeking sustainable dietary options. This section explores the various applications of plant-based proteins in food products.

Meat Alternatives

One of the most significant applications of plant-based proteins is in the production of meat substitutes. Derived from ingredients such as soy, pea, and wheat gluten, products like tempeh, tofu, and seitan have been staples in Asian diets for centuries (Andreani et al., 2023). In recent years, plant-based meats have gained momentum, in part due to innovations in technology that improve texture and flavour, making them closer in resemblance to animal products (Rochefort et al., 2023). The consumer shift towards vegetarianism and flexitarian diets has further fuelled this market (Barco Leme et al., 2022). Recent studies highlight that these protein alternatives can successfully mimic the taste and texture of traditional proteins while often offering lower caloric content and higher levels of fiber (Andreani et al., 2023; Neufingerl & Eilander, 2021).

Dairy Alternatives

Plant-based proteins are also extensively used to create dairy alternatives, such as almond milk, soy milk, and coconut yogurt. These products serve as substitutes for individuals with lactose intolerance or those who prefer vegan diets (Neufingerl & Eilander, 2021). The versatile nature of soy protein, in particular, allows it to function effectively in creating creams, cheeses, and yogurts, providing similar mouthfeel and nutritional value as dairy products (Wei et al., 2025). The increasing demand for plant-based dairy alternatives is reflected in consumer preferences shifting towards healthier options that align with their ethical and health concerns (Barco Leme et al., 2022).

Protein-Enriched Snacks and Beverages

The incorporation of plant-based proteins into snacks and beverages has become a growing trend as consumers look for convenient, high-protein options. Food products like protein bars, smoothies such as soy-based or pea-protein shakes, and fortified food items often rely on these sources for nutritional enhancement and functional attributes (Heredia-Leza et al., 2022). Advances in processing techniques have improved the solubility and bioavailability of these proteins, allowing them to be effectively integrated into mainstream food formats without compromising taste (Lin et al., 2017).

Bakery and Confectionery Products

Plant-based proteins have been identified as valuable ingredients in the bakery sector to enhance the nutritional profile of bread, cookies, and pastries. Their inclusion helps boost protein content while contributing to desirable structural properties such as elasticity and moisture retention (Skendi et al., 2021). Research indicates that protein isolates derived from peas, lentils, and other legumes can replace gluten flour in gluten-free baking, improving the nutritional value and texture of end products Fu et al., 2023).

Emulsifiers and Stabilizers

The functional properties of plant-based proteins make them excellent emulsifiers and stabilizers in food formulations. Proteins from sources like soy and hemp are utilized to improve texture and mouthfeel in sauces, dressings, and plant-based emulsified products. Their ability to stabilize emulsions enhances the shelf-life and product appeal Chen et al. (2021) and also facilitates the development of new functional foods that deliver bioactive ingredients effectively (Wan et al., 2015).

Fortified Foods and Nutraceuticals

Plant proteins are gaining traction in the development of fortified foods and nutraceuticals due to their health benefits. Enhanced with vitamins, minerals, or bioactive compounds, protein-enriched products can cater to specific dietary needs and promote overall health (Fu et al., 2023; Gomes & Sobral, 2021). Manufacturers are exploring innovative formulations that support health claims, such as improved muscle maintenance and enhanced satiety, particularly in plant-based diets (Akharume et al., 2021; Fu et al., 2023).

Conclusion

Plant-based proteins have emerged as critical components of sustainable and nutritious food systems, especially in light of expanding global population demands. Their various sources from legumes and grains to seeds, nuts, and algae provide important amino acid compositions, functional qualities, and health advantages. Advances in extraction and processing technology have improved its digestibility, purity, and applicability across the food industry, allowing for the creation of high-quality meat analogues, dairy substitutes, and protein-rich products. Growing consumer interest, motivated by environmental, ethical, and health concerns, has hastened the uptake of plant-based foods, strengthening their position in future dietary trends. Overall, the data reveals that plant-based proteins not only solve critical sustainability issues, but also provide flexible nutritional solutions, making them essential to the evolution of global food systems.

References

Akharume, F., Aluko, R., & Adedeji, A. (2021). Modification of plant proteins for improved functionality: a review. Comprehensive Reviews in Food Science and Food Safety, 20(1), 198-224. https://doi.org/10.1111/1541-4337.12688

Akyüz, A., Tekin, İ., Aksoy, Z., & Ersus, S. (2024). Plant protein resources, novel extraction and precipitation methods: a review. Journal of Food Process Engineering, 47(10). https://doi.org/10.1111/jfpe.14758

Amalraj, R. S., Selvaraj, N., Veluswamy, G. K., Ramanujan, R. P., Muthurajan, R., Palaniyandi, M., ... & Viswanathan, R. (2010). Sugarcane proteomics: establishment of a protein extraction method for 2-DE in stalk tissues and initiation of sugarcane proteome reference map. Electrophoresis, 31(12), 1959-1974.

Andreani, G., Sogari, G., Marti, A., Froldi, F., Dagevos, H., & Martini, D. (2023). Plant-based meat alternatives: technological, nutritional, environmental, market, and social challenges and opportunities. Nutrients, 15(2), 452. https://doi.org/10.3390/nu15020452

Axentii, M., & Codină, G. G. (2024). Exploring the nutritional potential and functionality of hemp and rapeseed proteins: A review on unveiling anti-nutritional factors, bioactive compounds, and functional attributes. Plants, 13(9), 1195.. https://doi.org/10.20944/preprints202402.1349.v1

Bagarinao, N., King, J., Leong, S., Agyei, D., Sutton, K., & Oey, I. (2024). Effect of germination on seed protein quality and secondary metabolites and potential modulation by pulsed electric field treatment. Foods, 13(11), 1598. https://doi.org/10.3390/foods13111598

Barco Leme, A. C., Laila, A., Hou, S., Fisberg, R. M., Ma, D. W., Fisberg, M., & Haines, J. (2022). Perceptions of the 2019 Canada's Food Guide: a qualitative study with parents from Southwestern Ontario. Applied Physiology, Nutrition, and Metabolism, 47(1), 34-40.

Boachie, R. and Aluko, R. (2025). Plant-based meat analogues: processing, product safety, protein quality, and contributions to environmental sustainability. Sustainable Food Proteins, 3(2). https://doi.org/10.1002/sfp2.70018

Bryant, C. and Sanctorum, H. (2021). Alternative proteins, evolving attitudes: comparing consumer attitudes to plant-based and cultured meat in belgium in two consecutive years. Appetite, 161, 105161. https://doi.org/10.1016/j.appet.2021.105161

Cavallo, C. and Califano, G. (2024). Editorial: alternative protein source for a sustainable and healthy nutrition. Frontiers in Sustainable Food Systems, 8. https://doi.org/10.3389/fsufs.2024.1451483

Chen, X., Fu, W., Luo, Y., Cui, C., Suppavorasatit, I., & Liang, L. (2021). Protein deamidation to produce processable ingredients and engineered colloids for emerging food applications. Comprehensive Reviews in Food Science and Food Safety, 20(4), 3788-3817. https://doi.org/10.1111/1541-4337.12759

Daniel, I. and Kassa, M. (2021). Advances in food development with plant-based proteins from seed sources.. https://doi.org/10.5772/intechopen.96273

Dyčka, F., Bobáľ, P., Mazanec, K., & Bobáľová, J. (2011). Rapid and efficient protein enzymatic digestion: an experimental comparison. Electrophoresis, 33(2), 288-295. https://doi.org/10.1002/elps.201100123

Florença, S., Correia, P., Costa, C., & Guiné, R. (2021). Edible insects: preliminary study about perceptions, attitudes, and knowledge on a sample of portuguese citizens. Foods, 10(4), 709. https://doi.org/10.3390/foods10040709

Fu, Q., Zhao, J., Rong, S., Han, Y., Liu, F., Chu, Q., … & Chen, S. (2023). Research advances in plant protein-based products: protein sources, processing technology, and food applications. Journal of Agricultural and Food Chemistry, 71(42), 15429-15444. https://doi.org/10.1021/acs.jafc.3c02224

Gomes, A., & Sobral, P. J. D. A. (2021). Plant protein-based delivery systems: An emerging approach for increasing the efficacy of lipophilic bioactive compounds. Molecules, 27(1), 60. https://doi.org/10.3390/molecules27010060

Grasso, A., Hung, Y., Olthof, M., Verbeke, W., & Brouwer, I. (2019). Older consumers' readiness to accept alternative, more sustainable protein sources in the european union. Nutrients, 11(8), 1904. https://doi.org/10.3390/nu11081904

Grudniewska, A., & Pastyrczyk, N. (2023). New insight for spent hops utilization: simultaneous extraction of protein and xanthohumol using deep eutectic solvents. Biomass Conversion and Biorefinery, 13(16), 14975-14986.. https://doi.org/10.1007/s13399-022-03462-5

Hassan, M., Yusoff, N., Aizat, W., Othman, N., & Ghani, I. (2018). Optimization method for proteomic analysis of the larva and adult tissues of plutella xylostella (l.) (lepidoptera: plutellidae). Sains Malaysiana, 47(12), 2975-2983. https://doi.org/10.17576/jsm-2018-4712-06

Heredia-Leza, G., Martínez, L., & Chuck-Hernández, C. (2022). Impact of hydrolysis, acetylation or succinylation on functional properties of plant-based proteins: patents, regulations, and future trends. Processes, 10(2), 283. https://doi.org/10.3390/pr10020283

Janssen, F., Pauly, A., Rombouts, I., Jansens, K. J., Deleu, L. J., & Delcour, J. A. (2017). Proteins of amaranth (Amaranthus spp.), buckwheat (Fagopyrum spp.), and quinoa (Chenopodium spp.): A food science and technology perspective. Comprehensive Reviews in Food Science and Food Safety, 16(1), 39-58.https://doi.org/10.1111/1541-4337.12240

Jin, X., Zhu, L., Tao, C., Xie, Q., Xu, X., Chang, L., … & Wang, X. (2019). An improved protein extraction method applied to cotton leaves is compatible with 2-de and lc-ms. BMC Genomics, 20(1). https://doi.org/10.1186/s12864-019-5658-5

Justino, H. D. F. M., dos Santos, I. F., de Souza, R. C. N., Sanches, E. A., Bezerra, J. D. A., Lamarão, C. V., ... & Campelo, P. H. (2024). Exploring ultrasound-assisted technique for enhancing techno-functional properties of plant proteins: a comprehensive review. International Journal of Food Science & Technology, 59(1), 498-511.https://doi.org/10.1111/ijfs.16673

Lacy-Nichols, J., Hattersley, L., & Scrinis, G. (2021). Nutritional marketing of plant-based meat-analogue products: an exploratory study of front-of-pack and website claims in the usa. Public Health Nutrition, 24(14), 4430-4441. https://doi.org/10.1017/s1368980021002792

Lin, D., Lü, W., Kelly, A., Zhang, L., Zheng, B., & Miao, S. (2017). Interactions of vegetable proteins with other polymers: structure-function relationships and applications in the food industry. Trends in Food Science & Technology, 68, 130-144. https://doi.org/10.1016/j.tifs.2017.08.006

Manzanilla-Valdez, M., Ma, Z., Mondor, M., & Hernández-Álvarez, A. (2024). Decoding the duality of antinutrients: assessing the impact of protein extraction methods on plant-based protein sources. Journal of Agricultural and Food Chemistry, 72(22), 12319-12339. https://doi.org/10.1021/acs.jafc.4c00380

Marrone, G., Lauro, M., Cornali, K., Masci, C., Vanni, G., Vita, C., … & Noce, A. (2025). Sustainability and role of plant-based diets in chronic kidney disease prevention and treatment. Frontiers in Pharmacology, 16. https://doi.org/10.3389/fphar.2025.1562409

Mohammed, M. A., Mohamed, E. A., Yagoub, A. E. A., Mohamed, A. R., & Babiker, E. E. (2017). Effect of processing methods on alkaloids, phytate, phenolics, antioxidants activity and minerals of newly developed lupin (Lupinus albus L.) cultivar. Journal of Food Processing and Preservation, 41(1), e12960.https://doi.org/10.1111/jfpp.12960

Nemś, A., Miedzianka, J., & Kita, A. (2022). Quality and nutritional value of cookies enriched with plant-based protein preparations. Journal of the Science of Food and Agriculture, 102(11), 4629-4639. https://doi.org/10.1002/jsfa.11821

Neufingerl, N. and Eilander, A. (2021). Nutrient intake and status in adults consuming plant-based diets compared to meat-eaters: a systematic review. Nutrients, 14(1), 29. https://doi.org/10.3390/nu14010029

Nirmal, N., Anyimadu, C., Khanashyam, A., Bekhit, A., & Dhar, B. (2024). Alternative protein sources: addressing global food security and environmental sustainability. Sustainable Development, 33(3), 3958-3969. https://doi.org/10.1002/sd.3338

Pasqualone, A., Costantini, M., Coldea, T., & Summo, C. (2020). Use of legumes in extrusion cooking: a review. Foods, 9(7), 958. https://doi.org/10.3390/foods9070958

Penchalaraju, M. and Bosco, S. (2022). Leveraging indian pulses for plant-based meat: functional properties and development of meatball analogues. International Journal of Food Science & Technology, 57(9), 5869-5877. https://doi.org/10.1111/ijfs.15908

Ren, S., Du, Y., Zhang, J., Zhao, K., Guo, Z., & Wang, Z. (2024). Commercial production of highly rehydrated soy protein powder by the treatment of soy lecithin modification combined with alcalase hydrolysis. Foods, 13(12), 1800. https://doi.org/10.3390/foods13121800

Rochefort, G., Brassard, D., Desroches, S., Robitaille, J., Lemieux, S., Provencher, V., … & Lamarche, B. (2023). Transitioning to sustainable dietary patterns: learnings from animal-based and plant-based dietary patterns in french canadian adults. Frontiers in Nutrition, 10. https://doi.org/10.3389/fnut.2023.1148137

Salles, J., Guillet, C., Bacquer, O., Malnero-Fernandez, C., Giraudet, C., Patrac, V., … & Walrand, S. (2021). Pea proteins have anabolic effects comparable to milk proteins on whole body protein retention and muscle protein metabolism in old rats. Nutrients, 13(12), 4234. https://doi.org/10.3390/nu13124234

Sá, A. G. A., Laurindo, J. B., Moreno, Y. M. F., & Carciofi, B. A. M. (2022). Influence of emerging technologies on the utilization of plant proteins. Frontiers in nutrition, 9, 809058.. https://doi.org/10.3389/fnut.2022.809058

Sharma, A., Khan, A., Sappati, S., Raman, A., Taylor, G., & Fletcher, M. (2014). Salivary proteins of plant-feeding hemipteroids – implication in phytophagy. Bulletin of Entomological Research, 104(2), 117-136. https://doi.org/10.1017/s0007485313000618

Skendi, A., Παπαγεωργίου, M., & Varzakas, T. (2021). High protein substitutes for gluten in gluten-free bread. Foods, 10(9), 1997. https://doi.org/10.3390/foods10091997

Tan, W., Ang, Y., Lim, T., Lim, T., Kumar, P., Loh, C., … & Lin, Q. (2015). Proteome profile of salt gland-rich epidermis extracted from a salt-tolerant tree species. Electrophoresis, 36(19), 2473-2481. https://doi.org/10.1002/elps.201500023

Traşcă, T., Ocnean, M., Gherman, R., Lile, R., Bălan, I., Brad, I., … & Negoescu, G. (2024). Synergy between the waste of natural resources and food waste related to meat consumption in romania. Agriculture, 14(4), 644. https://doi.org/10.3390/agriculture14040644

Wan, Z., Guo, J., & Yang, X. (2015). Plant protein-based delivery systems for bioactive ingredients in foods. Food & Function, 6(9), 2876-2889. https://doi.org/10.1039/c5fo00050e

Wei, X., Yu, X., Chen, X., Cui, S., Cui, J., Wei, R., ... & Tang, X. (2025). Jinyuan 601 a Novel High-Protein Soybean Variety with Improved Agronomic Traits and Nutritional Quality. Life, 15(9), 1414.

Van Vliet, S., Burd, N. A., & Van Loon, L. J. (2015). The skeletal muscle anabolic response to plant-versus animal-based protein consumption. The Journal of nutrition, 145(9), 1981-1991. https://doi.org/10.3945/jn.114.204305

Yimam, M., Andreini, M., Carnevale, S., & Muscaritoli, M. (2025). Postprandial aminoacidemia following the ingestion of alternative and sustainable proteins in humans: a narrative review. Nutrients, 17(2), 211. https://doi.org/10.3390/nu17020211

Yu, J., Wang, L., & Zhang, Z. (2023). Plant-based meat proteins: processing, nutrition composition, and future prospects. Foods, 12(22), 4180. https://doi.org/10.3390/foods12224180

MICROBIOTA-FRIENDLY PRODUCTS IN FOOD SCIENCE: PROBIOTICS, PREBIOTICS, AND POSTBIOTICS

AYŞE SEVGİLİ[1]

Introduction

In recent years, people have become more aware of the significance of nutrition and general health, resulting in an increased demand for better food alternatives. As a result, there has been a significant increase in the creation and promotion of food products that possess functional characteristics. In addition to products that undergo traditional fermentation, significant classifications of functional foods encompass nutraceuticals, probiotics, prebiotics, and synbiotics (Thorakkattu et al., 2022).

The human gastrointestinal (GI) tract contains a remarkably diverse and densely populated microbial ecosystem, consisting of over 100 trillion microorganisms (Rinninella et al., 2019).

Currently, probiotics, foods containing probiotics, and prebiotics have attracted growing scientific and consumer attention

[1] Assist. Prof. Dr., Gaziantep University, Naci Topçuoğlu Vocational School, Food Processing Department, aysesevgili@gantep.edu.tr, Orcid: 0000-0002-9579-5074

due to their extensively documented health benefits (Xia et al., 2023). The global market for functional food and beverage products has seen remarkable development, escalating from $33 billion in 2000 to $176.7 billion in 2013. This figure represents about 5% of the entire food market and serves as a crucial engine of growth in the food industry. Significantly, it is estimated that probiotic foods represent 60–70% of the total functional food market (Tripathi and Giri, 2014).

This chapter intends to provide a thorough overview of microbiota-friendly products in the domain of food science, focusing specifically on the mechanisms of action, primary sources, food applications, technological considerations, and emerging trends associated with probiotics, prebiotics, and postbiotics. By incorporating recent research findings and highlighting practical applications, the chapter aims to aid in the advancement of functional foods that promote gut health and improve overall well-being.

Probiotics

The term "probiotics" was initially put forth by Werner Kollath in 1953, rooted in the Latin prefix pro and the Greek word βίος, meaning "for life" (Latif et al., 2023). Additionally, the importance of probiotics was more extensively acknowledged in 2001, when a conclusive definition was created and later modified to describe them as "live microorganisms that, when administered in appropriate doses, provide health benefits to the host." (Chandrasekaran et al., 2024).

Lactic acid bacteria are a crucial part of the human gut microbiota and are widely employed as probiotics. The main probiotic microorganisms are from the genera *Lactobacillus* and *Bifidobacterium*; nevertheless, *Lactococcus, Streptococcus, Enterococcus, Propionibacterium,* and yeast species like

Saccharomyces also contribute significantly and are commonly found in probiotic products (Sionek et al., 2023). Among these, *Lactobacillus* spp. and *Bifidobacterium* spp. are the most commonly employed in the food industry, as they are widely acknowledged as safe (GRAS) by various regulatory authorities. Additionally, certain yeasts, including *Saccharomyces cerevisiae* and *S. boulardii*, demonstrate probiotic potential (Min et al., 2019).

Common probiotic genera encompass *Lactobacillus*, *Bifidobacterium*, *yeast, Bacillus* and genetically modified strains. Within the *Lactobacillus* genus, species such as *L. acidophilus*, *L. casei*, *L. crispatus*, *L. gasseri*, *L. reuteri*, *L. rhamnosus*, *L. plantarum*, *L. fermentum*, *L. helveticus*, *L. clausii*, *L. paracasei*, *L. salivarius*, and *L. delbrueckii* are particularly noteworthy for their capacity to ferment carbohydrates into lactic acid, thereby supporting the maintenance of intestinal microbial balance (Liu et al., 2023). Widely used probiotic strains include *L. rhamnosus*, *L. reuteri*, *Bifidobacterium* spp., selected strains of *Lactobacillus casei* and *Lactobacillus acidophilus*-group, *Bacillus coagulans*, *Escherichia coli* strain Nissle 1917, *Enterococcus faecium* SF68, and the yeast *S. cerevisiae* and *Saccharomyces boulardii* (Liu et al., 2023; Pandey et al., 2015).

In 2002, the Food and Agriculture Organization and the World Health Organization together established guidelines that outline the critical criteria for selecting probiotic microorganisms. These criteria consist of antimicrobial activity, the ability to adhere to epithelial tissues, resistance to the extreme physiological conditions within the human GI, and verified safety for human consumption (Al-Fakhrany and Elekhnawy, 2024; Pandey et al., 2015).

The key characteristics of an ideal probiotic strain can be summarized as follows (Pandey et. al., 2015):

- Non-pathogenic (GRAS)
- Acid&bile tolerant
- Effective adhesion to gut lining
- Short generation time
- Robust&surviving processing conditions
- Anti-genotoxic property
- Genetically stable
- Lactic acid producer

Microorganisms exist on both the internal and external surfaces of the human body in a symbiotic relationship, with around 95% found in the GI tract—mainly in the large intestine—while the stomach and small intestine are only lightly populated (Maftei et al., 2024). Probiotic microorganisms can thrive at 37°C and withstand the challenging conditions of the human digestive system, which includes exposure to digestive enzymes, pancreatic secretions, and acidic pH levels. They play a role in promoting host health by modulating the intestinal microbiota, providing various beneficial biological effects, and, in certain instances, adhering to the mucus layer of intestinal epithelial cells (Staniszewski and Kordowska-Wiater, 2021).

Probiotics can be found in numerous sources, including unprocessed foods such as milk, dairy items, and meat, in addition to fermented products like kimchi, pickles, and fermented sausages. They are also present in a variety of fruits and vegetables. In the natural environment, probiotics are detectable in water, air, and soil. Examples of probiotic types from different sources are summarized by Parichat and Pongsak (2023):

- Camel's milk *Leuconostoc mesenteroides, L. plantarum, Weissella paramesenteroides, Weissella confusa*

- Fermented milk *Bifidobacterium lactis* CNCM I-294
- Cheese *L. plantarum* LP049
- Raw and fermented milk *L. casei* MSJ1, Dwan5, *Lactobacillus plantarum* EyLan2, *Enterococcus faecium* Gail-BawZir8
- Dry-aged beef *Lactobacillus sakei, Enterococcus faecalis*
- Fermented sausages *Lactobacillus curvatus*
- Meat Products *Lactococcus lactis* subsp. *cremoris* CTC 204, *L. lactis* subsp. *hordinae* CTC 484, *L. plantarum* CTC 368 and CTC 469
- Kimchi *L. acidophilus* KFRI342
- Pickle *L. plantarum*
- Fruits and vegetables *L. plantarum*

Prebiotics

Prebiotics, which are components of food that are not digestible, include compounds like inulin and fructooligosaccharides. They confer health benefits to the host by selectively stimulating the growth and activity of beneficial gut bacteria, notably *Bifidobacteria*, in the GI tract (Khan et al., 2023).

Prebiotics have a positive impact on the host by selectively promoting the growth and metabolic functions of certain bacterial populations within the colon. By serving as a substrate or 'nourishment' for beneficial gut microorganisms, they facilitate the proliferation of these bacteria and aid in sustaining a balanced and healthier intestinal microbiome (Ji et al., 2023).

A diverse array of compounds can be categorized as prebiotics. Prebiotics can be categorized into disaccharides, oligosaccharides, and polysaccharides. Among these categories, fructooligosaccharides—including inulin and oligofructose—are acknowledged as particularly effective prebiotics. Furthermore, other substances such as gluco-oligosaccharides, xylo-oligosaccharides, galactooligosaccharides, maltooligosaccharides, trans-galactooligosaccharides, stachyose, and raffinose also demonstrate prebiotic potential (Khan et al., 2023; Balthazar et al., 2022). The majority of studies have concentrated on non-digestible carbohydrates, which include fructooligosaccharides (FOS), inulin, galactooligosaccharides, mannanoligosaccharides, and xylooligosaccharides. However, additional substances have also shown prebiotic capabilities, such as human milk oligosaccharides, conjugated linoleic acid, polyphenolic compounds, and polyunsaturated fatty acids (Balthazar et al., 2022).

Prebiotics have been linked to a range of health benefits, including (Charalampopoulos and Rastall, 2012):

- an increase in the bioavailability of minerals, particularly calcium,
- modulation of the immune system,
- prevention of the incidence or improvement in the severity and duration of GI infections, such as traveller's diarrhea, acute diarrhea and antibiotic-associated diarrhea,
- modification of inflammatory conditions, such as irritable bowel syndrome, ulcerative colitis and inflammatory bowel disease (IBD), regulation of metabolic disorders related.

Many common foods are rich sources of prebiotics. Incorporating these into a regular diet can significantly enhance gut health. Key examples include in Table 1:

Table 1. *Types and sources of prebiotics (Al-Sheraji et. al., 2013)*

Sources of prebiotic	Type of prebiotic
Asparagus, sugar beet, garlic, chicory, onion, Jerusalem artichoke, wheat, honey, banana, barley, tomato and rye	Fructooligosaccharides
Honey, sugarcane juice	Isomaltulose
Bamboo shoots, fruits, vegetables, milk, honey and wheat bran	Xylooligosaccharides
Human's milk and cow's milk	Galactooligosaccharides
Water-soluble glucans	Cyclodextrins
Seeds of legumes, lentils, peas, beans, chickpeas, mallow composite, and mustard	Raffinose oligosaccharides
Soybean	Soybean oligosaccharide
Lactose (Milk)	Lactulose
Lactose	Lactosucrose
Sucrose	Isomaltulose
Sucrose	Palatinose
Starch	Maltooligosaccharides
Starch	Isomaltooligosaccharides
Wheat bran	Arabinoxylooligosaccharides
Potato starch	Enzyme-resistant dextrin

Postbiotics

The term "postbiotic" is derived from the Greek words post, which translates to "after," and bios, meaning "life." It is part of the larger "biotic" family that encompasses probiotics, prebiotics, synbiotics, and postbiotics, all of which relate to microorganisms or their substrates (Vinderola et al., 2022). The International Scientific Association for Probiotics and Prebiotics (ISAPP) defines postbiotics as "preparations of inanimate microorganisms and/or their components that confer a health benefit on the host" (Thorakkattu et al., 2022). Additionally, in 2019, the ISAPP consensus panel officially defined postbiotics as:

Postbiotics are described as "a preparation of inanimate microorganisms and/or their components that confers a health benefit on the host" (Salminen et al., 2021).

Postbiotics, which are also known as metabolites, biogenics, or cell-free supernatants, are characterized as "soluble factors secreted by living bacteria or released through bacterial lysis" (Liang and Xing, 2023). Postbiotics are categorized as metabolites generated by the microbiota, encompassing SCFAs, exopolysaccharides, fragments of cell walls, enzymes, proteins, and various other bioactive substances (Thorakkattu et al., 2022).

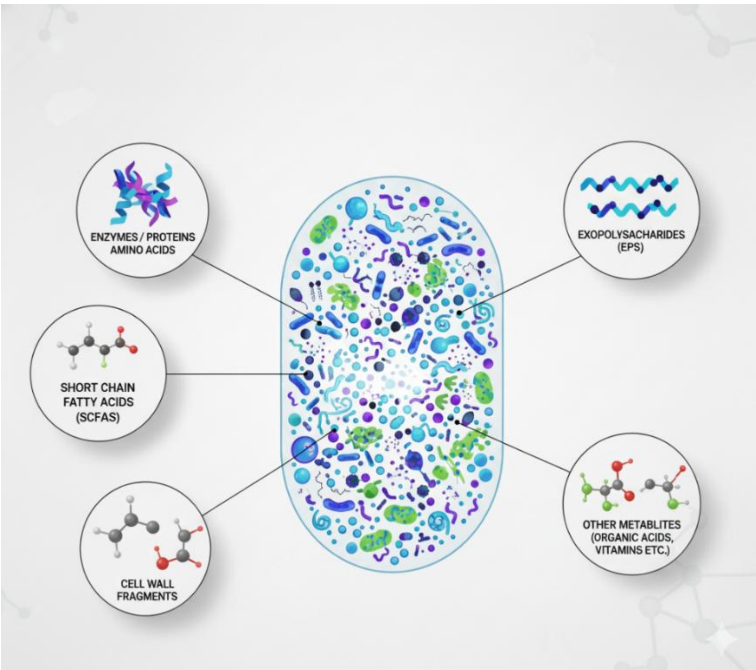

Figure 1 *Schematic representation of postbiotic classification (Thorakkattu et. al., 2022)*

Postbiotics naturally occur in various fermented foods, such as yogurt, sauerkraut, pickled vegetables, and kombucha, and are produced by diverse bacterial and fungal species. The primary strains involved include *Lactobacillus*, *Bifidobacterium*, *Streptococcus*, *Eubacterium*, *Faecalibacterium*, and *Saccharomyces* (Thorakkattu et al., 2022).

Conclusion

Microbiota-friendly products, including probiotics, prebiotics, and postbiotics, represent a significant advancement in food science and human nutrition. Incorporating these functional ingredients into food systems offers the potential to modulate gut microbiota, strengthen immune responses, improve metabolic health, and promote overall well-being.

Probiotics exert their effects through live microbial colonization, competitive inhibition of pathogens, production of bioactive compounds, and modulation of host immune responses. Prebiotic foods play a crucial role in sustaining a healthy and diverse gut microbiome. Prebiotics selectively promote the growth of beneficial microorganisms and lead to the generation of metabolites, such as SCFAs, that support both intestinal health and systemic physiological functions. Postbiotics provide stable, safe, and bioactive alternatives to live microbes, broadening the scope of functional food applications while overcoming challenges related to microbial viability and storage.

In conclusion, microbiota-friendly products offer substantial potential for enhancing human health through dietary interventions. Ongoing research, technological advancements, and supportive regulatory frameworks are crucial to translating scientific findings into practical, effective, and safe functional foods. Thoughtful integration of probiotics, prebiotics, and postbiotics into diverse food matrices presents a comprehensive strategy to harness the gut microbiota's potential for promoting long-term health and well-being.

References

Al-Fakhrany, O. M., & Elekhnawy, E. (2024). Next-generation probiotics: the upcoming biotherapeutics. *Molecular biology reports*, *51*(1), 505.

Al-Sheraji, S. H., Ismail, A., Manap, M. Y., Mustafa, S., Yusof, R. M., & Hassan, F. A. (2013). Prebiotics as functional foods: A review. *Journal of functional foods*, *5*(4), 1542-1553.

Balthazar, C. F., Guimarães, J. F., Coutinho, N. M., Pimentel, T. C., Ranadheera, C. S., Santillo, A., & Sant'Ana, A. S. (2022). The future of functional food: Emerging technologies application on prebiotics, probiotics and postbiotics. *Comprehensive Reviews in Food Science and Food Safety*, *21*(3), 2560-2586.

Chandrasekaran, P., Weiskirchen, S., & Weiskirchen, R. (2024). Effects of probiotics on gut microbiota: an overview. *International journal of molecular sciences*, *25*(11), 6022.

Charalampopoulos, D., & Rastall, R. A. (2012). Prebiotics in foods. *Current opinion in biotechnology*, *23*(2), 187-191.

Ji, J., Jin, W., Liu, S. J., Jiao, Z., & Li, X. (2023). Probiotics, prebiotics, and postbiotics in health and disease. *MedComm*, *4*(6), e420.

Khan, F. F., Sohail, A., Ghazanfar, S., Ahmad, A., Riaz, A., Abbasi, K. S., ... & Arshad, M. (2023). Recent innovations in non-dairy prebiotics and probiotics: physiological potential, applications, and characterization. *Probiotics and Antimicrobial Proteins*, *15*(2), 239-263.

Latif, A., Shehzad, A., Niazi, S., Zahid, A., Ashraf, W., Iqbal, M. W., & Korma, S. A. (2023). Probiotics: mechanism of action, health benefits and their application in food industries. *Frontiers in microbiology*, *14*, 1216674.

Liang, B., & Xing, D. (2023). The current and future perspectives of postbiotics. *Probiotics and Antimicrobial proteins*, *15*(6), 1626-1643.

Liu, C., Ma, N., Feng, Y., Zhou, M., Li, H., Zhang, X., & Ma, X. (2023). From probiotics to postbiotics: Concepts and applications. *Animal Research and One Health*, *1*(1), 92-114.

Maftei, N. M., Raileanu, C. R., Balta, A. A., Ambrose, L., Boev, M., Marin, D. B., & Lisa, E. L. (2024). The potential impact of probiotics on human health: an update on their health-promoting properties. *Microorganisms*, *12*(2), 234.

Min, M., Bunt, C. R., Mason, S. L., & Hussain, M. A. (2019). Non-dairy probiotic food products: An emerging group of functional foods. *Critical reviews in food science and nutrition*, *59*(16), 2626-2641.

Pandey, K., Naik, S., & Vakil, B. (2015). Probiotics, prebiotics and synbiotics-a review. *Journal of food science and technology*, *52*(12), 7577-7587.

Parichat, P., & Pongsak, R. (2023). Probiotics: Sources, selection and health benefits. *Res J Biotechnol*, *18*, 5.

Rinninella, E., Raoul, P., Cintoni, M., Franceschi, F., Miggiano, G. A. D., Gasbarrini, A., & Mele, M. C. (2019). What is the healthy gut microbiota composition? A changing ecosystem across age, environment, diet, and diseases. *Microorganisms*, *7*(1), 14.

Salminen, S., Collado, M. C., Endo, A., Mayer, H. K., Vinderola, G., Gueimonde, M., & Isolauri, E. (2021). The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on the definition and scope of postbiotics. *Nature Reviews Gastroenterology & Hepatology*, *18*(9), 649–667.

Sionek, B., Szydłowska, A., Zielińska, D., Neffe-Skocińska, K., & Kołożyn-Krajewska, D. (2023). Beneficial bacteria isolated from food in relation to the next generation of probiotics. *Microorganisms*, *11*(7), 1714.

Staniszewski, A., & Kordowska-Wiater, M. (2021). Probiotic and potentially probiotic yeasts—Characteristics and food application. *Foods*, *10*(6), 1306.

Thorakkattu, P., Khanashyam, A. C., Shah, K., Babu, K. S., Mundanat, A. S., Deliephan, A., ... & Nirmal, N. P. (2022). Postbiotics: current trends in food and pharmaceutical industry. *Foods*, *11*(19), 3094.

Tripathi, M. K., & Giri, S. K. (2014). Probiotic functional foods: Survival of probiotics during processing and storage. *Journal of functional foods*, *9*, 225-241.

Vázquez-Fresno, R., Saborido-Basalo, S., Aranda, C., & Jofre, E. (2019). Postbiotics: a new challenge in the development of functional foods. *Food Chemistry*, *297*, 124803.

Vinderola, G., Sanders, M. E., & Salminen, S. (2022). The concept of postbiotics. *Foods*, *11*(8), 1077.

Xia, B., Liu, X., Li, Z., Ren, J., & Liu, X. (2023). The effects of microbiota-targeted approaches in inflammatory bowel disease: probiotics, probiotic foods, and prebiotics. *Current Opinion in Food Science*, *49*, 100956.

THE ROLE OF NATURAL ANTIOXIDANTS FOR ENHANCING OXIDATIVE STABILITY OF VEGETABLE OILS

PINAR GÜMÜŞ[1]

Introduction

The primary issue with food product preservation during storage is oxidation (Leyva-Porras et al., 2021). Food quality is affected by oxidative processes, which harm proteins and lipids (Decker, 1998). As consumer demand for clean label and chemical-free options has grown, similarly has interest in natural substances to prevent lipid oxidation (Goksen and Gumus 2021). Reactive oxygen species, which mostly harm food's proteins and fats, are prevented by antioxidants (Leyva-Porras et al., 2021). Rancid flavor and odors in fats and oils are caused by the oxidative process, which lowers the nutritional value of food (Taghvaei and Jafari, 2015). Antioxidants are substances that can enhance the oxidative stability of oils and retard or prevent oxidation processes (Mishra et al., 2021).

[1] Assist. Prof. Dr., Kilis 7 Aralık University, Nutrition and Dietetics, Orcid: 0000-0003-4085-9859

In order to improve antioxidant systems, it is important to figure out the chemical and physical factors which affect interactions between lipids, prooxidants and antioxidants (Decker, 1998). Natural antioxidants are replacing synthetic ones in food systems as a result of growing consumer awareness of health and wellness (Karka and Ozcan et al., 2025). It is crucial to use suitable food packing techniques and storage conditions that shield the product from lipid oxidation and microbiological contamination in order to protect food quality and increase shelf life. Food products that have undergone oxidation typically have lower nutritional content and shorter shelf life. Due to the growing trend of replacing hydrogenated oils including saturated fatty acids (SFAs) with monounsaturated and polyunsaturated fatty acids (PUFAs), which are thought to be healthier by consumers but are far more prone to oxidation than SFAs, lipid peroxidation is a major concern for the food industry (Fadda et al., 2022; Gumus, 2024; Eze et al., 2025).

Lipid oxidation is a complicated process that involves a number of interacting pathways. It has been established that the autoxidation, photooxidation, and enzymatic pathways are responsible for lipid oxidation in animal diets (Petcu et al., 2023). Autoxidation, thermal oxidation, and photosensitized oxidation are the three forms of oxidations that occur during the heating process. The mechanism of auto-oxidation, which includes initiation, propagation, and termination, is largely comparable to the science underlying thermal oxidation. Lipid oxidation is the fundamental issue that causes deterioration of cooking oil quality resulting in off-flavours and an unpleasant odour called rancidity. Oxidative stability can directly affect oil quality and shelf life (Loganathan et al., 2022). Lipid oxidation can cause edible oils to deteriorate during handling, storage, or cooking. The primary reason of oil quality loss is oxidation, which lowers an oil's nutritional value and produces unwanted off-flavors that make food-containing oils more unpleasant to customers. Edible oil producers and the food processing industry are looking for alternatives to synthetic antioxidants to prevent oils from oxidizing in order to satisfy consumer demand for natural foods (Fadda et al., 2022). A crucial step in the production of edible oils is lipid peroxidation. Various studies have explored the use of synthetic antioxidants to enhance the oxidative stability of edible vegetable oils during processing and storage. Because bulk oil oxidation occurs via various ways influenced by extrinsic characteristics such as light and temperature and intrinsic factors such as degree of saturation, free fatty acids, phospholipids, pigments, it is rational to utilize multiple antioxidants in combination. Antioxidants are now required for food products that are susceptible to this kind of chemical change in order to prevent oxidation-related food deterioration (Mishra et al., 2021; Viana da Silva et al., 2022). This chapter presents an overview of lipid oxidation in vegetable oils and summarize current knowledge on the role of natural antioxidants for improving the oxidative stability of vegetable oils.

Vegetable Oils

Oils and fats have an important functional role in foods, both those cooked at home and those manufactured industrially. It is critical to figure out the comparative shelf stability of oils used in food production since oil quality has a significant effect on food quality and shelf life (Syed, 2016). Triglycerides are the primary constituents of vegetable oils, with tiny amounts of free fatty acids, phospholipids, phytosterols, tocopherols, and waxes (Machado et al., 2023). In recent years, there has been an increasing interest in creating sustainable techniques to improving the stability of edible oils (Yildiz et al., 2025). The oxidative stability of oils is influenced by a number of factors, including fatty acid composition, oil processing conditions, the type and amount of oxygen available, and the availability of a wide range of minor compounds such as free fatty acids, mono- and diacylglycerols, transition metals, peroxides, antioxidant compounds, and pigments (Machado et al., 2023). Oxygen is the primary reactant responsible for lipid oxidation, which causes rancidity in foods. Its presence, whether dissolved in the oil or in the headspace of bulk oil systems, significantly influences the extent of oxidative processes, and lowering oxygen levels in foods has long been recognized as an effective technique for slowing lipid oxidation and preserving food quality (Johnson and Decker, 2015).

Oxidation of vegetable oils reduces their nutritional value, generates undesirable flavors, and ultimately limits their quality and shelf life. Although synthetic antioxidants have traditionally been used to enhance oxidative stability, concerns regarding their potential health risks have prompted the edible oil industry to seek safer natural alternatives. Natural antioxidants extracted from various plant sources have shown strong protective effects, sometimes even surpassing those of synthetic additives, in preventing oxidative degradation and meeting consumer preferences for more natural and health-conscious products (Oubannin et al., 2024). Vegetable oils naturally contain antioxidants. As previously stated, polyphenols, tocopherols, and sterols are naturally occurring in vegetable oils and play a key role in their stability (Machado et al., 2023). While synthetic antioxidants have long been utilized, rising consumer awareness in food safety and sustainability has switched the attention to natural alternatives (Yildiz et al., 2025).

Lipid Oxidation

Lipids as vital macronutrients essential for human growth and maintenance, play a key role as a fundamental component of food. One of the main reasons that natural and processed foods lose quality is lipid oxidation, which is a significant financial issue for the food sector (Cui and Decker, 2016). Lipid oxidation is a significant concern of food quality degradation, causing a problem for manufacturers and food scientists. Oxidation is a key reason of deterioration of fats and oils, by producing harmful compounds during cooking and processing resulting in rancid smells, color changes and off-flavors, texture, as well as nutrient loss and reduces product quality and shelf life (Tian et al., 2013; Homma et al 2015; Roman et al., 2016; Gazwi, 2017). The properties and shelf life of food products containing lipids are negatively impacted by deteriorative intermediates of lipid oxidation (Şahin et al., 2019).

Lipid oxidation is one of the main problems in foods since it produces rancid odors and flavors, changes texture and color, and reduces nutritional value and shelf life (Alamed et al., 2009). One of the primary reasons of quality degradation in oil and fatty foods is oxidation, which is started by free radicals and facilitated by chain reactions. Lipid oxidation in foods has been broadly researched, and many gas chromatographic methods were used for monitoring this process. Popular methods for preparing samples to track lipid oxidation are Static headspace (SHS), dynamic headspace (DHS), direct injection (DI), thermal desorption (TD), and headspace solid phase microextraction (HS-SPME). Deterioration of oils are determined by acid value which represents hydrolytic reactions; peroxide value, Conjugated dienes (CD) and conjugated trienes (CT) as indicators of primary oxidative reactions and; anisidine value and Thiobarbituric acid reactive substances (TBARS) as indices to secondary oxidative reactions. None of these parameters can be used alone to determine lipid oxidation. Certain aldehydes, ketones, and other substances have been suggested as potential indicators of oil and fat oxidation; hexanal has been suggested as an alternative marker for lipid oxidation (Ha et al., 2011; Azarbad and Jeleń, 2015; Baştürk et al., 2018).

Rancidity caused on by lipid oxidation reduces the product's shelf life, nutritional value, and, eventually, its marketability and earnings. In order to make healthier meals and increase food security by reducing spoilage, strategies to delay lipid oxidation are required (Barden et al., 2015). Because it causes rancidity and the development of unpleasant aromas that frequently prompt customers to reject food goods, lipid oxidation is a significant factor in food deterioration. This complex process happens when unsaturated fatty acids react with molecular oxygen via a photosensitized oxidation pathway or a free radical mechanism. During this process, hydroperoxides degrade into a wide range of volatile chemicals, including aldehydes, ketones, alcohols, acids, esters, alkanes, alkenes, and other hydrocarbons, which influence food scent and produce unpleasant notes such as rancid, soapy, greasy, and fishy odor (Azarbad and Jeleń, 2015). The ability of oils to resist oxidation during processing and storage is referred to as oxidative stability, and it is commonly quantified by the amount of time needed to reach a critical stage characterized by either apparent sensory alterations or a sharp rise in oxidative reactions. The off-flavor compounds make oil less acceptable or unacceptable to consumers or for industrial use as a food ingredient, this attribute is important to determine overall oil quality and shelf life. Controlling oxidation is crucial for maintaining the flavor, nutritional value, and safety of edible oils because the process also breaks down important fatty acids and produces hazardous substances and oxidized polymers (Choe and Min, 2006).

The oxygen-dependent degradation of lipids has been identified as a significant issue in fat and oil storage (Ramadan and Wahdan, 2012). Lipid oxidation refers to the complicated sequence of chemical interactions between unsaturated fatty acyl groups in lipids and active oxygen molecules (Chaiyasit et al., 2007). The susceptibility of dietary oils to quality deterioration is heavily impacted by their exposure to oxygen, as the unsaturated fatty acids in them rapidly undergo damaging interactions with this highly reactive atmospheric molecule. Because oxygen is abundant and quickly interacts with these unsaturated components, it is critical in promoting the oxidative processes that, in turn, decrease lipid quality (Johnson and Decker, 2015).

Controlling lipid oxidation involves preventing the generation of lipid hydroperoxides and free radicals, or scavenging them in food systems (Tian et al., 2013). Unsaturated fatty acids such as oleic, linoleic, linolenic, and long chain PUFA are found in the lipids involved in the oxidation process; however, additional unsaturated lipids such as sterols are also oxidized (Ramadan and Wahdan, 2012). The inhibition of the lipid free radical chain reaction during oxidation is of practical importance because it can limit the degree of deterioration of unsaturated fatty acids. Antioxidants prevent oxidation in foods by deactivating free radicals, quenching oxygen and photosensitizers, and chelating prooxidative metal ions (Johnson and Decker, 2015).

Natural Antioxidants

Oxidative stability and antioxidant properties affect the quality, shelf-life, and nutritional value of food (Suhag et al., 2025). There is interest in creating natural antioxidant strategies to develop the quality and shelf life of the lipids in plant-based foods (Gumus-Bonacina et al., 2024). Since several other approaches have demonstrated their limitations, the use of antioxidants in food has proven to be an effective way to prevent lipid oxidation (Cui and Decker, 2016). Several antioxidant technologies have the ability to stabilize foods that are susceptible to oxidative rancidity. These methods involve controlling prooxidants and minimizing the harmful effects of free radicals (Chaiyasit et al., 2007). Prooxidants promote lipid hydroperoxide production, free radical generation, and hydroperoxide breakdown. Antioxidants are compounds that slow the oxidation of lipids. Antioxidants are divided into main and secondary antioxidants based on their chemical processes. Primary antioxidants scavenge free radicals that cause oxidation, whereas secondary antioxidants prevent lipid oxidation by reducing other prooxidative variables or regenerating primary antioxidants (Cui and Decker, 2016).

Antioxidants are substances that prevent the auto-oxidation of oils and fats by providing hydrogen to free radicals produced during the initiation and propagation stages of autoxidation (Taghvaei and Jafari, 2015). Primary and secondary antioxidants are two major categories into which antioxidants can be divided. Primary antioxidants can scavenge lipid peroxy radicals, which stop the oxidation chain reaction, and neutralize free radicals by giving hydrogen atoms to lipid alkyl radicals. By inhibiting oxidation promoters such as metal ions, singlet oxygen, pro-oxidative enzymes, and other oxidants, secondary antioxidants stop or slow down oxidation (Mishra et al., 2021). Antioxidants can be classified into two types: natural and synthetic (Petcu et al., 2023). Antioxidants are classified into different types based on their source and mechanism of action. They may be endogenous or exogenous. Exogenous antioxidants are dietary components such vitamins C and E, polyphenols, and flavonoids (Karka and Ozcan et al., 2025).

Naturally occurring antioxidants are categorized based on the chemical structures of carotenoids, vitamins, polyphenols, quinones, and minerals, with the most researched being vitamins like tocopherols and ascorbic acid, stilbenes such as resveratrol, polyphenols like gallic acid and quercetin, and plant extracts containing combinations of antioxidant molecules from several families, primarily polyphenols (Leyva-Porras et al., 2021). The most commonly used synthetic antioxidants include butylated hydroxyl anisole (BHA), butylated hydroxyl toluene (BHT), propyl gallate (PG), and tertbutyl hydroquinone (TBHQ) (López-Pedrouso et al., 2022). Adding natural or artificial antioxidants to food products to increase their shelf life and improve their sensory attributes is gaining popularity. Natural antioxidants found in foods and medicinal plants are favored over synthetic antioxidants, which are generated through chemical processes in a laboratory for health and safety reasons (Eze et al., 2025).

Natural antioxidants represent a promising alternative to synthetic additives in the oil industry, as they effectively inhibit oxidative deterioration and help maintain the overall quality of vegetable oils. Their incorporation into oils enhances stability, while advances in both conventional and innovative extraction techniques have improved the availability and efficiency of these bioactive compounds. Moreover, a variety of enrichment methods can be employed to naturally fortify vegetable oils with antioxidant constituents (Oubannin et al., 2024).

Many ways for enhancing oil stability have been explored, including the use of natural and synthetic antioxidants, as well as the more recent application of encapsulating techniques (Machado et al., 2023). Both scientific literature and food industry standards agree that antioxidants play an important role in decreasing these oxidation processes. Natural antioxidants including polyphenols, vitamins, and carotenoids, which scavenge free radicals, can slow down oxidation reactions and extend food shelf life (Karka and Ozcan et al., 2025).

Antioxidants are added to oils in order to increase oxidative stability during storage and processing of edible vegetable oils (Yildiz et al., 2025). Tocopherols and tocotrienols occur in plants in variable amounts, and their biological and antioxidant activity differs between individual compounds (Gliszczyńska-Świgło et al., 2007). Vitamin E is a natural antioxidant composed of four homologs: α-, β-, γ-, and δ-tocopherols. It is an essential component of the human diet and provides numerous health benefits. Tocopherols can be utilized as food additives because of their excellent oxidative reaction chain-breaking capacity, which makes them suitable for protecting against lipid oxidation or autoxidation processes (Athanasiadis et al., 2023). Natural antioxidants are widely present in fruits and vegetables, fruit seeds, cereals, berries, wine, tea, olive oil, and numerous aromatic plants. Among these, phenolic compounds constitute one of the most important classes and are generally categorized into flavonoids and nonflavonoid polyphenols, with phenolic acids and other nonflavonoids occurring abundantly in many foods. The ability of phenolic compounds to slow down lipid oxidation is largely attributed to their potent free radical–scavenging activity, which enables them to effectively interrupt oxidative processes in lipid-rich systems (Maqsood et al., 2014).

Herbal extracts are recognized as valuable sources of bioactive compounds, including phytochemicals, polyphenols, and carotenoids. When combined with preservation technologies such as vacuum or modified-atmosphere packaging, these extracts enhance product stability, while their incorporation into biodegradable packaging films offers an effective strategy for delaying oxidation, inhibiting foodborne pathogens, and reducing overall food deterioration. Such applications not only extend shelf life but also improve the safety and quality of food products, meeting consumer demands for natural and sustainable solutions (Gumus, 2024). Essential oils are considered a "green" option in the nutritional, medicinal, and agricultural industries because of their demonstrated antibacterial, antiviral, nematicidal, antifungal, insecticidal, and antioxidant properties. Because of their diverse bioactive qualities, they have been proposed as natural antioxidants and preservatives in food systems, representing a possible alternative to synthetic chemicals (Turek and Stintzing, 2013). Essential oils have antioxidant activity, but essential oils have lesser antioxidants than commercial antioxidants (Gulden and Goksen, 2021).

Conclusion

In recent years, there has been an increased focus in creating sustainable techniques to improving the stability of edible oils, particularly in light of increasing customer demand for healthier and safer foods. The stability of edible oils has a considerable impact on their quality, safety, and shelf life. The most popular technique to preventing or delaying lipid oxidation is to add natural or synthetic antioxidants to diet. While synthetic antioxidants have long been utilized, rising consumer awareness in food safety and sustainability has drawn the attention to natural alternatives. Replacing synthetic antioxidants with natural sources could help meet the demand for healthier products.

References

Alamed, J., Chaiyasit, W., McClements, D. J., & Decker, E. A. (2009). Relationships between free radical scavenging and antioxidant activity in foods. Journal of agricultural and food chemistry, 57(7), 2969-2976.

Azarbad, M. H., & Jeleń, H. (2015). Determination of hexanal—an indicator of lipid oxidation by static headspace gas chromatography (SHS-GC) in fat-rich food matrices. Food analytical methods, 8(7), 1727-1733.

Athanasiadis, V., Chatzimitakos, T., Kalompatsios, D., Palaiogiannis, D., Makrygiannis, I., Bozinou, E., & Lalas, S. I. (2023). Evaluation of the efficacy and synergistic effect of α-and δ-tocopherol as natural antioxidants in the stabilization of sunflower oil and olive pomace oil during storage conditions. International Journal of Molecular Sciences, 24(2), 1113.

Barden, L., Vollmer, D., Johnson, D., & Decker, E. (2015). Impact of iron, chelators, and free fatty acids on lipid oxidation in low-moisture crackers. Journal of agricultural and food chemistry, 63(6), 1812-1818.

Baştürk, A., Ceylan, M. M., Çavuş, M., Boran, G., & Javidipour, I. (2018). Effects of some herbal extracts on oxidative stability of corn oil under accelerated oxidation conditions in comparison with some commonly used antioxidants. Lwt, 89, 358-364.

Chaiyasit, W., Elias, R. J., McClements, D. J., & Decker, E. A. (2007). Role of physical structures in bulk oils on lipid oxidation. Critical reviews in food science and nutrition, 47(3), 299-317.

Choe, E., & Min, D. B. (2006). Mechanisms and factors for edible oil oxidation. Comprehensive reviews in food science and food safety, 5(4), 169-186.

Cui, L., & Decker, E. A. (2016). Phospholipids in foods: prooxidants or antioxidants? Journal of the Science of Food and Agriculture, 96(1), 18-31.

Decker, E. A (1998). Strategies for manipulating the prooxidative/antioxidative balance of foods to maximize oxidative stability. Trends in food science & technology, 9(6), 241-248.

Eze, C. N., Aduba, C. C., Ezema, B. O., Ayoka, T. O., Nnadi, C. O., & Onyeaka, H. (2025). The role of antioxidants in food safety and preservation: mechanisms, applications, and challenges. Cogent Food & Agriculture, 11(1), 2591436.

Fadda, A., Sanna, D., Sakar, E. H., Gharby, S., Mulas, M., Medda, S., ... & Durazzo, A. (2022). Innovative and sustainable technologies to enhance the oxidative stability of vegetable oils. Sustainability, 14(2), 849.

Gazwi, H. (2017). Oxidative stability of Sunflower oil as affected by Carica papaya leaves extracts during accelerated oxidative storage. International Journal of Biosciences, 1(11), 116-126.

Gharby, S., Asbbane, A., Ahmed, M. N., Gagour, J., Hallouch, O., Oubannin, S., ... & Ibourki, M. (2025). Vegetable oil oxidation: Mechanisms, impacts on quality, and approaches to enhance shelf life. Food Chemistry: X, 102541.

Gliszczynska-Swiglo, A., Sikorska, E., Khmelinskii, I., & Sikorski, M. (2007). Tocopherol content in edible plant oils. Polish journal of food and nutrition sciences, 57(4 [A]), 157-161.

Gökşen, G., & Gümüş, P. (2021). The future trend natural preservatives in the food system: essential oils. Avrupa Bilim ve Teknoloji Dergisi, (28), 441-443.

Gumus, P. (2024). Scope of Herbal Extracts and Essential Oils for Extension of Shelf-Life of Packaged Foods. In Food Process Engineering and Technology: Safety, Packaging, Nanotechnologies and Human Health (pp. 233-242). Singapore: Springer Nature Singapore.

Gumus-Bonacina, C. E., Mcclements, D. J., & Decker, E. A. (2024). Replacing animal fats with plant-based lipids: Challenges and opportunities. Current Opinion in Food Science, 58, 101193.

Ha, J., Seo, D. W., Chen, X., Hwang, J. B., & Shim, Y. S. (2011). Determination of hexanal as an oxidative marker in vegetable oils using an automated dynamic headspace sampler coupled to a gas chromatograph/mass spectrometer. Analytical Sciences, 27(9), 873-878.

Homma, R., Suzuki, K., Cui, L., McClements, D. J., & Decker, E. A. (2015). Impact of association colloids on lipid oxidation in triacylglycerols and fatty acid ethyl esters. Journal of agricultural and food chemistry, 63(46), 10161-10169.

Johnson, D. R., & Decker, E. A. (2015). The role of oxygen in lipid oxidation reactions: a review. Annual review of food science and technology, 6(1), 171-190.

Karka, H. U., & Özcan, A. U. (2025). Antioxidants as Food Additives. Current Research on Food Engineering and Science, 61.

Leyva-Porras, C., Román-Aguirre, M., Cruz-Alcantar, P., Pérez-Urizar, J. T., & Saavedra-Leos, M. Z. (2021). Application of antioxidants as an alternative improving of shelf life in foods. Polysaccharides, 2(3), 594-607.

Loganathan, R., Tarmizi, A. H. A., Vethakkan, S. R., & Teng, K. T. (2022). A review on lipid oxidation in edible oils. Malaysian Journal of Analytical Sciences, 26(6), 1378-1393.

López-Pedrouso, M., Lorenzo, J. M., & Franco, D. (2022). Advances in natural antioxidants for food improvement. Antioxidants, 11(9), 1825.

Machado, M., Rodriguez-Alcalá, L. M., Gomes, A. M., & Pintado, M. (2023). Vegetable oils oxidation: mechanisms, consequences and protective strategies. Food Reviews International, 39(7), 4180-4197.

Maqsood, S., Benjakul, S., Abushelaibi, A., & Alam, A. (2014). Phenolic compounds and plant phenolic extracts as natural antioxidants in prevention of lipid oxidation in seafood: A detailed review. Comprehensive Reviews in Food Science and Food Safety, 13(6), 1125-1140.

Mishra, S. K., Belur, P. D., & Iyyaswami, R. (2021). Use of antioxidants for enhancing oxidative stability of bulk edible oils: A review. International Journal of Food Science and Technology, 56(1), 1-12.

Nguyen, K. A., Hennebelle, M., van Duynhoven, J. P., Dubbelboer, A., Boerkamp, V. J., & Wierenga, P. A. (2024). Mechanistic kinetic modelling of lipid oxidation in vegetable oils to estimate shelf-life. Food Chemistry, 433, 137266.

Oubannin, S., Bijla, L., Ahmed, M. N., Ibourki, M., El Kharrassi, Y., Devkota, K., ... & Gharby, S. (2024). Recent advances in the extraction of bioactive compounds from plant matrices and their use as potential antioxidants for vegetable oils enrichment. Journal of Food Composition and Analysis, 128, 105995.

Petcu, C. D., Tăpăloagă, D., Mihai, O. D., Gheorghe-Irimia, R. A., Negoiță, C., Georgescu, I. M., ... & Ghimpețeanu, O. M. (2023). Harnessing natural antioxidants for enhancing food shelf life: Exploring sources and applications in the food industry. Foods, 12(17), 3176.

Ramadan, M. F., & Wahdan, K. M. M. (2012). Blending of corn oil with black cumin (Nigella sativa) and coriander (Coriandrum sativum) seed oils: Impact on functionality, stability and radical scavenging activity. Food chemistry, 132(2), 873-879.

Roman, M. J., Decker, E. A., & Goddard, J. M. (2016). Retaining oxidative stability of emulsified foods by novel nonmigratory polyphenol coated active packaging. Journal of Agricultural and Food Chemistry, 64(27), 5574-5582.

Suhag, R., Kellil, A., Ferrentino, G., Morozova, K., Zatelli, D., & Scampicchio, M. (2025). Lipid oxidation kinetics and antioxidant efficiency in foods using isothermal calorimetry. Trends in Food Science & Technology, 155, 104801.

Syed, A. (2016). Oxidative stability and shelf life of vegetable oils. In Oxidative stability and shelf life of foods containing oils and fats (pp. 187-207). AOCS Press.

Şahin, S. (2019). Evaluation of stability against oxidation in edible fats and oils. Journal of Food Science and Nutrition Research, 2(3), 283-298.

Taghvaei, M., & Jafari, S. M. (2015). Application and stability of natural antioxidants in edible oils in order to substitute synthetic additives. Journal of food science and technology, 52(3), 1272-1282.

Tian, F., Decker, E. A., & Goddard, J. M. (2013). Controlling lipid oxidation of food by active packaging technologies. Food & function, 4(5), 669-680.

Turek, C., & Stintzing, F. C. (2013). Stability of essential oils: a review. Comprehensive reviews in food science and food safety, 12(1), 40-53.

Viana da Silva, M., Santos, M. R. C., Alves Silva, I. R., Macedo Viana, E. B., Dos Anjos, D. A., Santos, I. A., ... & Lannes, S. C. D. S. (2022). Synthetic and natural antioxidants used in the oxidative stability of edible oils: An overview. Food Reviews International, 38(sup1), 349-372.

Yildiz, A. Y., Öztekin, S., & Anaya, K. (2025). Effects of plant-derived antioxidants to the oxidative stability of edible oils under thermal and storage conditions: Benefits, challenges and sustainable solutions. Food Chemistry, 143752

MODERN APPROACHES TO EXTENDING THE SHELF LIFE OF MEAT PRODUCTS

ANIL UZUN ÖZCAN[1]
HİCRAN UZUN KARKA[2]

Introduction

Meat is a highly perishable food due to its rich nutrient profile, high moisture content, and favorable pH for microbial proliferation. Spoilage in meat typically results from microbial growth, lipid oxidation, protein degradation, and enzymatic reactions, all of which reduce sensory quality and compromise safety (Karanth et al., 2023; Dave and Ghaly, 2011). The shelf life of meat is determined by a range of factors, including storage temperature, enzymatic activity, oxygen exposure, humidity levels, light, and microbial presence. These variables are of particular concern, as they exert direct effects on the nutritional integrity and sensory quality of meat products. Their impact may lead to undesirable alterations in key attributes such as texture, color, odor, flavor, and overall aroma (Pateiro et al., 2018).

[1] Assist. Prof. Dr., Kilis 7 Aralık University, Nutrition and Dietetics Department, Orcid: 0000-0003-4039-9389
[2] Assist. Prof. Dr., Gaziantep University, Food Processing Department, Orcid: 0000-0003-1098-3197

Extending the shelf life of meat products has therefore been a major focus of food science research, combining advances in packaging, processing, natural antimicrobial compounds, and emerging non-thermal technologies. Modern approaches aim not only to inhibit spoilage but also to maintain nutritional quality and minimize the use of synthetic additives. This chapter provides an overview of contemporary strategies used to prolong the shelf life of meat products, including natural antimicrobial and antioxidant interventions, modern packaging technologies, non-thermal processing techniques, and novel edible films and coatings.

Natural Antimicrobials and Antioxidants

Using plant-derived extracts in food offers a natural and environmentally friendly approach to improving food safety and extending shelf life. These bioactive compounds can inhibit microbial growth, delay oxidation, and maintain product quality, thereby reducing the need for synthetic preservatives and chemical additives (Gümüş, 2024). The meat and meat products sector has undergone notable development in response to evolving market expectations, particularly the growing consumer demand for high-quality food products. Concurrently, concerns regarding the widespread application of synthetic additives—such as preservatives and antioxidants—have intensified, prompting increased scientific interest in natural, safe, and health-oriented alternatives. Within this framework, essential oils and plant-based extracts have been identified as viable candidates, owing to their entirely natural origin and their demonstrated biological activities, most notably their capacity to inhibit oxidative processes and suppress microbial proliferation. These attributes have significantly strengthened their appeal to both industry professionals and consumers (Campolina et al., 2023).

Lipid peroxidation, as well as the oxidation of pigments and proteins, diminishes both the quality and nutritional value of meat products. The incorporation of antioxidants mitigates these oxidative processes, helping to preserve the product's characteristics during storage and extending its shelf life. While synthetic antioxidants have been extensively evaluated in toxicological studies, there is an increasing emphasis on the use of antioxidants derived from natural sources (Ribeiro et al., 2019). Natural antioxidants from fruits, vegetables, herbs, and spices can serve as antioxidant, antimicrobial, and preservative agents in meat products. Rich in bioactive compounds, these plant-derived ingredients help inhibit or delay oxidation, enhancing product quality during processing and storage. Among them, sage and rosemary are particularly effective in maintaining oxidation and color stability, while grape seeds and olive derivatives, high in polyphenols, also provide notable antioxidant effects. Such natural antioxidants offer a promising alternative to synthetic preservatives in meat products (Horbańczuk et al., 2019).

Organic acids and their derivatives—including lactic and acetic acids—are commonly generated through microbial fermentation and serve as effective natural preservatives in food systems. Their antimicrobial efficacy is largely attributed to their capacity to reduce the pH of the surrounding matrix and to diffuse across microbial cell membranes in their undissociated state, thereby disrupting cellular homeostasis (Kumar et al., 2025). Commonly utilized organic acids in meat preservation include acetic, citric, lactic, propionic, malic, succinic, and tartaric acids. These compounds offer several advantages—such as FDA recognition as GRAS substances, absence of restrictions on acceptable daily intake, low cost, and practical applicability—but their use must be carefully managed, as certain *Salmonella* strains have demonstrated the ability to adapt to and withstand acidic environments (Bodie et al., 2024).

Encapsulation has emerged as a promising strategy for enhancing the functionality and applicability of natural preservatives in food systems. Using GRAS-certified carrier materials—such as alginate, chitosan, starch, dextrins, and various proteins—bioactive compounds can be incorporated through diverse techniques including spray drying, extrusion, freeze-drying, complex coacervation, and emulsification. The direct incorporation of natural preservatives into meat products is often limited by their inherent drawbacks, including poor water solubility, low bioavailability, rapid volatilization, and susceptibility to chemical degradation. In addition, extrinsic factors such as pH, storage temperature, duration, and exposure to oxygen or light can further compromise their stability and antimicrobial performance. Encapsulation addresses these constraints by protecting the active molecules, particularly hydrophobic substances such as essential oils, thereby enhancing their stability, controlling their release, and broadening their potential applications in meat processing while preserving their antimicrobial efficacy (Yu et al., 2021).

Modern Packaging Innovations

Vacuum Packaging (VP): Vacuum packaging constitutes a well-established intervention to limit oxidative processes and thereby prolong product shelf life. The anaerobic environment produced—characterized by reduced oxygen tension, the presence of NaCl and $NaNO_2$, and lowered water activity—effectively suppresses Gram-negative spoilage bacteria, including members of the genera Pseudomonas, Acinetobacter, and Enterobacter (Siddi et. al.,2023).

Modified Atmosphere Packaging (MAP): It entails the controlled displacement of ambient air with a defined gas mixture prior to sealing meat in impermeable barrier materials. This intervention modulates the gaseous microenvironment, thereby attenuating oxidative reactions, inhibiting the proliferation of spoilage and pathogenic microorganisms, and preserving sensory and visual attributes. Carbon dioxide (CO_2) exerts bacteriostatic and fungistatic effects by lowering intracellular pH, nitrogen (N_2) functions as an inert filler to prevent package collapse and oxidative interactions, and oxygen (O_2) is regulated to maintain desirable myoglobin redox states, thereby stabilizing meat color. The precise composition and partial pressures of these gases critically dictate the kinetics of lipid oxidation, microbial metabolism, and enzymatic degradation, ultimately determining the shelf life and quality stability of packaged meat products (Zabek et al.,2021).

Active Packaging (AP): Active packaging represents an advanced packaging strategy incorporating functional compounds—such as antioxidants, antimicrobial agents, moisture and gas scavengers, and ultraviolet (UV) radiation absorbers—that actively interact with the food matrix or its surrounding environment. By mitigating oxidative reactions, inhibiting microbial proliferation, controlling moisture migration, and reducing exposure to deleterious radiation, these active components enhance product stability and extend shelf life beyond the capabilities of conventional passive packaging systems, thereby preserving the quality, safety, and structural integrity of food during storage. Active packaging (AP) represents a promising approach for enhancing the sustainability of the meat industry by promoting responsible packaging practices and extending the shelf life of meat products. Moreover, AP systems incorporating antioxidant and antimicrobial functionalities can mitigate quality deterioration associated with freezing and thawing cycles, preserving both the physicochemical and microbiological integrity of meat (Li et al., 2022).

Intelligent Packaging (IP): Intelligent packaging represents an emerging technology in the food sector, including applications for meat and meat products, designed to communicate real-time information about product quality and environmental conditions. These systems utilize sensors, indicators, and radio-frequency identification (RFID) devices to monitor parameters such as freshness, temperature, and package integrity, providing timely warnings of quality deterioration during storage. Advances in intelligent packaging for meat aim to integrate innovative monitoring solutions throughout production and supply chains, thereby enhancing storage management, reducing spoilage, and ensuring safer, higher-quality products (Khodaei et al.,2023).

Non-Thermal Processing Technologies

High-Pressure Processing (HPP): High-pressure processing (HPP) is one of the most widely implemented nonthermal preservation technologies in the food industry, with meat products representing a major share of HPP-treated foods. At the molecular level, pressure induces changes in microorganisms and key meat components such as structural proteins, enzymes, myoglobin, and lipids which explain the texture, color, and oxidative alterations observed in processed meat. Applied as a cold pasteurization method, HPP effectively inactivates vegetative spoilage and pathogenic microorganisms in ready-to-eat meat products, thereby extending shelf life and helping reduce food waste. In addition, HPP supports product innovation by enabling cleaner-label formulations, salt reduction, improved use of lower-value cuts, and the development of stable, high-quality meat products with enhanced safety, nutritional value, and sustainability (Bolumar et al., 2021)

Cold Plasma Treatment: Cold plasma has emerged as an effective, energy-efficient nonthermal intervention capable of achieving substantial microbial inactivation without heat-induced quality deterioration, positioning it as a promising alternative to conventional preservation methods. The reactive oxygen and nitrogen species generated during plasma treatment not only disrupt and inactivate microbial cells but also allow the technology to be safely applied to biological materials, including fresh and processed meats. Moreover, plasma-treated liquids can produce nitrite species, offering potential use as a natural curing agent in cured meat formulations (Jayasena et al, 2023).

Pulsed Electric Field (PEF) Technology: As a promising non-thermal preservation approach, pulsed electric field (PEF) technology is receiving heightened attention for its potential to improve meat quality and safety (Baldi et al., 2021). Pulsed electric field (PEF) technology is an emerging non-thermal processing method in which short, high-voltage electrical pulses are applied between two electrodes, inducing reversible or irreversible electroporation in cellular membranes. This electroporation effect alters the permeability and structural integrity of muscle tissues in a controlled, non-invasive manner. As a result, PEF has been shown to facilitate multiple processing advantages in meat systems, including improved microbial inactivation for preservation, enhanced proteolytic activity contributing to tenderization, and accelerated biochemical changes associated with meat aging. In addition to its effects on whole-muscle quality, PEF has gained attention for its role in the valorization of meat by-products, as increased membrane permeability can significantly enhance the release and recovery of high-value compounds such as proteins, peptides, and bioactive molecules. This positions PEF as a multifunctional technology with broad potential for quality improvement, resource efficiency, and sustainability within the meat industry (Gómez et al., 2019).

Ultraviolet (UV-C) and Pulsed Light: Ultraviolet (UV) radiation is recognized as an efficient, easily operated, and highly manageable non-thermal technology that has been widely implemented in meat products. Exposure to short-wavelength UV radiation, particularly UV-C, induces structural damage to microbial DNA by causing thymine dimer formation and strand breaks. These alterations inhibit DNA replication and cell division, ultimately leading to the inactivation and death of microbial cells. Pulsed light (PL) treatment offers rapid microbial inactivation with minimal chemical residues compared to conventional methods such as thermal processing or chemical sanitizers. This technology delivers high-intensity, broad-spectrum light pulses that effectively disrupt microbial cells. In meat applications, PL has been shown to significantly reduce *Listeria monocytogenes* and *Salmonella Typhimurium* on the surfaces of cured meats and sausages, demonstrating its potential as a non-thermal decontamination strategy for enhancing product safety and shelf life (Liu et al., 2019).

Ozone and Electrolyzed Water Applications: Ozone is a highly reactive oxidant widely recognized for its ability to lower microbial populations and thereby prolong the storage life of meat and meat products. It exhibits strong antimicrobial activity against a wide spectrum of organisms, including Gram-positive and Gram-negative bacteria, vegetative cells, and bacterial spores. The overall effectiveness of ozone is influenced by several operational factors, such as its applied concentration, the mode of application (gaseous or aqueous), temperature, and the presence of organic matter that may reduce its activity. Because ozone rapidly decomposes into oxygen and leaves no chemical residues, it represents a more sustainable and environmentally favorable alternative to conventional sanitizing agents. Numerous studies have demonstrated that ozone interventions can improve product safety and extend the shelf life of various meats, although treatment conditions must be optimized individually for each meat type and processing scenario (Giménez et al., 2024). Slightly acidic electrolyzed water is an effective alternative sanitizer containing high levels of hypochlorous acid at a mildly acidic pH of 5.0–6.5, produced by electrolyzing dilute hydrochloric acid in a membrane-free chamber. Compared with conventional chlorine-based disinfectants, it offers reduced risks from chlorine off-gassing and is considered a more environmentally friendly decontamination option. Studies have shown that slightly acidic electrolyzed water effectively reduces microbial loads and extends the shelf life of aquatic products, vegetables, and beef, often outperforming traditional sanitizing treatments (Sheng et al., 2018).

Edible Coatings and Films

Edible coatings form a supplementary layer on the surface of meat, which helps limit water evaporation and slow the permeation of oxygen into the product. Growing consumer expectations for high-quality, affordable, eco-friendly, natural, and safe packaging materials have created significant challenges for the meat processing sector, especially as the industry seeks alternatives to non-renewable, non-biodegradable petroleum-derived plastics. Edible films and coatings have emerged as promising candidates, as they typically exhibit suitable mechanical strength, effective barriers against gases and moisture, and often improve sensory attributes when applied to meat and meat products. In industrial applications, these materials can be incorporated through dipping, spraying, brushing, casting, foaming, rolling, or individual wrapping techniques. Because they are biodegradable and based on renewable sources, edible films provide a sustainable substitute for conventional petrochemical packaging, thereby helping mitigate the growing issue of environmental waste. A wide spectrum of biopolymers—including polysaccharides, chitosan, proteins of plant and animal origin, and lipid-based materials—can be formulated into edible films suitable for meat protection. Current research focuses on achieving optimal blends of biopolymer matrices and functional bioactive compounds, as the performance of edible films largely depends on the specific materials used and the incorporation of additives that enhance their preservative and functional characteristics (Song et al., 2021; Antonino et al., 2024).

Conclusions

Extending the shelf life of meat and meat products remains a critical objective for the food industry, driven by increasing consumer demand for safe, high-quality, minimally processed, and environmentally sustainable foods. This chapter demonstrates that modern preservation strategies rely on a multifaceted approach in which natural antimicrobials and antioxidants, advanced packaging systems, non-thermal technologies, and innovative edible films and coatings work either independently or synergistically to retard spoilage and maintain product integrity.

Natural antimicrobial and antioxidant compounds from plant and microbial sources offer effective, clean-label alternatives to synthetic preservatives. Meanwhile, advances in active, intelligent, and biodegradable packaging have transformed packaging into a functional system that inhibits microbial growth and monitors product quality. Non-thermal technologies such as high-pressure processing, pulsed electric fields, ozone, and cold plasma achieve microbial inactivation with minimal impact on sensory and nutritional attributes. Additionally, novel edible films and coatings improve surface protection, serve as carriers for bioactive compounds, and support sustainability by reducing plastic use.

Overall, the future of meat preservation lies in the integration of these diverse technologies into smart, efficient, and consumer-friendly systems. By leveraging scientific innovation and sustainable practices, the meat industry can significantly improve product safety, quality, and shelf life while addressing global challenges in food waste and resource efficiency.

References

Antonino, C., Difonzo, G., Faccia, M., & Caponio, F. (2024). Effect of edible coatings and films enriched with plant extracts and essential oils on the preservation of animal-derived foods. *Journal of Food Science, 89*(2), 748–772. https://doi.org/10.1111/1750-3841.16894

Baldi, G., D'Elia, F., Soglia, F., Tappi, S., Petracci, M., & Rocculi, P. (2021). Exploring the effect of pulsed electric fields on the technological properties of chicken meat. *Foods, 10*(2), 241. https://doi.org/10.3390/foods10020241

Bodie, A. R., Wythe, L. A., Dittoe, D. K., Rothrock, M. J., Jr., O'Bryan, C. A., & Ricke, S. C. (2024). Alternative additives for organic and natural ready-to-eat meats to control spoilage and maintain shelf life: Current perspectives in the United States. *Foods, 13*(3), 464. https://doi.org/10.3390/foods13030464

Bolumar, T., Orlien, V., Sikes, A., Aganovic, K., Bak, K. H., Guyon, C., de Lamballerie, M., & Mortensen, M. (2021). High-pressure processing of meat: Molecular impacts and industrial applications. *Comprehensive Reviews in Food Science and Food Safety, 20*(1), 332–368. https://doi.org/10.1111/1541-4337.12670

Campolina, G. A., Cardoso, M. das G., Caetano, A. R. S., Nelson, D. L., & Ramos, E. M. (2023). Essential oils and plant extracts as preservatives and natural antioxidants applied to meat and meat products: A review. *Food Technology and Biotechnology, 61*(2), 212-225. https://doi.org/10.17113/ftb.61.02.23.7883

Dave, D., & Ghaly, A. E. (2011). Meat spoilage mechanisms and preservation techniques: A critical review. *American Journal of Agricultural and Biological Sciences, 6*(4), 486–510. https://doi.org/10.3844/ajabssp.2011.486.510

Giménez, B., Zaritzky, N., & Graiver, N. (2024). Ozone treatment of meat and meat products: A review. *Frontiers in Food Science and Technology, 4*, Article 1351801. https://doi.org/10.3389/frfst.2024.1351801

Gómez, B., Munekata, P. E. S., Gavahian, M., Barba, F. J., Martí-Quijal, F. J., Bolumar, T., Campagnol, P. C. B., Tomasevic, I., & Lorenzo, J. M. (2019). Application of pulsed electric fields in meat and fish processing industries: An overview. *Food Research International, 123*, 95–105. https://doi.org/10.1016/j.foodres.2019.04.047

Gümüs, P. (2024). Scope of herbal extracts and essential oils for extension of shelf-life of packaged foods. In J. A. Malik, M. R. Goyal, & A. Kumari (Eds.), *Food process engineering and technology: Safety, packaging, nanotechnologies and human health* (233-242). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-6831-2

Horbańczuk, O. K., Kurek, M. A., Atanasov, A. G., Brnčić, M., & Rimac, S. (2019). The effect of natural antioxidants on quality and shelf life of beef and beef products. *Food Technology and Biotechnology, 57*(4), 439–451. https://doi.org/10.17113/ftb.57.04.19.6267

Jayasena, D. D., Kang, T., Wijayasekara, K. N., & Jo, C. (2023). Innovative application of cold plasma technology in meat and its products. *Food Science of Animal Resources, 43*(6), 1087–1110. https://doi.org/10.5851/kosfa.2023.e31

Karanth, S., Feng, S., Patra, D., & Pradhan, A. K. (2023). Linking microbial contamination to food spoilage and food waste: The role of smart packaging, spoilage risk assessments, and date labeling. *Frontiers in Microbiology, 14*, 1198124. https://doi.org/10.3389/fmicb.2023.1198124

Khodaei, S. M., Gholami-Ahangaran, M., Esfandiari, Z., & Eghbaljoo, H. (2023). Application of intelligent packaging for meat products: A systematic review. *Veterinary Medicine and Science, 9*, 481–493. https://doi.org/10.1002/vms3.1084

Kumar, A., Das, S., Ali, S., Jaiswal, S. G., Rabbani, A., Rahman, S. M. E., Chelliah, R., Oh, D.-H., Liu, S., & Wei, S. (2025). Mechanisms, applications and challenges of natural antimicrobials in food system. *Food Bioscience, 74*, 107864. https://doi.org/10.1016/j.fbio.2025.107864

Li, X., Zhang, R., Hassan, M. M., Cheng, Z., Mills, J., Hou, C., Realini, C. E., Chen, L., Day, L., Zheng, X., & others. (2022). Active packaging for the extended shelf-life of meat: Perspectives from consumption habits, market requirements and packaging practices in China and New Zealand. *Foods, 11*, 2903. https://doi.org/10.3390/foods11182903

Liu, N., Zhu, Q., Zeng, X., Yang, B., Liang, M., Hu, P., He, L., Deng, L., Liang, C., Zhang, R., & Zhou, J. (2019). Influences of pulsed light-UV treatment on the storage period of dry-cured meat and shelf life prediction by ASLT method. *Journal of Food Science and Technology, 56*(4), 1744–1756. https://doi.org/10.1007/s13197-019-03603-1

Pateiro, M., Barba, F. J., Domínguez, R., Sant'Ana, A. S., Khaneghah, A. M., Gavahian, M., Gómez, B., & Lorenzo, J. M. (2018). Essential oils as natural additives to prevent oxidation reactions in meat and meat products: A review. *Food Research International, 113*, 156–166. https://doi.org/10.1016/j.foodres.2018.07.014

Ribeiro, J. S., Santos, M. J. M. C., Silva, L. K. R., Pereira, L. C. L., Santos, I. A., Lannes, S. C. da S., & Silva, M. V. da. (2019). Natural antioxidants used in meat products: A brief review. *Meat*

Science, 148, 181–188. https://doi.org/10.1016/j.meatsci.2018.10.016

Sheng, X., Shu, D., Tang, X., & Zang, Y. (2018). Effects of slightly acidic electrolyzed water on the microbial quality and shelf life extension of beef during refrigeration. *Food Science & Nutrition, 6*(8), 1975–1981. https://doi.org/10.1002/fsn3.779

Siddi, G., Piras, F., Meloni, M. P., Casti, D., Spanu, C., Pala, C., Mocci, A. M., Piga, C., Di Salvo, R., De Santis, E., & Scarano, C. (2023). Evaluation of vacuum packaging for extending the shelf life of Sardinian fermented sausage. *Italian Journal of Food Safety, 12*, 10819. https://doi.org/10.4081/ijfs.2023.10819

Song, D.-H., Hoa, V. B., Kim, H. W., Khang, S. M., Cho, S.-H., Ham, J.-S., & Seol, K.-H. (2021). Edible films on meat and meat products. *Coatings, 11*(11), 1344. https://doi.org/10.3390/coatings11111344

Yu, H. H., Kim, S. A., Park, S. Y., & Rhee, M. S. (2021). Application of natural preservatives for meat and meat products: A review. *Foods, 10*(12), 2911. https://doi.org/10.3390/foods10122911

Novel Foods and SUSTAINABILITY in Food Science