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Review Paper

Phytonutrients in meat products: plant extraction and formulation of new functional products

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A B S T R A C T

Enriching meat products with plant extracts has become an innovative strategy to improve product quality, extend shelf life and meet the growing demand for natural, functional foods. Plant extracts, especially those rich in polyphenols, flavonoids and terpenes, have strong antioxidant, antimicrobial and health properties. This article deals with the application of innovative extraction techniques in the isolation of biologically and pharmacologically active molecules from different plant species and that could be used as functional additives in meat products. Enrichment with plant extracts is a sustainable approach for the production of meat products with a clean label and added value. Therefore, this manuscript aims to present potent plant species, but also innovative extraction techniques, through the application of which, biologically valuable molecules are isolated, ensuring safety, quality and longer shelf life of meat products.

1. Introduction

Since the beginning of human civilisation, meat has been an essential part of the human diet. It is highly valued for its richness in high-quality protein, essential fatty acids, vitamin B_{12} and important minerals, such as iron and selenium, nutrients that are essential for the proper functioning of the human body (*Leroy et al*., 2023). The importance of meat in the human diet is also reflected in the growth of the global meat products market, which reached a value of $US 1,730.57 billion in 2024 and is expected to rise to around $US 2,710.39 billion by 2034, at a compound annual growth rate (CAGR) of 4.59% between 2025 and 2034 (*Precedence Research*, 2025).

Due to their high moisture and fat content, minimally processed meat products, especially those that are fresh or cooked with water or steam, are particularly susceptible to oxidative degradation and microbial spoilage (*FoodData Central*, 2019). In addition, meat processing itself can also contribute to contamination risks (*Mediani et al*., 2022). Inadequate implementation of preservation methods during processing can increase susceptibility to microbial contamination by bacteria, yeasts and moulds, which can lead to foodborne illness. At the same time, growing public concern over the health risks associated with synthetic additives, such as nitrates, has prompted the food industry to look for safer, natural alternatives, such as plant extracts (*Sabzal et al*., 2025).

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One promising approach is the fortification of meat products with plant extracts from medicinal plants. Thanks to advances in modern extraction technologies, various groups of bioactive phytonutrients, such as phenolic acids, flavonoids, terpenes, tannins and saponins, can now be efficiently isolated from these plants (*Terzić et al*., 2023). These compounds have strong antioxidant and antimicrobial effects by scavenging free radicals, chelating metal ions and destroying microbial membranes. As a result, they improve the stability, safety and shelf life of meat products. The production of high-quality plant extracts depends crucially on the effective extraction of biologically and pharmacologically active metabolites (*Olvera-Aguirre et al*., 2023).

In addition to medicinal plant extracts, essential oils, which are products of secondary metabolism in plants, also offer considerable potential for improving the quality and safety of meat products (*da Silva et al*., 2021). These volatile compounds have strong antimicrobial and antioxidant properties, making them effective natural preservatives. In recent years, innovative extraction methods have attracted considerable attention in the food industry due to their improved efficiency, lower energy consumption and higher extraction yields. These advanced techniques are particularly beneficial for maintaining the integrity of thermolabile compounds and promoting more sustainable small-scale production. The use of modern extraction technologies represents a pioneering approach in the development and formulation of new, safe and functional foods tailored to different consumer groups (*da Silva et al*., 2021).

For all these reasons, this article aims to emphasise the importance of using extracts of medicinal plants and essential oils, obtained with modern and environmentally friendly extraction technologies, as natural preservatives. Their use can significantly improve the quality, safety and shelf life of meat and meat products.

2. Plants as natural preservatives for meat products

The use of medicinal plants is closely linked to the global "clean label" movement, which reflects a growing consumer demand for products without synthetic preservatives and additives (*Beya et al*., 2021). This section introduces the various parts of medicinal plants, such as leaves, roots, seeds and bark of various species, that are used in specific concentrations to improve the quality and extend the shelf life of meat and meat-based products

Fruit-derived extracts

- lemon essential oil: applied at 1–4% in packaging films for fresh pork meat, it improved color, odour, and overall acceptance over 21 days at 4 °C (*Munekata et al*., 2023);
- pomegranate peel extract: used at 0.5–1% in films for fresh beef and 1–1.5% as powder in minced beef, it enhanced sensory attributes and reduced lipid oxidation (*Bellucci et al*., 2022);
- apple peel powder: incorporated at 3% in coating solutions for raw beef patties, it decreased lipid oxidation and *Salmonella* counts over 10 days at 4 °C (*Munekata et al*., 2023).

2.1 Seed and leaf extracts

- guarana seed extract: used at 250–500 mg/kg in raw lamb burgers, it improved color and reduced lipid and protein oxidation over 18 days at 2 °C (*Carvalho*, 2020);
- grape seed extract: employed at 100–600 mg/kg in beef sausages and 1000 mg/kg in pork liver pâté, it enhanced oxidative stability over extended storage periods (*El-Kholie et al*., 2014);
- broccoli leaf extract: applied at 0.1–0.5% w/w in ground beef patties, it significantly reduced lipid oxidation over 12 days at 4 °C (*Şimşek & Kılıç*, 2024);
- cranberry concentrate: used at 10% w/w in ground beef, it effectively suppressed various pathogens over seven days at both 21 °C and 7 °C (*Qiu & Wu*, 2007).

2.2 Herbal extracts and essential oils

- rosemary extract (E392): permitted at maximum levels ranging from 100 mg/kg in dried sausages to 5000 mg/kg in breakfast sausages and processed fishery products (*Plaskova & Mlcek*, 2023);
- cinnamon bark oil: included at 0.1–2% in natural preservative formulations for processed meats, it contributed to extended shelf life and microbial inhibition (*Hussain et al*., 2021);
- celery seed oil: used at 1–2% in combination with other essential oils for natural meat preservation, it enhanced antimicrobial properties (*Ghoname et al*., 2023).

To improve the oxidative stability, microbiological safety and overall quality of meat products, numerous plant-based additives were tested for their natural preservative potential. In addition to the plant species already studied, thyme (*Thymus vulgaris*), clove (*Syzygium aromaticum*), garlic (*Allium sativum*), green tea (*Camellia sinensis*) and sage (*Salvia officinalis*) have shown remarkable antioxidant and antimicrobial properties, making them promising candidates for extending the shelf life of fresh and minimally processed meat (*Shah et al*., 2014).

3. Extraction methods for plant-based meat preservatives

Ultrasound-assisted extraction (UAE) is based on the application of ultrasonic waves, typically in the frequency range of 20 kHz to 100 kHz, to a plant material–solvent mixture. The basic principle of UAE is acoustic cavitation, in which microscopic bubbles form, grow and collapse implosively in the solvent as the ultrasonic waves generate alternating high- and low-pressure cycles. This mechanical effect breaks up the cell walls, increases the penetration of the solvent and improves the mass transfer of target compounds from the material into the solvent. The ultrasonic energy breaks the cell walls and makes intracellular compounds more accessible. Cavitation enables deeper and faster penetration of the solvent into the plant matrix, and reduces extraction time and solvent consumption. The most important advantages are: preservation of thermolabile (heat sensitive) compounds, operation at relatively low temperatures, being environmentally friendly (often uses lower amounts or green solvents), scalable and adaptable for different matrices (*Singla & Sit*, 2021).

Microwave-assisted extraction (MAE) is based on the principle of dielectric heating, which occurs when polar molecules (e.g. water or polar solvents) align with an alternating electromagnetic field generated by microwaves (typically at 2.45 GHz). As these polar molecules are rapidly realigned by the alternating field, heat is generated by internal friction, resulting in rapid and uniform heating of the plant material-solvent mixture. Increased temperatures during the process improve the solubility and diffusion of the target compounds from the material into the solvent. Compared to conventional methods, MAE is faster, uses less solvent, is efficient for polar and moderately polar compounds, suitable for thermally stable bioactives and environmentally friendly when combined with green solvents (*Gonzaga et al*., 2025).

Supercritical fluid extraction (SFE) is a separation technique in which a supercritical fluid, i.e., a substance at a temperature and pressure above its critical point, is used to extract components from solid or liquid matrices. The most commonly used supercritical fluid is CO_2, due to its moderate critical conditions (critical temperature ~31.1 °C and pressure ~73.8 bar), its non-toxicity, its non-flammability and its easy removal from the final extract. The supercritical CO_2 acts as a selective solvent that dissolves specific bioactive compounds based on their solubility under controlled temperature and pressure. By changing the pressure and temperature, the dissolving power of CO_2 can be customised to specific desired compounds. Sometimes co-solvents (e. g. ethanol) are added to improve the extraction of polar substances. This extraction method, when based on solvent-free extracts (CO_2 evaporates without residue), works at low temperatures, is ideal for thermolabile compounds, is environmentally friendly and safe, with high selectivity and adjustable extraction parameters, and is suitable for applications in the food, pharmaceutical, cosmetic and food industries. Some of the limitations of SFE are the high initial cost, low effectiveness with very polar compounds unless modified with co-solvents, and precise control of temperature and pressure (*Sairam et al*., 2012).

Subcritical water extraction (SWE) — also known as hot water extraction under pressure — is an environmentally friendly extraction technique in which water is used at high temperatures (100 to 374 °C) and high pressure (to keep it in a liquid state) to extract bioactive compounds from various matrices. The dielectric constant of water decreases with increasing temperature, making it behave more like an organic solvent (e.g., ethanol or methanol). The viscosity and surface tension of the water are also reduced, which improves its ability to penetrate the plant material and dissolve both polar and moderately non-polar compounds. The advantages of this extraction process are: no toxic solvents (only water is used, making it environmentally friendly); efficient extraction of polar and semi-polar compounds; suitable for thermally stable compounds; potential for hydrolysis of glycosides, proteins and polysaccharides. Some of the limitations are: requires precise control of temperature and pressure; not ideal for thermolabile compounds that degrade at high temperatures; can cause undesirable chemical transformations if not properly optimised (*Nastić et al*., 2018).

Table 1. Extraction techniques of plant bioactive for improving meat product quality

Extraction method	Secondary metabolites	Application in meat products
Ultrasound-Assisted (UAE)	Polyphenols, flavonoids	Antioxidant/antimicrobial marinades, coatings
Microwave-Assisted (MAE)	Heat-sensitive compounds	Lipid oxidation prevention
Supercritical (SFE)	Essential oils, terpenes	Clean-label antimicrobial agents
Accelerated Solvent (ASE)	Phenolic-rich extracts	Processed meat shelf-life extension
Subcritical Water (SWE)	Polar compounds (e.g., tannins)	Green technology for antioxidant delivery

Accelerated solvent extraction (ASE) — also known as pressurised liquid extraction (PLE) — is a modern technique that increases the efficiency of solid–liquid extraction by accelerating the extraction process using conventional solvents (e.g., ethanol, methanol, hexane) with high temperatures (typically 50–200 °C) and high pressure (10–20 MPa or 1500–3000 psi). The high pressure keeps the solvent in a liquid state even above its boiling point, allowing it to better penetrate the plant material and dissolve the target compounds. The main mechanisms of this extraction process are elevated temperature, high pressure and a closed system that minimises solvent loss and environmental impact. The advantages of ASE are: faster extraction than conventional methods (e.g., Soxhlet); low solvent consumption; good recovery of thermally stable compounds; automatable and reproducible; suitable for high throughput laboratories; compatible with a wide range of sample types and solvents. Some of the limitations of ASE extraction are: not ideal for thermolabile compounds unless temperature is carefully optimised; initial equipment costs are relatively high; solvent must be removed after extraction (*Priego-Capote & Delgado de la Torre*, 2013).

Table 1. provides an overview of modern extraction techniques, the phytonutrients extracted through their application to plant species and their roles in meat products.

4. Conclusion

The integration of plant phytonutrients into meat products is a promising strategy to improve food quality, safety and functionality in response to growing consumer demand for environmentally friendly and natural products. Modern extraction techniques, including UAE, MAE, SFE, ASE and SWE, offer significant advantages in the efficient and sustainable isolation of bioactive compounds while preserving their antioxidant, antimicrobial and health-promoting properties. Bioactive compounds from medicinal plants, especially from extracts and essential oils, not only extend the shelf life and prevent spoilage of meat products, but also contribute to the development of functional foods with added value and potential health benefits. In addition, the use of environmentally friendly extraction technologies and unused plant resources supports sustainable food production and is in line with the principles of the circular economy. To fully exploit the potential of phytonutrients in the meat industry, continuous interdisciplinary research and innovation in plant extraction and formulation is essential.

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