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Review paper

Agricultural waste: a source of bioactive compounds for potential application in meat products

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ABSTRACT

Globalization and population growth have led to the development of a modern agricultural system that currently produces millions of tons of waste. This waste is disposed of by burning, dumping or accumulating in landfills, resulting in environmental, health, and economic issues. The agro-industrial residues are abundant with phenolic bioactive compounds, such as phenolic acids, flavonoids, tannins, and carotenoids, which, among others, exhibit antioxidant and antimicrobial capacities and have good potential as food flavorings and colorants. The most common method for isolating these compounds is solvent extraction. However, there is a trend towards eco-innovative extraction methods that offer better possibilities for implementation on an industrial scale. The oxidation of lipids and proteins is one of the main causes of quality deterioration in meat and meat products during processing and storage. Therefore, the application of natural antioxidants extracted from these new, unconventional raw materials could be a sustainable alternative to synthetic antioxidants. This review summarizes the data on natural antioxidants derived from agro-industrial by-products and their incorporation in various meat product formulations. It also addresses limiting factors related to safety and changes in sensory properties.

1. Introduction

Approximately 1,300 million tons of waste from the agricultural sector are produced worldwide annually, with a tendency to increase due to the demand for greater production as a result of economic growth and rising living standards (*Amran et al*., 2021). Failure to ensure proper disposal procedures or treatment for up to 50% of this waste represents one of the main causes of environmental pollution with a harmful effect on human and animal health and the economy (*Amran et al*., 2021). In Serbia, data regarding the quantity of agro-industrial waste from processed crops, fruits and vegetables are very scarce. According to Serbian government data, the total amount of waste in 2021 was 72,183 kt, to which agriculture contributed 0.8% and the processing industry 2.1%, while household waste makes up 82.4%, with the estimation that only 5% of the total produced waste is recycled (*Anon*, 2023).

Considering that most agricultural waste is untreated and underutilized, mainly disposed of by burning, dumping, or unplanned landfilling, the strategies and technology for conversion of agricultural wastes into valuable by-products are constantly devel-

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oping for the purpose of ensuring economically sound, sustainable, cleaner, and socially beneficial production (*Santana-Méridas et al.*, 2012). Agricultural waste can be converted directly, through different physical, chemical, and biochemical processes, or separated into components to produce fuels, energy, fiber-based products, and chemical-based high-value products (*Spatafora & Tringali*, 2012; *Sadh et al.,* 2018). The potential of crop residues for phytochemical extraction has not yet been fully explored (*Sadh et al*., 2018), but conversely, there has been a growing interest in agro-industrial residues as low-value raw materials abundant with different bioactive compounds having antioxidant and antimicrobial properties (*Amran et al*., 2021).

2. Agro-industrial waste as a source of natural antioxidants

Industrial by-products generated in the form of peels, cores, seeds, leaves, etc., account for more than 50% of the raw material that is generally discarded by the food industry. *Diamanti et al*. (2017) indicated that for every ton of pomegranate juice produced, nine tones of by-products are obtained. However, in most cases, these non-edible parts contain high nutritional properties and are excellent sources of dietary fiber, carbohydrates, proteins, flavorings, colorants, minerals, and especially phenolic compounds (*Coman et al*., 2020). For example, jabuticaba (*Myrciaria cauliflora*) residues from jelly and liquor-processing industries are an excellent source of natural pigments with antioxidant properties (anthocyanins and flavonoids) (*Baldin et al*., 2016). The processing of grapes for wine production generates up to 30% waste, including pomace, peels, and seeds, which are considered a source of flavonoids and phenolic acids (*Carpes et al*., 2020). Other good sources of functional compounds are apple pomace and olive pomace (*Lourenço et al.*, 2019). The phenolic compound content in peels of lemons, oranges and grapefruits is 15% higher than the peeled fruits. The total phenolic content in pineapple by-products is higher than in fresh pulp (*da Silva et al.*, 2013). A higher concentration of lycopene, ascorbic acid, and phenolic compounds is also found in tomato peels compared to pulp (*George et al.*, 2004).

3. Extraction technologies

The quality of plant-originated antioxidants depends on the features of the raw materials and the technology used for their extraction. There is no standard procedure for the extraction, because these compounds have various physical and chemical properties and are constrained in different vegetal matrices (*Lourenço et al*., 2019). The most common method used is solvent extraction, which comprises different solvents, separately or in mixtures, including ethanol, acetone, methanol, hexane, petroleum ether, ethyl ether, ethyl acetate, and water (*Lai et al*., 2017). From the aforementioned solvents, only water, ethanol, ethyl acetate and acetone have GRAS (generally recognized as safe) status for use in the preparation of food ingredients (*Marriott*, 2010). This conventional method has several disadvantages, such as the use of a large amount of solvent, the use of toxic solvents (hexane and chloroform), evaporation, compound thermal degradation, and the long extraction process (*Azmir et al*., 2013). In this regard, great efforts have been made to develop eco-innovative technologies in the extraction process, so-called "green extraction methods", to replace potentially harmful organic solvents with non-toxic or food-safe ones (water, aqueous ethanol solutions, carbon dioxide, natural deep eutectic solvents), to speed up the extraction process and make it more efficient, reduce the size of the equipment, and reduce the harmful impact on the environment (*Pateiro et al*., 2021). Some of these technologies are accelerated solvent extraction, enzyme-assisted extraction, supercritical fluid extraction, high hydrostatic pressure extraction, pressurized liquid extraction, infrared-assisted extraction, pulsed electric field extraction, ultrasound-assisted extraction, and microwave-assisted extraction (*Lourenço et al.*, 2019). The current technologies were developed only at a laboratory scale, so recent research is dedicated to the possibilities of their implementation at the plant level in order to establish commercial sustainability. Promising results in scaling up extraction processes were obtained with solvent extraction, solvent-free microwave extraction, and supercritical fluid extraction (*Lourenço et al*., 2019).

4. The safety of natural antioxidants application

Many plant-derived compounds can act as antioxidants, but only a small percentage of them are safe for human consumption. The natural antioxidants must undergo a safety evaluation by the regulatory bodies including the European Food Safety Authority (EFSA) and the United States Food and Drug Administration (FDA) in order to be approved as food additives. This procedure implies a multi-step standard methodology: specification of the chemical structure and physicochemical properties, risk assessments overview, proposed uses, exposure assessment, and toxicological studies (*EFSA*, 2012).

Beyond safety issues, the selection of natural additives is equally conditioned by organoleptic characteristics (especially odor and flavor), bearing in mind that they can significantly change the sensory attributes of the product, which could be unacceptable for consumers (*Mansour and Khalil*, 2000). From the application point of view, natural antioxidants must meet requirements similar to other food additives. Accordingly, they have to be compatible with the food matrix, easy to use, effective in low concentrations (0.001%–0.01%), stable during processing and shelf-life, economical, and must not negatively affect color, odor, or taste (*Hadidi et al*., 2022). However, since natural antioxidants usually exhibit lower antioxidant activities compared to synthetic ones, this implies that they would have to be used in higher concentrations, so for these compounds, the GRAS safety criterion should be fulfilled even in much higher doses (*Lourenço et al.,* 2019).

An additional aggravating factor in the application of by-products is the extensive use of various herbicides, insecticides and fungicides in agriculture, which consequently accumulate in agricultural residues. Byproduct safety hazards are also associated with mycotoxins (oil seed cake, corn by-products), heavy metals (arsenic in rice bran) and bacterial contamination of agricultural crops (*Lai et al*., 2017). Accordingly, the characterization and separation of toxins from agro-industrial raw materials are necessary so that bioactive compounds obtained from these sources are safe for use in value-added products, both for human health and for the environment (*Fritsch et al*., 2017).

5. Natural antioxidants in meat products

Lipid and protein oxidation is a common deterioration process responsible for the generation of undesirable, potentially toxic, chemical compounds, such as aldehydes, ketones, and organic acids, and for inducing protein modification through changes in amino acid composition, protein polymerization, and loss of proteolytic activity (*Hadidi et al.*, 2022). The high concentration of unsaturated fatty acids, heme pigments, metal catalysts, and oxidizing agents makes meat and meat products prone to oxidation, and consequently discoloration, off-flavor/odor development, nutrient loss, and drip loss during storage (*Amoli et al.*, 2021). Furthermore, meat and meat products are highly susceptible to bacterial spoilage and contamination by pathogenic microorganisms. Therefore, different measures, including good manufacturing and good hygienic practices, salting, heat treatments, drying, smoking, fermentation, use of additives, active packaging, and low temperatures during storage are implemented to prolong shelf life and preserve the safety and quality of meat products (*Gonçalves et al*., 2021).

The use of preservatives during the processing of meat products plays an important role in maintaining the products' overall quality. Due to their availability, high stability, good performance, and low-cost, synthetic antioxidants, like butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), propyl gallate (PG), and tert-butyl hydroquinone (TBHQ) are widely used to mitigate oxidation (*Lourenço et al*., 2019). In the European Union, the list of approved additives, the conditions of their use, and labelling are prescribed by the Regulation on Food Additives No 1333/2008 (*Regulation EC*, 2008). The use of synthetic additives in meat products in Serbia is regulated by the Rulebook on Food Additives No. 53/2018-22 (*Anon*, 2018). However, controversy has arisen in recent years regarding the use of synthetic additives in food, due to research that has shown the potential carcinogenic effects of these substances and the formation of toxic and mutagenic compounds during exposure to certain conditions, such as high temperature, which is a common procedure in the manufacture of meat products (e.g., nitrosamines generation from sodium nitrite) (*Gonçalves et al*., 2021). As a consequence, increasing consumer demand for fresh, natural, and healthier food rich in natural and biologically active compounds with additional health benefits, so-called "wellness foods" became a global trend embraced worldwide in industries, including the meat industry (*Pateiro et al.*, 2021). The use of natural antioxidants in order to reduce the consumption of synthetic additives and to obtain cleaner-label meat products could be considered as one of the promising alternatives (*Gonçalves et al.*, 2021, *Pateiro et al*., 2021).

However, the addition of natural antioxidants, rich in phenolic compounds, in the meat matrix results in unpleasant taste and aroma, notably a perceived astringency. Encapsulation technologies, such as micro- and nanoencapsulation, developed to overcome deteriorated sensory attributes of the product, offer enhanced stability against light and

Table 1. Natural antioxidants derived from agro-industrial waste incorporated in the formulation of meat products

Byproducts	Meat product Extract dose Storage	Application and Bioactive Compounds	Main Outcomes	Reference
Microencapsulated jabuticaba residue peels and seeds, water extract	- Fresh sausage - 2% and 4% - 15 days	- Natural dyes; antioxidant and antimicrobial - Phenolic compounds, mainly anthocyanins	↓TBARS (<0.1 mg MDA/kg) ↓Aerobic psychrotrophic count - Negatively influenced sensory color	*Baldin et al.*, 2016
Lyophilized and microencapsulated grape pomace, ethanolic extracts	- Chicken pâté - 3 mg/g - 42 days	- Natural antioxidant - Gallic acid, trans-resveratrol, ferulic acid, coumaric acid, vanillic acid, caffeic acid	↓TBARS (≤2.5 mg MDA/kg)	*Carpes et al.*, 2020
Rice bran extract	- Pork burgers - 0.5%, 1%, 2% - 21 days	- Natural antioxidant - Phenolic compounds and γ-oryzanol	↓Protein oxidation ↑b* value; ↑C* ↑Unpleasant taste	*Martillanes et al.*, 2020
Pomegranate peel water, acetone extract	- Uncured dry sausages - 1% and 2% - 28 days drying period	- Sodium nitrite substitute; natural antioxidant - Phenolic compounds, tannins, flavonoids	↓TBARS w(1.1-1.4 mg MDA/kg) ↓Carbonyls (10.5–14 nmol/mg protein) ↓Thiols (12.9–23.2 nmol Cys eq/mg protein) ↓a* value; ↑ b* value	*Cava & Ladero*, 2023
Ground buckwheat husk	- Frankfurter-type sausages - 1%, 2% and 3% - 14 days	- Natural antioxidant - Phenolic compounds (vitexin, quercetin), amino acid, mineral, fiber	↑Amino acid, Mn, Ca, K, Mg ↑Hardness ↓L* value; ↓b* value ↓Sensory acceptability	*Salejda et al.*, 2022
Persimmon flour	- Liver pork pâté - 3% and 6%	- Natural antioxidant; colorant; nitrite-reducing agent - Carotenoids and phenolic acids	↓Residual nitrite levels ↓Emulsion stability ↓TBARS (<0.5 mg MDA/kg) ↓L* value; ↑ a* value ↑Sensory color intensity	*Lucas-González et al.*, 2019
Avocado varieties "Hass" and "Fuerte" peel, acetone/water extracts	- Porcine patties - 5% extract water solution -15 days	- Natural antioxidant - Catechins, procyanidins, hydroxycinnamic acids	↑% inhibitions against TBARS ↑% inhibitions against protein carbonyls	*Rodríguez--Carpena et al.*, 2011
Sunflower and maize stalk residue, ethanolic extracts	- Liver pork pâté - 1% - 90 days	- Natural antioxidant and antimicrobial - Flavonoids, flavonolignans	↓TVC; ↓LAB; ↓Psychrotrophic count ↓L* value; ↑ b* value ↓Sensory acceptability	*Glišić et al.,* 2023

temperature, controlled release, and increased bioavailability of active compounds during meat processing and storage (*dos Santos Silva et al.*, 2022).

Several papers have been published with the purpose of studying the incorporation of natural antioxidants extracted from different agro-industrial wastes into meat products, and some of them are presented in Table 1.

6. Conclusion

To replace synthetic antioxidants in the meat industry with active compounds from agro-industrial residues, efficient extraction methods and identification of active compounds are essential. Testing antioxidant activity *in vitro* and *in producto* while considering various processing conditions, including cooking, pressure, pH, ingredients, meat matrix, etc., is crucial. However, sensory properties and consumer acceptance may be affected by natural antioxidants. Nutritional and toxicological studies are necessary to ensure safety, and consumer perception should be considered for adopting these new additives in meat products.

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