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A CRITICAL REVIEW ON THE INFLUENCE OF BIOACTIVE COMPOUNDS ON MEAT AND THEIR EFFECT ON *Salmonella* CONTROL: PROMOTING FOOD SAFETY AND QUALITY

Antoneta-Elena SIMA[1], Alexandru-Ionut ȘTEFAN[1, 2], Elena-Narcisa POGURSCHI[1]

[1]University of Agronomic Sciences and Veterinary Medicine of Bucharest,
59 Marasti Blvd, District 1, Bucharest, Romania
[2]ICA Research & Development, 202 Splaiul Independentei, District 6, Bucharest, Romania

Corresponding author email: alexandruionut_stefan@yahoo.ro

Abstract

Meat, an essential component of the human diet, is susceptible to contamination by pathogens such as Salmonella, posing significant public health risks. In this context, bioactive compounds offer innovative solutions for enhancing food safety through their antimicrobial and antioxidant effects. This study explores the influence of bioactive compounds on meat, with a focus on preventing and controlling Salmonella contamination. Studies show that their application in surface treatments or active packaging materials inhibits the development of pathogenic bacteria, including Salmonella, thereby reducing contamination risks. In addition, plant extracts rich in polyphenols and flavonoids contribute to meat stabilization by preventing lipid and protein oxidation. Modern processing methods allow the incorporation of these bioactive substances into meat products through techniques such as marination, injection, or active packaging. This study highlights the importance of technological advancements and interdisciplinary collaboration for harnessing the potential of bioactive compounds for combating Salmonella and ensuring safe and high-quality food.

Key words*: bioactive compounds, contamination, essential oils, meat, Salmonella.*

INTRODUCTION

Food safety is a global priority with a direct impact on public health and the economy. The meat industry is one of the sectors most exposed to microbiological contamination, and issues related to meat safety can have serious consequences for consumer health, often leading to the recall of contaminated products. The greatest risks are associated with the presence of microbial pathogens, particularly bacteria. In recent years, several outbreaks of foodborne illnesses caused by pathogenic bacteria have drawn attention to meat safety and have become a major societal concern (Sofos, 2007).

Among the pathogens responsible for foodborne illnesses, *Salmonella* is one of the most important. As reported by the European Food Safety Authority (EFSA), this microorganism is a leading cause of salmonellosis, with more than 91,000 cases reported annually in Europe. *Salmonella* is commonly found in eggs and raw meat from pigs, turkeys, and chickens, and is transmitted to humans through contaminated food. The World Health Organization (WHO) confirms that *Salmonella* infections are among the most common causes of foodborne illness worldwide (WHO, 2022). Meat and meat products are important sources of high-quality protein, essential amino acids, B vitamins, and minerals. However, the chemical composition of meat makes it a perishable product, vulnerable to spoilage at all stages of processing, distribution, and storage. Microbiological contamination can be caused by both spoilage bacteria, such as *Acinetobacter*, *Brochothrix thermosphacta*, *Enterobacter*, *Lactobacillus sakei*, and *Pseudomonas*, as well as yeasts and molds, which generate unpleasant odors and flavors (Jayasena & Jo., 2013).

Furthermore, certain pathogenic bacteria, including *Aeromonas hydrophila, Campylobacter jejuni, Clostridium perfringens, Escherichia coli, Listeria monocytogenes,* and *Salmonella enterica*, pose a major risk to public health. In addition, *Bacillus cereus* and *Clostridium botulinum* are bacteria capable of forming spores resistant to common heat treatments. *Salmonella* contamination of food has become a global public health problem, a leading cause of foodborne diarrhea in both the EU and the USA, as well as the third leading cause of death associated with foodborne infections worldwide (Yang et al., 2015).

An important aspect of food safety is the implementation of effective strategies to prevent and control microbiological contamination. Traditional methods of pathogen reduction include heat treatments, the use of chemical preservatives, and controlled atmosphere packaging. However, these methods can affect the nutritional and sensory quality of meat products (Jayasena & Jo., 2013). For this reason, recent research has focused on the use of alternative solutions, such as the application of bioactive compounds with antimicrobial and antioxidant properties, offering a more sustainable approach to food safety.

MATERIALS AND METHODS

The data and information required to achieve the purpose of the paper were gathered through an assessment of the state of knowledge from the ScienceDirect, Google Scholar, PubMed, and Scopus databases. To gather relevant information, the following search terms were used: 'bioactive plant compounds', 'Salmonella contamination', 'meat preservation', 'essential oils', 'antimicrobial properties', 'Salmonella', 'meat', 'antimicrobial peptides', and 'food safety'. The included studies were published between 1999 and 2023, were available in English, and focused on evaluating the effects of bioactive compounds on *Salmonella* contamination in meat products. The selection was limited to articles published in peer-reviewed journals that described relevant experiments with bioactive compounds and provided clear evidence of their efficacy. Data from the included studies were analyzed narratively, focusing on the main findings related to the prevention of *Salmonella* contamination, identifying trends based on the types of compounds used and their impact on food safety.

RESULTS AND DISCUSSIONS

Studies on bioactive plant compounds have shown that they can play a key role in improving the safety and quality of meat, with significant antimicrobial effects, particularly against *Salmonella* contamination. Essential oils from plants such as oregano, thyme, and rosemary have proven effective in preventing Salmonella biofilm formation on meat surfaces. For instance, the essential oils derived from *Origanum vulgare* (oregano) and *Rosmarinus officinalis* (rosemary) were successful in eliminating biofilms of *Salmonella enteritidis* from stainless steel surfaces, with their effects varying over time and employing a multi-target approach on the bacterial membrane (Lira et al., 2020).

In addition, active compounds such as carvacrol and thymol, present in the essential oils of oregano and thyme, have demonstrated inhibitory effects on *Salmonella* biofilm formation at sublethal concentrations, although they failed to completely eliminate *Salmonella* biofilms (Soni et al., 2013). However, the use of high concentrations of essential oils may negatively affect the sensory characteristics of meat products, influencing their acceptability to consumers (Pietrasik et al., 2013).

Antimicrobial peptides, such as nisin Z, have also shown efficacy against *Salmonella* and play an important role in stimulating host immunity. Studies have suggested that their mode of action is similar to that of natural human defense peptides (Kindrachuk et al., 2013).

Despite promising results, using bioactive compounds in the meat industry faces challenges, such as low solubility, low bioavailability, and limited thermal stability.

The Role of Bioactive Compounds in Food Protection

Plants have long been a rich source of bioactive compounds, used not only as folk medicines (Chandrasekara & Shahidi, 2017) but also as natural preservatives for food since ancient times (Prakash et al., 2017). Currently, interest in these compounds has increased significantly due to food safety concerns and the desire to reduce the use of synthetic preservatives. Herbs are intensively studied in scientific research and are widely incorporated into the chemical and pharmaceutical industries owing to their antioxidant benefits (Nunes et al., 2016; Zugravu et al., 2022), antibacterial (Parham et al., 2020; Trifunschi et al., 2022), and antifungal (Chojnacka et al., 2020; Di Sotto et al., 2020) properties.

In the food industry, the use of bioactive compounds as natural preservatives represents a promising alternative to traditional methods of preventing contamination. These compounds are effective in inhibiting the growth of pathogenic microorganisms and can also enhance the shelf life of food products, retaining their sensory characteristics (Ribeiro-Santos et al., 2017).

Plant-derived antimicrobials are the main category of natural preservatives, consisting of secondary metabolites that target microbial cells. Various parts of plants, including seeds, fruits, bark, leaves, and roots, contain these antimicrobials in abundance (McClements et al., 2021). Among the key bioactive compounds that play a protective role in food are phenolic compounds (such as simple phenols, phenolic acids, anthocyanins, flavonoids, and quinones), terpenes, catechins, alkaloids, saponins (such as dihydropyranones), and coumarins, which function as both antioxidants and antimicrobials (Bouvard et al., 2015; Velázquez et al., 2021).

There is considerable interest in essential oils, as they are natural substances and are classified as GRAS (Generally Recognized as Safe) food additives by the Food and Drug Administration (2016). In addition, they have received Qualified Presumption of Safety (QPS) status in both the USA and the EU (Saeed et al., 2019).

Due to their antimicrobial and antioxidant efficacy, polyphenols, terpenoids, alkaloids, and antimicrobial peptides are among the most studied classes of bioactive compounds. Polyphenols, found in plants, these substances are known for their effectiveness in reducing the growth of pathogenic bacteria, including *Salmonella* and *Listeria monocytogenes*, in meat products. Their functional mechanism involves disrupting the bacterial cell membrane and inhibiting the activity of enzymes essential for pathogen survival (Burt, 2004).

Antimicrobial peptides, such as nisin and pediocin, have widespread applications in the meat, dairy, and fermented beverage industries. They act by destabilizing the bacterial cell wall, leading to microbial cell death (Cotter et al., 2005). For example, nisin is approved as a food additive (E234) and is commonly used to extend the shelf life of cheeses and processed meats (Gharsallaoui et al., 2015).

An important challenge in the application of bioactive compounds is ensuring their efficacy in the food matrix. Factors such as solubility, bioavailability, and thermal stability can influence the antimicrobial effects of these substances. Therefore, current research is exploring innovative technologies, such as nanoemulsion encapsulation and antimicrobial active films, o optimize the stability and sustained release of bioactive compounds in food matrices (Ribeiro-Santos et al., 2017; Sharma et al., 2022).

The application of bioactive compounds in the meat industry is a viable strategy for enhancing food safety. The results demonstrate that these compounds have a significant antimicrobial effect on *Salmonella* spp., thereby helping to reduce the risk of contamination. Furthermore, certain bioactive compounds have been shown not only to inhibit bacterial growth but also to help maintain the sensory and nutritional characteristics of meat.

Bioactive Compounds and Their Effects on Meat

Bioactive compounds are natural or synthetic substances that, when taken in optimal doses, they contribute to human health by affecting specific biological pathway. These compounds can be found in various food sources (Yehmed et al., 2023) and feature a broad spectrum of biologically active compounds (Munekata et al., 2020).

Natural and Synthetic Sources of Bioactive Compounds

Within the food industry, bioactive compounds fall into two categories: natural and synthetic. Although synthetic variants are the most widely utilized and have regulated safe consumption limits, concerns over their possible harmful effects, including carcinogenicity (Georgantelis et al., 2007), have raised doubts about their safety. Consequently, the demand for natural alternatives has surged (Georgantelis et al., 2007). As a result, the search for natural compounds has increased (Bauer et al., 2001; Souza et al., 2006).

The natural sources of bioactive compounds in meat are diverse and include proteins, lipids, and minerals that are important for human health. Bioactive compounds are a heterogeneous group of substances with varying chemical characteristics, primarily found in plants and plant-derived matrices (Oswell et al., 2018). As widely reported in the scientific literature, antioxidants are utilized to prevent oxidation by interrupting the early stages or propagation of oxidation chain reactions (Gómez et al., 2019). Notably, several studies indicate that plant extracts can positively impact consumer health, may have a stronger antioxidant capacity than synthetic antioxidants (Zhang et al., 2018; Jayawardana et al., 2019). As a result, the activity of natural antioxidants offers protection to biologically significant cellular components against oxidative damage caused by reactive oxygen species (ROS) (Lin et al., 2020). Yet, in the meat industry, the utilization of bioactive compounds has been restricted by challenges such as poor bioavailability, rapid release, low solubility, and vulnerability to environmental stress. Process-related conditions, such as pH, temperature, oxygen and light exposure, and storage time, can also affect their efficacy (Aguiar et al., 2016).

Synthetic sources of bioactive compounds include food additives and supplements that can be used to improve the nutritional profile of meat. For example, butylated hydroxytoluene (BHT), propyl gallate (PG), butylated hydroxyanisole (BHA), and tert-butyl hydroquinone (TBHQ) are some of the most commonly used synthetic antioxidants (Takemoto et al., 2009). Scientific studies have revealed the toxicity of BHT, BHA, and TBHQ (Cruces-Blanco et al., 1999).

Based on scientific research, the acceptable daily intake of synthetic antioxidants has been adjusted. Given the potential risks associated with synthetic antioxidants, there has been a shift toward replacing them with natural antioxidants or blends of natural compounds, thereby lowering the consumption of synthetic antioxidants (Coneglian et al., 2011; Soares, 2002).

In addition to influencing meat quality, the use of bioactive compounds can play a important role in increasing the competitiveness of local producers and integrating them into the agri-food chain by promoting quality schemes and enhancing the added value of agricultural products. Thus, the development and certification of quality products contribute to the promotion of an organized food chain, support local heritage, stimulate rural tourism, and help develop competitive local brands. Studies conducted in Romania have highlighted an uneven distribution of certified products across regions, which indicates a significant potential for expanding certification and adapting the supply to meet consumer demands (Maloș & Maloș, 2016).

Influence of Bioactive Compounds on *Salmonella* Contamination

Salmonella infections are among the most common foodborne diseases worldwide. According to the WHO, *Salmonella* is responsible for millions of gastroenteritis cases annually, with many of these linked to eating contaminated meat (WHO, 2023). In the meat industry, sources of contamination include intensive handling, insufficient sanitation processes, and cross-contamination during meat processing (Fernandes et al., 2017).

From an economic perspective, *Salmonella* outbreaks result in significant losses (Kim et al., 2024). In particular, poultry and minced meat are considered the most vulnerable to contamination risks (Gonçalves-Tenório et al., 2018). Gram-negative bacteria tend to be less responsive to antimicrobial agents than Gram-positive bacteria. Several components of essential oils have been identified as effective antibacterial agents, including carvacrol, thymol, eugenol, perylaldehyde, cinnamaldehyde, and cinnamic acid, with minimum inhibitory concentrations (MICs) ranging from 0.05-5 $\mu l\ ml^{-1}$ *in vitro* (Burt, 2004). Herbs and spices, despite their potential as food preservatives, are still generally accepted as safe according to Burt (2004). The antimicrobial effects of essential oils have been investigated in fresh meat, although limited studies focus on their application in dried meat products (Martín-Sánchez et al., 2011). Different essential oils exhibit varying inhibitory effects (García et al., 2011), so *in vitro* testing is essential before their use in food (Gutierrez et al., 2009). Sensory properties are important for consumer acceptance, and the organoleptic effects of essential oils must be carefully managed, as high concentrations needed for antimicrobial efficacy may result in the rejection of the product due to unpleasant odors and tastes (Pietrasik et al., 2013).

Terpenoids found in essential oils, including thymol, carvacrol, eugenol, and menthol, are recognized for their strong antimicrobial activity against a variety of microorganisms (Husain et al., 2015; Kalemba & Kumato, 2003). Several research studies have proven the efficacy of various essential oils and their individual components in inhibiting *Salmonella* biofilms. In particular, sublethal levels of thyme oil, oregano oil, and carvacrol (at concentrations of 0.006-0.012%) inhibited *Salmonella* biofilm formation by 2 to 4 times, but they could not fully eradicate the biofilm (Soni et al., 2013).

Essential oils from *Origanum vulgare* (0.25%) and *Rosmarinus officinalis* (4%) successfully eradicated both young and mature biofilms of *Salmonella enteritidis* on stainless steel surfaces. These oils showed a time-dependent effect and employed a multi-target approach on the bacterial cell membrane (Lira et al., 2020). The essential oils of *Satureja montana* and *Thymus vulgaris* demonstrated strong antibiofilm, anti-adhesive, and bactericidal effects against *Salmonella typhimurium* and 12 *Salmonella* strains isolated from food (Miladi et al., 2016). Čabarkapa et al. (2019) examined the antimicrobial and antibiofilm properties of essential oils from *Origanum heracleoticum*, *O. vulgare, T. vulgaris,* and *T. serpyllum* against *S. enteritidis*. Their research indicated that these oils, along with their principal components (carvacrol and thymol), were effective in preventing biofilm formation at sub-MIC concentrations and eliminating 48-hour preformed biofilms in a dose-dependent manner.

Additionally, cinnamaldehyde, the main component of cinnamon bark EO (55-76%), at 2000 ppm/kg, Reduced the initial biofilm populations (7-7.5 log CFU/cm²) formed by *Salmonella* isolates from a conventional pig farm environment by a 6 log CFU reduction (Keelara et al., 2016).

Moreover, nisin Z has proven effective in providing protection against both Gram-positive *S. aureus* and Gram-negative *Salmonella enterica* sv. The authors suggest that nisin Z modulates the host immune system by utilizing mechanisms similar to those of natural human host defense peptides, involving various signal transduction pathways and growth factor receptors (Kindrachuk et al., 2013).

The antibacterial effects of essential oils, tested using the disk diffusion assay (DDA), are outlined in Table 1. Essential oils from thyme, cinnamon, rosemary, cumin, garlic, bay, black pepper, lemon, parsley, and nutmeg formed inhibition zones larger than 10 mm. Conversely, oils from orange, basil, and tarragon showed inhibition zones of 10 mm or less and were therefore considered non-inhibitory (García-Díez et al., 2016).

Table 1. The inhibitory effect of essential oils on *Salmonella* spp.

Essential oil	Thyme	Bay	Black papper	Cinnamon	Cumin	Garlic	Lemon	Nutmeg	Parsley	Rosemary
Salmonella spp	29.1 ± 9.5	12.5 ± 1.4	NI	13.7 ± 1.0	NI	10.5 ± 1.6	NI	NI	NI	13.4 ± 3.8

The inhibition zones were calculated, including the disk diameter of 6 mm.
NI indicates non-inhibitory.
Data are shown as mean (mm) ± standard deviation.
The essential oils of basil, orange, and tarragon are excluded due to no inhibition being observed.

Current research is therefore focused on the development of advanced delivery technologies, such as nanoemulsions and antimicrobial active films, to increase the stability and manage the controlled release of these compounds within food products (Ribeiro-Santos et al., 2017; Sharma et al., 2022). The incorporation of bioactive compounds as antimicrobial agents represents a promising alternative for improving food safety and controlling *Salmonella* contamination in the meat industry.

CONCLUSIONS

In conclusion, the use of bioactive compounds from natural sources presents a promising solution to improve the safety and quality of meat, given their ability to control Salmonella contamination and prevent spoilage. Bioactive compounds, such as polyphenols, terpenoids, and antimicrobial peptides, have demonstrated significant effects against *Salmonella* by inhibiting bacterial growth and biofilm formation. Additionally, these compounds help preserve the sensory and nutritional characteristics of meat, protecting it from oxidation and rancidity.

Case studies and experimental results support the efficacy from essential oils and different plant extracts in combating *Salmonella*, positioning them as viable and natural alternatives to traditional preservation methods that may affect meat quality. However, to optimize the application of these compounds in the meat industry, further research on their bioavailability, stability, and interactions with food matrices is essential to ensure maximum efficiency without negatively affecting the organoleptic characteristics of the products.

Finally, bioactive compounds offer significant potential to enhance food safety and improve meat quality while reducing the risks of microbiological contamination, such as *Salmonella*. Their adoption in a sustainable and well-regulated manner could transform the food industry, providing consumers with safer and more natural products.

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