DOI: 10.26599/FSHW.2025.9250898

Contents lists available at SciOpen

Food Science and Human Wellness

journal homepage: https://www.sciopen.com/journal/2097-0765

China Food Publishing Co.

Research Progress on the Application of Clean Label in the Meat Products Industry

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ABSTRACT: The food industry is currently navigating significant challenges in developing clean-label food products that minimize synthetic additives while maintaining quality and safety. This review primarily outlines the research progress on the application of the “clean label” concept in meat production and processing. The “clean label” concept emphasizes natural, healthy, and transparent attributes, encompassing various aspects such as animal welfare, production and processing technologies, natural additive alternatives, and meat nutritive value. The article elaborates on how to achieve “clean label” meat production from these perspectives. In terms of animal farming, optimizing feeding management, adopting natural feed additives, and improving farming environments and slaughtering processes can enhance animal welfare and meat quality and safety. In meat product processing, novel non-thermal processing technologies such as high pressure and ultrasound can reduce nutrient loss and improve meat product quality. Natural plant extracts can replace chemical additives, offering multiple benefits and extending shelf life. In summary, by implementing the "clean label" concept in farming, processing, and additive selection, it is possible to meet consumer demand for natural and healthy meat products, enhancing the market value and competitiveness of meat products. However, further in-depth research is needed in optimizing farming models, applying new processing technologies, developing functional products, and establishing detection and traceability systems to develop systematic solutions and promote the widespread application of the “clean label” concept in the meat industry.

Keywords: Clean Label, Meat Processing, Animal Welfare, New Technologies, Additives, Nutrition

1. Introduction

Meat is an indispensable component of the human diet, playing a crucial role in providing high-quality protein, minerals, B vitamins, and other essential nutrients[1-3]. However, traditional meat processing often involves the use of numerous food additives, such as phosphates, nitrites, and preservatives. While these additives can improve the color, flavor, and shelf life of meat products, they have also raised consumer concerns regarding food safety[4, 5]. Additionally, issues such as the misuse of antibiotics in animal farming and the illegal addition of drugs have further tarnished the safety image of meat products[6, 7]. With the increasing awareness regarding health issues among consumers, the development of meat products with low

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Received 3 July 2025
Received in revised from 21 August 2025
Accepted 28 September 2025

levels of salt, phosphorus, fat, nitrite/nitrate, additives and antibiotics has become a hot and key issue in the meat industry[8-11]. In recent years, the new consumer demand for “clean label” products have gradually emerged. How to achieve the processing of meat products with reduced levels of synthetic additives while meeting the “clean label” concept is a new challenge faced by the meat industry. Therefore, the application of the clean label concept in the field of meat production and processing is particularly urgent and important.

The term "clean label" first emerged in the 1980s, referring to minimally processed ingredients, easily understandable ingredient lists, and the reduced use of additives, vitamins, minerals, and other substances corresponding to E numbers[12]. Although there is no unified legal definition, relevant guidelines have been established in various regions. In the European Union, clean labeling emphasizes minimal processing, avoidance of E number additives, and the use of natural ingredients[13]. The U.S. FDA requires accurate ingredient labeling[14]. The clean labeling standards in China focus on reducing additives and using natural, recognizable ingredients[11]. Within the meat industry, this term carries a broader connotation. Firstly, clean raw materials involve improved animal welfare and high quality feed, clean water, and adequate environmental conditions. It is essential to minimize stress-induced hormone production during slaughtering, which can adversely affect blood properties and meat quality. Secondly, during the meat processing stage, non-thermal new technologies such as high pressure, ultrasound, and pulsed electric fields can be employed to reduce chemical additives while preserving natural nutrients and flavor. Thirdly, unnecessary additives should be minimized or avoided to maintain a clean label. Fourthly, the focus is on nutritional aspects, including the absence of trans fats, reduced salt, and lower fat content, gradually meeting consumer demand for natural, simple, and healthy choices. Research indicates that clean label meat products typically enjoy higher sales prices and profit margins, with 60 % of consumers willing to pay a 10–20 % premium[15]. Meat products with strong clean label branding are more likely to gain consumer preference and trust, thereby securing a competitive advantage in the market. Moreover, its production practice can achieve commercial value and ecological benefits simultaneously by optimizing breeding and reducing the use of additives (Figure 1). Therefore, for meat enterprises, vigorously developing clean label products is a strategic choice that aligns with consumer trends and enhances market competitiveness.

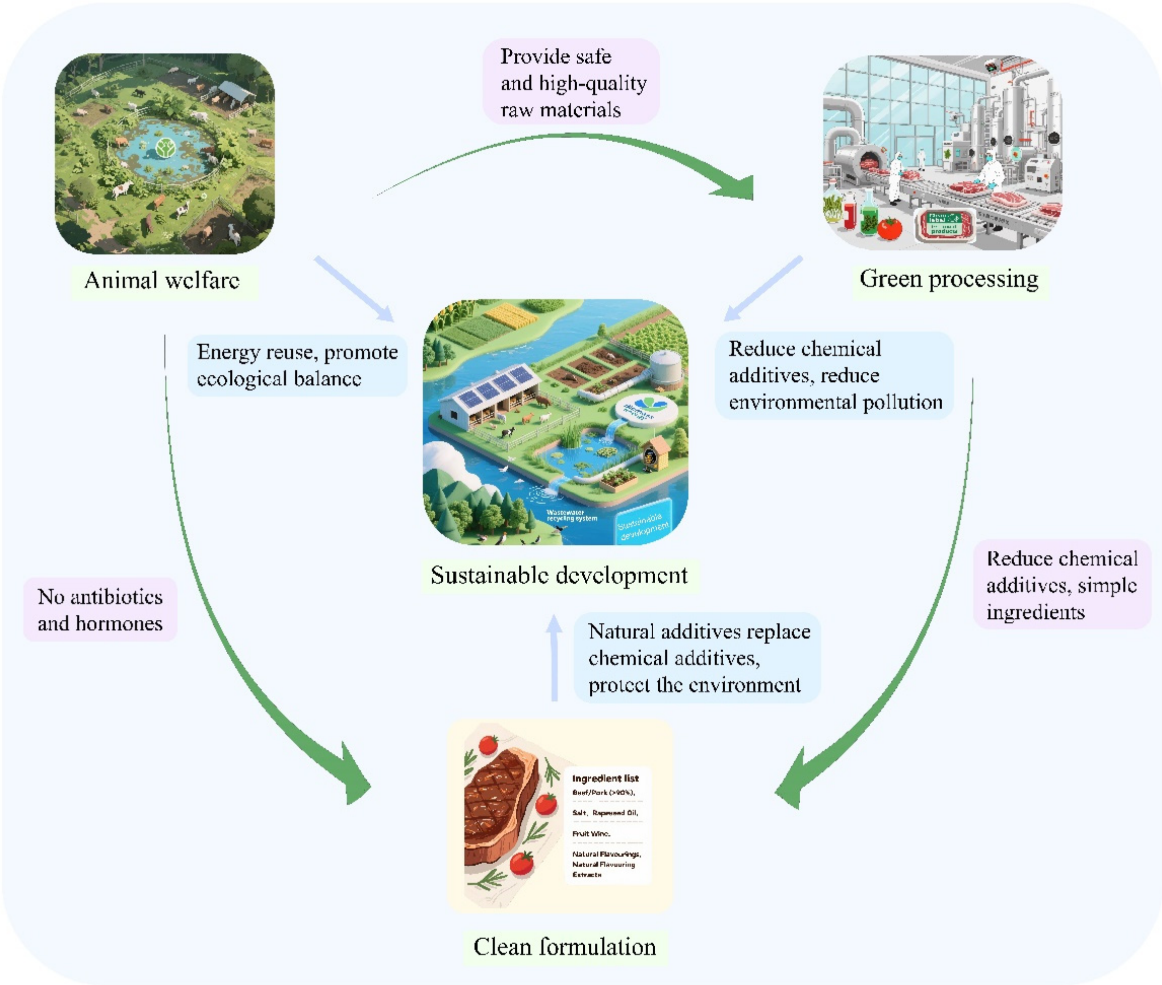

Figure 1. Through a commitment to animal welfare, clean formulation, and green technology, clean labeling is transforming food manufacturing towards a more sustainable future.

With the rapid growth in demand for clean label meat products, related research has also deepened. This review summarizes the application and research progress of clean label in meat production and processing, covering pre-slaughter animal husbandry (through optimizing the breeding environment, controlling stress responses, and developing antibiotic alternatives to significantly enhance animal welfare and meat quality), mid-processing technologies (the application of novel physical technologies such as high-pressure processing and pulsed electric fields to effectively maintain the nutritional value and sensory characteristics of meat products), and natural alternatives to additives (plant extracts, natural antioxidants, and other natural additives gradually replacing chemical additives and demonstrating important roles in preservation and color protection) (Figure 2).

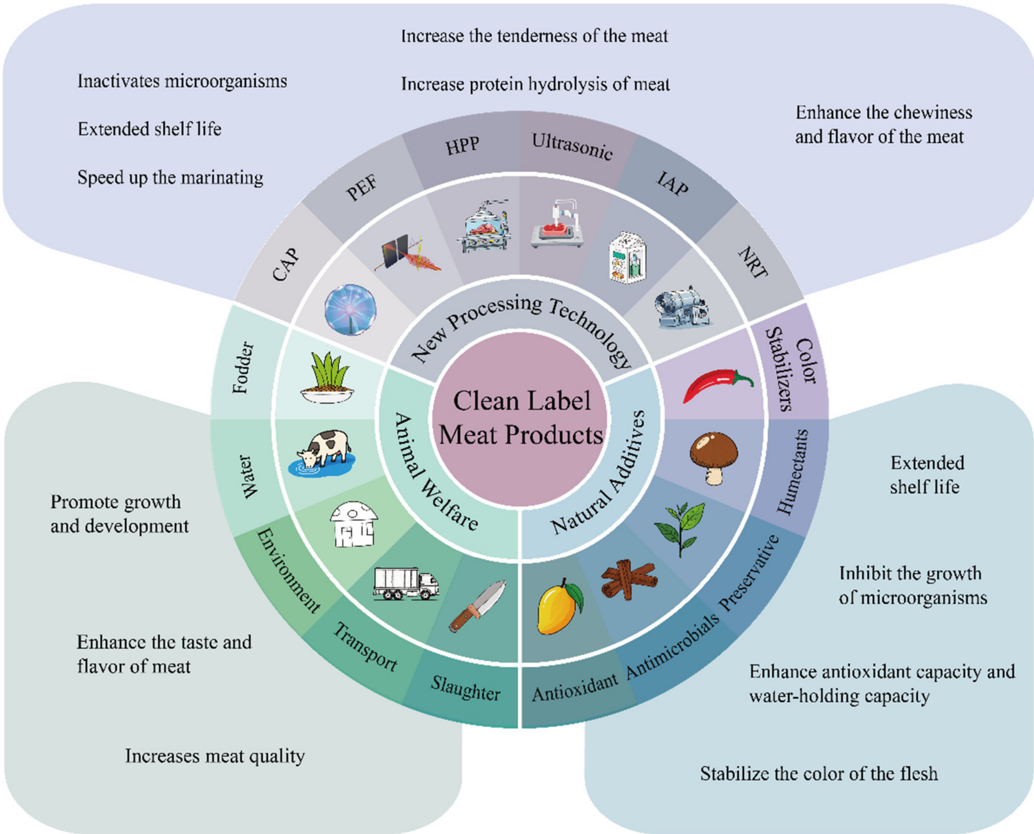

Figure 2. The application of clean label in animal welfare, new processing technologies, and natural additives. CAP: Cold Atmospheric Plasma Technology; PEF: Pulsed Electric Field Technology; HPP: High-Pressure Processing Technology; IAP: Intelligent Active Packaging Technology; NRT: New Tumbling Technology.

2. The clean label aspects involved in animal farming to slaughter

The World Organisation for Animal Health has provided the latest definition of "animal welfare": animal welfare refers to the physical and mental state of an animal in relation to the conditions in which it lives and dies[16]. In short, it means that animals are able to express their natural behaviors in a healthy, comfortable, well-nourished, and safe environment without experiencing suffering, fear, or distress[17]. The implementation of animal welfare standards is crucial for ensuring the production of clean label meat products. Clean label meat products emphasize the attributes of being natural, healthy, and transparent. Good animal welfare is not only a matter of ethical treatment of animals but also directly impacts the quality of meat and consumer health. Improving animal welfare can enhance livestock productivity and product quality, ensure the supply of high-quality food, and improve human well-being[18].

The key factors influencing animal welfare and meat quality include feed, water, temperature, lighting, stocking density, and other husbandry conditions, as well as the transportation and slaughtering processes[19]. High-quality feed and adequate water supply promote animal growth and improve meat quality[20], while natural additives can replace antibiotics to reduce the risk of antibiotic resistance[21]. A good husbandry environment can reduce stress responses and enhance meat quality[22]. Stress during transportation and slaughtering can significantly affect meat quality, and the use of humane slaughtering methods can alleviate animal suffering and improve meat quality characteristics[23]. Optimizing these aspects not only improves animal welfare but also enhances meat quality and safety, providing consumers with higher-quality products.

2.1 Animal feed and water

The feed and water provided to animals are critical components of animal welfare and directly impact the quality of meat products[24]. The nutritional composition of feed is essential for muscle development, as providing high-quality protein, moderate energy, balanced mineral elements, and vitamins helps promote animal growth and development, improving the texture and flavor of meat[25]. Water intake affects dry matter consumption, and water deficiency can lead to weight loss, reduced feed intake and impaired growth performance and welfare levels in animals. Water deficiency also results in drier post-slaughter meat, reduced tenderness, and darker color, thereby lowering meat quality and negatively affecting production and economic efficiency[26-28]. The use of veterinary drug additives such as antibiotics and hormones in animal feed and water can lead to residues of these substances in animal bodies[29], increasing the risk of antimicrobial resistance and ultimately diminishing the efficacy of antibiotics in treating human diseases[30]. Optimizing feed formulations and adopting natural, safe feed additives, such as plant extracts and probiotics, can improve feed utilization, eliminate harmful microorganisms, and promote animal growth, aligning with the clean label concept[31]. Probiotics not only play a crucial role in enhancing gut health, organism immunity, growth performance, and altering host metabolism of macromolecules and small molecules but also significantly contribute to improving meat quality[32]. Hossain[33] found that the addition of high doses of probiotics to feed significantly increased the body weight gain of broilers, laying hens, and ducks by 6.14%, 6.54%, and 32.33%, respectively. Hu et al.[34] added different concentrations of broccoli stem and leaf meal to broiler diets, which significantly improved the yellowness (b value) of the skin in leg and breast meat, increased carotenoid content in abdominal fat and breast meat, and reduced drip loss in breast meat by approximately 28.32%. Rajput et al.[35] added two types of carotenoids to broiler feed and found that lutein more effectively enhanced skin pigmentation efficiency in broilers, while curcumin significantly boosted immune responses. Hao et al.[36] incorporated sea buckthorn flavonoids at a level of 3.0 g/kg into the diet , which significantly increased the daily weight gain, digestive metabolism rate, and microbial protein production of finishing lambs. Luan et al.[37] added varying levels of vitamin E (VE) to the diet and discovered that VE significantly increased the average daily weight gain (15.9%), meat texture (18.3%), and intramuscular fat content (18.1%) of fattening bulls, while reducing drip loss (15.2%) and cooking loss (5.8%) and improving beef tenderness. These findings provide scientific evidence for using natural additives to improve meat quality.

2.2 Animal rearing environment and hygiene

The rearing methods of poultry and livestock can influence the physicochemical and sensory properties of meat, and these welfare issues also affect consumer acceptance of meat and consumer health[38]. Environmental parameters such as temperature, lighting[39], humidity[40], and ventilation[41] directly impact animal growth performance and meat quality. Inappropriate rearing temperatures and humidity can induce stress responses in animals, leading to reduced feed intake, increased weight gain, elevated fat deposition, decreased protein content, restricted muscle growth, and diminished meat quality[22, 42]. Heat stress in farm animals can result in various physiological consequences. For example, common diseases in cattle, camels, sheep, and pigs, such as acute hemorrhagic septicemia, are often triggered during heat stress, typically presenting with high fever and potentially leading to death within hours to days[43]. Heat stress not only causes physiological and metabolic disturbances in live animals but also affects carcass and meat characteristics by altering the rate and extent of postmortem muscle glycolysis and the resulting pH value[44]. Yang et al.[45] studied two different durations of heat stress suffered by WuZong geese at 35°C, including short-term treatment with heat stress of 4 hours before slaughter and long-term treatment with heat stress of 4 hours per day for 25 consecutive days, and found that short-term heat stress reduced muscle drip loss, decreased meat lightness (L value), increased pH, and enhanced redness (a value) and yellowness (b value), while long-term heat stress decreased the geese's body weight and increased the pH and yellowness of leg muscles.

Excessive stocking density can restrict the activity space of animals, deteriorate air quality, and lead to insufficient lighting, thereby affecting animal welfare and ultimately resulting in higher meat pH, darker meat color, and reduced tenderness. Additionally, high-density rearing worsens litter hygiene, increases animals' exposure to feces, and raises the risk of bacterial diseases, ultimately compromising meat safety[30]. Van der Eijk et al.[46] observed that broilers reared at lower stocking densities (24 or 30 kg/m²) exhibited higher levels of comfort, foraging, playfulness, running, and fighting behaviors compared to those at higher stocking densities (36 or 42 kg/m²), indicating better animal welfare under low-density conditions. Sevim et al.[47] reared broilers at low (12 birds/m²) and high (18 birds/m²) stocking densities and found that high stocking density reduced weight gain and feed intake, increased the incidence and severity of footpad dermatitis, and negatively impacted the growth performance and welfare of broilers. PASQUALE V et al.[48] compared commercial pigs housed at 0.46 m^2/pig (high density) versus 0.53 m^2/pig (low density) in winter mechanical-ventilated truck transport, the results showed that serum CK in the high-density group rose by 0.14 log U/L, while hematocrit decreased by 2.3%.

The hygiene of farming environments is closely related to pathogenic microbial contamination and serves as a critical safeguard for meat safety. Inadequate cleaning and disinfection of farms, along with incomplete removal of fecal waste, can lead to the proliferation of intestinal pathogens such as streptococci, staphylococci, pseudomonas, Escherichia coli, and Salmonella. These pathogens can spread through the fecal-oral route, causing diseases such as mastitis and gastroenteritis in animals, ultimately reducing meat quality and safety[49]. Environmental pathogens (e.g., Salmonella, Staphylococcus) can also contaminate carcasses through pre-slaughter pathways, leading to spoilage and deterioration of meat products[30]. Iannetti et al.[50] analyzed the relationship between animal welfare levels in 13 broiler flocks and the contamination of Campylobacter and Salmonella at slaughterhouses. The study found that low-welfare batches had Salmonella contamination rates of 43.6% and 19.3% in neck skin and cecal content, respectively, while high-welfare batches showed contamination rates of only 2.9% and 0%. These results indicate that improving farm animal welfare not only enhances the quality of life for animals but may also reduce microbial contamination in meat products, thereby enhancing their microbiological safety and providing additional protection for consumers.

2.3 Transport and Slaughter of Animals

During the transportation process from farms to slaughterhouses, animals may be subjected to adverse conditions during loading, transport and unloading, such as restraint, harsh weather, hunger, thirst and fatigue, which can compromise animal welfare and reduce meat quality[51] [52]. For instance, transportation can cause motion sickness and stress responses in animals, including increased vomiting and reduced rumination in ruminants[53]. Rough handling or fights not only cause fear and pain to animals but also lead to carcass bruising, abrasions, and hemorrhages. These injuries result in the accumulation of blood outside blood vessels, creating a potential medium for microbial growth, accelerating meat spoilage, and directly affecting meat quality. Trimming the affected parts also reduces meat yield and value, increases costs and processing time, and causes economic losses[18, 54, 55]. Stress responses in animals affect meat quality through changes in hormone levels. Physiological changes impact meat quality by depleting muscle glycogen, which reduces the rate of postmortem lactic acid synthesis, ultimately leading to higher pH, tougher meat, and affecting water-holding capacity, color, and tenderness[56]. Reducing stress and pain during transportation and slaughter can lower the pH and lactic acid levels in meat, thereby improving its flavor and texture[57]. Jacobs et al.[58] evaluated the welfare of broilers during 81 commercial transports and slaughter processes, finding that the pre-slaughter phase caused an average weight loss of 5.3%, with a 1.4% incidence of leg bruising and a 3.7% incidence of breast or wing bruising, the incidence of wing fractures during catching increased from 0.1% to 1.9%, feather soiling increased, and body temperature decreased by 0.7 °C. Bekuma et al.[52] investigated the effects of pre-slaughter handling and transportation on animal welfare and beef quality in the Dendi and Welmara regions of Ethiopia. The results showed that transport distance and methods significantly affected beef pH, with approximately 47% of the beef exhibiting dark, firm, and dry characteristics due to microbial proliferation.

During the slaughter process, it is essential to ensure that animal handling facilities are in good condition, allowing livestock to move smoothly and efficiently. Livestock handlers should be well-versed in the principles of animal handling. Animals should always be handled in a calm and quiet manner to prevent harm to both the livestock and the staff [56]. The adoption of humane slaughter methods, most common method of stunning for beef cattle, such as stunning animals with electricity before slaughtering and bleeding, can effectively reduce animal struggle and suffering, improve slaughter efficiency and meat quality, lower the incidence of quality defects like pale, soft, and exudative meat and blood-splashed meat, and enhance commercial value. Controlled atmosphere stunning, particularly with carbon dioxide (CO_2), is also increasingly adopted in practice. This method is valued for its capacity to mitigate pre-slaughter stress, which in turn leads to improved meat quality outcomes, including a reduced incidence of blood splash and enhanced color stability[59]. Govindaiah et al.[60] compared traditional slaughter methods (without stunning, NST) and commercial slaughter methods (electrical stunning, ST) for slow-growing broilers. The results showed that the ST group had lower post-slaughter pH and higher redness values, but no significant differences were observed in bleeding efficiency, sarcoplasmic reticulum fragmentation index, or water-holding capacity compared to the NST group. Both slaughter methods had no negative impact on meat quality, but ST slaughter improved animal welfare as much as possible. Jankowiak et al.[61] compared the effects of electrical stunning and gas stunning on the quality of pork from fattening pigs. The results indicated that electrical stunning led to higher drip loss and thermal drip loss, while gas stunning resulted in better meat color and texture. Both stunning methods had no significant impact on the chemical composition or tenderness of the meat, and neither method showed a significant difference in stress levels for the pigs, while both improved animal welfare.

On the basis of ensuring animal welfare in farming, further improvement in meat quality and safety also relies on innovative processing technologies that meet clean label requirements. These new technologies enable producers to reduce or even eliminate the use of artificial additives while maintaining high product standards, thereby better fulfilling the production requirements for clean-label meat products.

3. Clean Label in Meat Processing

3.1 New Technologies Related to Clean Label Meat Products

In summary, the animal welfare is crucial for the production of clean-label meat products. Once the meat enters the processing stage, a series of new technologies must be adopted to further align with the clean-label concept and reduce the use of additives. the application of these technologies enables processors to better meet clean label requirements. For instance, high-pressure and ultrasonic technologies can enhance processing efficiency and improve the palatability of meat products[62]; pulsed electric fields and vacuum tumbling techniques improve the texture and flavor of meat through physical methods, minimizing the need for chemical additives[63]. Cold plasma and smart packaging technologies ensure the safety and hygiene of meat, and reduce waste and pollution, thereby enhancing environmental sustainability[64, 65](as shown in Table 1). The pursuit of clean label foods by consumers has spurred the development of new technologies to produce clean label meat products.

Table 1. Research on the application of clean label new technology in meat products.

Processing technology	Process objects	Processing conditions	Main effects	References
Cold Atmospheric Plasma Technology	Pork meat	15 V, 50 kHz, for 6/9 min	Saturated fat decreased by approximately 7%, antioxidant capacity improved, levels of aldehydes, alcohols, and ketones increased, and sulfides were reduced after 6-9 minutes.	[162]
	Beef meat	40 W, 15 kHz, and 25 L/min ambient air, 30 min	Increased the redness of roasted beef overall, decreased lipid oxidation-derived off-flavors in beef and did not increase heterocyclic amine formation.	[163]

	Channa argus surimi gel	40 kV, 60, 90, 120 s, store at 4 ℃	The water-holding capacity of the CAP90 group was the highest, reaching 76.13 %, and its gel strength was also the highest, at 285.6 g·cm.	[164]
High-Pressure Processing Technology	Ready-to-eat clam meat	121 ℃, 0.14 MPa, 5/10/ 15/20 min	Gradually decreased with longer HTP time, chewiness initially decreased, then increased, enhanced production of esters and aldehydes, best umami and saltiness at 15 min.	[165]
	Latilactobacillus sakei	400-600 MPa, 180-480 s	The inactivation of the microorganism ranged from 0.99 to 4.12 UFC/g.	[90]
New Tumbling Technology	Chicken breast	Breathing (pressure change) tumbling combined with ultrasonication (40 kHz, 140 W)	Significantly enhanced marinating absorptivity, accelerated degradation of myosin light chain, significantly improved tenderness, remarkably better taste.	[166]
	Restructured pork chops	V 100 mbar, 2500 mbar with a gas mixture of CO_2: N_2 = 1:1, 8 min vacuum + 7 min pressure + 1 min rest, total 40 min	Significantly improving product yield and tenderness while optimizing myofiber structure and maintaining protein secondary structure integrity	[167]
	Chicken breast	Ultrasound treatment at 40 kHz and 300 W for 45 min, followed by vacuum tumbling at 1 kPa for 45 min	The shear force was reduced by 87.12 %, the cooking loss was decreased to 11.67 %, and the moisture content was increased to 71.65 %.	[168]
Intelligent Active Packaging Technology	Shrimp	Aronia melanocarpa anthocyanins as pH-sensitive indicator, tea polyphenol as anthocyanin stabilizer	Extended shrimp shelf life by 12 h, enabled real-time visual freshness monitoring.	[169]
	Shrimp, Pork	Packaged with CP-Cur150 film, shrimp stored at 25 ℃ for 5 days, pork stored at 4 ℃ for 7 days	PPH free radical scavenging rate of 87 % and an ABTS free radical scavenging rate of 98 %, *Staphylococcus aureus* and *E. coli* were reduced by 2.7 and 1.3 Log10 CFU/mL.	[170]
Ultrasound Technology	Cured sea bass	300 W ultrasound for 60 min	Significantly increased NaCl transfer rate, reduced hardness and chewiness, improved water retention.	[171]
	Beef (*E. coli* and harmless *listeria monocytogenes)*	US: 33 + 20 kHz, 1 h, stored at 4 ℃ and 10 ℃ for 60 days	25 % reduction in sodium and a major drop in microbial count.	[172]
	Chicken, breast meat	24.5 kHz, 300 W, 10 min	Cooking loss reduced by 28.78%, enhanced moisture retention, reduced hardness, chewiness, and gumminess.	[173]

3.1.1 Cold Atmospheric Plasma Technology

Plasma is a state of matter composed of a mixture of ionized gases, including electrons, positive and negative ions, free radicals, and excited molecules. Cold Atmospheric Plasma (CAP) treatment generates various reactive species (RS), such as hydrogen peroxide (H_2O_2), ozone (O_3), superoxide anions (O^{2-}), and hydroxyl radicals (OH•), collectively referred to as reactive oxygen species (ROS), as well as reactive nitrogen species (RNS), such as nitrogen dioxide (NO_2), nitrogen trioxide (NO_3), nitrous oxide (N_2O), dinitrogen trioxide (N_2O_3), or dinitrogen tetroxide (N_2O_4) [66, 67]. The antimicrobial effects of plasma are attributed to the presence of these RS, as ROS and RNS can effectively inactivate various microorganisms, including those responsible for spoilage and foodborne illnesses[68]. The ions and neutral particles in cold plasma are maintained at low temperatures, preventing thermal damage to the target material[69]. Therefore, cold plasma treatment can be used for bacterial decontamination in meat and meat products, effectively reducing microbial load and extending the shelf life of poultry, beef, pork, mutton, and other meats[66]. This non-thermal processing method offers a promising alternative to traditional thermal and chemical treatments, minimizing the risk of altering the physical and nutritional properties of food. González-González et al.[70] demonstrated that a 5-minute treatment with CAP significantly reduced Salmonella and Escherichia coli in ready-to-eat chicken by 1.4 to 1.8 log CFU/g. GöK V et al.[71] utilized CAP technology for periodic treatment of dry-cured beef and found that maximum reduction of 0.85 log CFU/cm^2 for *S. aureus* counts and 0.83 log CFU/cm^2 for *L. monocytogenes* counts.

RNS dissolved in liquid samples can react with water molecules to generate nitrites, providing a potential clean label alternative to synthetic food additives such as nitrites E 250 and E 249[67, 72]. Lee et al.[73] used CAP as a curing process for canned ham, demonstrating that a 60-minute CAP treatment increased the nitrite content in the meat batters from 0.64 mg/kg to 60.50 mg/kg. Compared to traditional curing methods using chemical nitrites or celery powder, ham treated with CAP for 30 minutes showed no significant differences in physicochemical properties such as pigment formation, color, residual nitrite levels, texture, lipid oxidation, and protein oxidation, indicating that CAP can serve as a green alternative to chemical nitrites. Chen et al.[74] applied CAP technology to roasted lamb, showing that CAP could inhibit lipid oxidation with an inhibition rate of up to 86.69% to 89.89%. Jo et al.[75] remotely injected CAP into cured ham powder and found that 100 mg/kg of nitrite could be generated in 3.2 kg of meat batter within 14.78 minutes. These results highlight the potential of plasma technology in meat preservation and enhanced curing, offering a viable alternative for more natural processing methods.

CAP technology offers new perspectives for the development of clean label meat products, promising high-quality processing with reduced preservatives to meet consumer demand for natural and healthy meat products. However, the application of CAP in meat processing still faces numerous challenges. Further research is needed to enhance sterilization efficacy, optimize and standardize processes, elucidate the mechanisms of reactive species, ensure equipment cleanliness and safety, and improve cost-effectiveness. Addressing these challenges will facilitate the industrialization of CAP technology and contribute to the advancement of the clean label meat product industry.

3.1.2 Pulsed Electric Field Technology

Pulsed Electric Field (PEF) is an emerging non-thermal food processing technology. By employing the principle of electroporation, it alters the microstructure of meat, enhancing the availability of water both inside and outside the cells, and softening the muscle texture. This results in increased tenderness and juiciness of the meat[76, 77], which helps to reduce the use of additives, particularly phosphates. The micro-pores generated by PEF treatment enhance water transfer during freezing, promoting faster and more uniform freezing and thawing of meat [76], and improving curing efficiency[78]. PEF has been shown to inhibit microbial growth and regulate enzyme activity[79]. Additionally, it can enhance meat proteolysis and myofibril breakdown, increasing protein digestibility and solubility[77, 80]. Bhat et al.[81] found that PEF treatment of beef can induce electroporation and increase cell permeability, affecting salt diffusion and sodium transport, thereby enhancing flavor while directly reducing the amount of salt (NaCl) used without adversely affecting the product's sensory quality, lipid oxidation, or microbial stability. Yao et al.[82] reported that both constant current pulsed electric field and constant voltage pulsed electric field thawing could reduce structural damage during pork thawing, maintaining relatively intact muscle fiber structures and ensuring good texture properties. Zhang et al.[83] applied PEF pretreatment technology to beef, significantly shortening the curing time by nearly 33%, while increasing the diffusion coefficients of NaCl and moisture. The tenderness of the beef improved by 22.9%, with no significant impact on color, drip loss, or cooking loss. Chian et al.[84] applied PEF treatments of varying intensities to beef longissimus thoracis muscles, showing that PEF did not alter the muscle's pH, color, or protein thermal profiles, but significantly reduced moisture content by 1.3% to 4.6% and increased in vitro protein digestibility by 8% to 31%.

3.1.3 High-Pressure Processing Technology

High-Pressure Processing (HPP), also known as high hydrostatic pressure, is an emerging technology that improves meat texture and enhances tenderness by applying pressures ranging from 100 to 1000 MPa. This technology can be combined with natural clean label ingredients, helping to reduce the use of additives such as salt, phosphates, nitrates, and nitrites in cured meat products while maximizing the retention of sensory and nutritional properties[85-87]. HPP can dissolve and extract myofibrillar proteins without the need for additives and induce myosin denaturation in myofibrils, forming heat-set gels with improved properties at both low and high salt concentrations. This enhances the binding properties of meat particles, offering advantages over traditional additives used to improve the binding performance of meat products[88]. Additionally, HPP effectively inactivates microorganisms in low-salt, low-phosphate, and low-water-activity meat products[89]. It affects microbial cell membranes, biochemical functions, and genetic mechanisms through protein denaturation, thereby disrupting cell stability and inactivating microorganisms, thus improving the safety of meat products[90, 91]. Chen et al.[92] investigated the inactivation effect of HPP on Salmonella in raw chicken breast. The data showed that after 450 MPa HPP treatment, Salmonella counts in the 3-hour and 5-hour PaExt pretreatment groups dropped below the detection limit, while the tenderness and color of the chicken were improved. MA F et al.[93] applied HPP to pork meat, the results showed that 300–400 MPa improved water-binding capacity, and 100 MPa could increase hardness and chewiness of the gels.

3.1.4 New Tumbling Technology

New tumbling technologies include vacuum tumbling, variable-pressure tumbling, ultrasound-assisted tumbling, and pulsed electric field synergistic tumbling[94, 95]. These technologies alter protein conformation through the application of mechanical force during meat processing, thereby enhancing the chewiness and flavor of meat[96]. They can disrupt muscle structure, weaken the mechanical strength of muscle fibers, and improve meat tenderness without the need for additional chemical tenderizers, while also promoting marinade penetration and further enhancing curing efficiency[97]. Additionally, new tumbling technologies facilitate protein solubilization and restructuring, improving the water-holding capacity of meat products and reducing reliance on chemical additives such as phosphates[98]. As a result, these technologies are widely used in the development of low-phosphate, clean-label healthy meat products[99]. Ge et al.[97] compared vacuum tumbling and immersion curing methods, finding that vacuum tumbling significantly improved the curing absorption rate, tenderness, and water-holding capacity of Xueshan chicken. At the same time, vacuum tumbling reduced total sulfhydryl content and increased protein surface hydrophobicity and free sulfhydryl content, indicating enhanced protein denaturation. Kim et al.[100] investigated the effects of tumbling time and temperature on protein solubility in soy sauce-marinated pork loin. The results showed that protein solubility increased with extended tumbling time, with total protein solubility increasing by 40% and salt-soluble protein solubility increasing by 60% after 5 hours of tumbling. Jiang et al.[101] applied ultrasound-assisted vacuum tumbling technology to spiced beef, significantly increasing the types and contents of alcohols, aldehydes, and ethers. This demonstrates that ultrasound-assisted vacuum tumbling can effectively enhance the flavor of spiced beef, offering significant practical value for improving the flavor quality of meat products.

New tumbling technologies can reduce phosphate addition while improving product tenderness and flavor[96], making a positive contribution to the development of low-phosphate, clean-label meat products. However, due to high production costs and complex equipment, implementing new tumbling and curing technologies poses challenges for production enterprises.

3.1.5 Intelligent Active Packaging Technology

In meat processing, active packaging aims to release or absorb active substances into packaged meat products[102]. This method extends shelf life or enhances the safety and quality of meat products by slowing down the maturation process or inhibiting microbial growth[103]. Intelligent packaging involves incorporating indicators into packaging materials that respond to changes in temperature, water activity, gas concentration, pH, and other factors, providing observable changes to convey real-time information about the freshness, quality, or safety of meat products[103, 104]. Intelligent active packaging materials can actively regulate the internal packaging environment through their physical, chemical, and biological properties, such as oxygen barrier properties, antimicrobial activity, and aroma release, thereby inhibiting microbial growth, slowing meat spoilage, and extending shelf life[105]. For example, some edible coating materials containing natural antimicrobial substances (e.g., tea polyphenols, curcumin, anthocyanins) can significantly inhibit the growth of pathogens such as Escherichia coli and Staphylococcus aureus in meat products[106-108]. Liu et al.[109] incorporated cinnamon oil Pickering emulsions and curcumin into a gelatin/chitosan film matrix, resulting in a film with long-lasting antimicrobial activity and antioxidant capacity. Even after 60 days of storage, the DPPH radical scavenging rate remained above 44%. Yana et al.[110] prepared a biodegradable colorimetric film using anthocyanins from purple tomatoes, chitosan, and polyvinyl alcohol as raw materials. They found that pork packaged with composite films containing higher chitosan content showed significantly reduced total viable count growth during storage, effectively extending the preservation period. Guo et al.[111]

successfully developed a novel pH-responsive antioxidant film containing beetroot extract (BTE). When meat begins to spoil, the BTE-rich film changes color from red to yellow, visually indicating changes in meat freshness. Lu et al.[112] developed a smartphone-assisted dual-color ratiometric fluorescent smart probe that, with increasing levels of spermine and histamine, observed enhanced green fluorescence from carbon dots and weakened blue fluorescence from Fe/Zr-MOF, enabling real-time monitoring and qualitative analysis of the freshness of agricultural products such as pork. These studies provide new solutions for meat processing enterprises to extend the shelf life of meat products, reduce preservatives, and detect meat freshness, aligning with the clean label concept of natural, healthy, and safe meat products.

3.1.6 Ultrasound Technology

Ultrasound technology in the meat industry significantly improves meat quality through cavitation, mechanical action, and thermal effects, including tenderizing the meat texture, enhancing water-holding capacity, improving color, and enhancing flavor[113]. It also enhances the rheological properties and structural quality of myofibrillar proteins, improves marination efficiency, and water retention ability, resulting in juicier and more palatable meat[113, 114]. Additionally, ultrasound treatment effectively reduces harmful microorganisms in meat while decreasing the need for salt and improving cooking results[115, 116]. During freezing, ultrasound promotes crystallization by controlling nucleation and crystal growth, increasing ice nucleation efficiency, accelerating freezing speed, producing finer ice crystals, and improving the texture and uniformity of frozen meat[117, 118]. In the development of clean-label, low-salt meat products, ultrasound technology can maintain the texture, flavor, and shelf life of meat products while reducing the use of salt and phosphates[119], meeting consumers' demands for healthy and natural foods. Roobab et al.[113] found that 300W/10-minute ultrasound treatment reduced the pH, cooking loss, and hardness of chicken breast, thereby improving tenderness, juiciness, and overall texture. A 500W/10-minutes ultrasound treatment significantly increased the content of essential amino acids, enhancing the savory and umami flavors of chicken breast. Tong et al.[120] used ultrasound-assisted phosphate curing (UPC) for chicken breast, showing that the UPC treatment group had a 31.99% increase in curing solution absorption, a 39.38% reduction in cooking loss, and a 51.08% reduction in centrifugal loss. The volatile flavor components also increased, indicating that ultrasound-assisted curing can partially restore flavor components reduced by phosphate treatment. Guo[121] applied ultrasound curing at different frequencies to pork and found that at 26.8 kHz, the tenderness of pork increased by 44%, cooking loss decreased from 27% in untreated samples to 22%, and the content of volatile flavor compounds in roasted pork was significantly higher than in statically marinated pork and fresh pork. Xu et al.[122] used multi-frequency ultrasound-assisted immersion freezing (MUIF) to treat Macrobrachium rosenbergii, finding that MUIF significantly increased freezing speed, reduced the average ice crystal diameter from 28 μm to 8 μm, effectively minimized protein oxidation and denaturation, and significantly enhanced the water-holding capacity of the meat.

In summary, emerging non-thermal processing technologies effectively improve the quality and safety of meat products through physical means, reducing reliance on external chemical additives[123]. However, in certain processing stages, completely avoiding the use of additives remains challenging. Therefore, in promoting the development of clean-label meat products, in addition to innovations in processing technologies, the development and use of natural, recognizable additive alternatives are also critical. The following section will provide a systematic review of natural components that can be used to replace traditional synthetic additives and their application progress in meat products.

3.2 Clean Label Alternatives to Common Additives in Meat Processing

In meat production and processing, additives are used to maintain or improve food quality and stability, as well as enhance sensory characteristics. Common food additives include antioxidants, antimicrobials, preservatives, color stabilizers, and humectants. However, consumers increasingly prefer simpler, more natural ingredients in their diet. Clean labeling allows consumers to clearly understand the ingredients and origins of the products they consume. As a result, replacing or reducing synthetic additives with substances derived from natural products is becoming a new trend in meat processing, making the clean labels of meat products increasingly transparent. Natural ingredients that can replace common meat processing additives, along with their specific applications are presented in Table 2.

Table 1. Research on the application of clean label new technology in meat products.

Processing technology	Process objects	Processing conditions	Main effects	References
Cold Atmospheric Plasma Technology	Pork meat	15 V, 50 kHz, for 6/9 min	Saturated fat decreased by approximately 7%, antioxidant capacity improved, levels of aldehydes, alcohols, and ketones increased, and sulfides were reduced after 6-9 minutes.	[162]
	Beef meat	40 W, 15 kHz, and 25 L/min ambient air, 30 min	Increased the redness of roasted beef overall, decreased lipid oxidation-derived off-flavors in beef and did not increase heterocyclic amine formation.	[163]
	Channa argus surimi gel	40 kV, 60, 90, 120 s, store at 4 °C	The water-holding capacity of the CAP90 group was the highest, reaching 76.13 %, and its gel strength was also the highest, at 285.6 g·cm.	[164]
High-Pressure Processing Technology	Ready-to-eat clam meat	121 °C, 0.14 MPa, 5/10/ 15/20 min	Gradually decreased with longer HTP time, chewiness initially decreased, then increased, enhanced production of esters and aldehydes, best umami and saltiness at 15 min.	[165]
	Latilactobacillus sakei	400-600 MPa, 180-480 s	The inactivation of the microorganism ranged from 0.99 to 4.12 UFC/g.	[90]
New Tumbling Technology	Chicken breast	Breathing (pressure change) tumbling combined with ultrasonication (40 kHz, 140 W)	Significantly enhanced marinating absorptivity, accelerated degradation of myosin light chain, significantly improved tenderness, remarkably better taste.	[166]
	Restructured pork chops	V 100 mbar, 2500 mbar with a gas mixture of CO_2: N_2 = 1:1, 8 min vacuum + 7 min pressure + 1 min rest, total 40 min	Significantly improving product yield and tenderness while optimizing myofiber structure and maintaining protein secondary structure integrity	[167]
	Chicken breast	Ultrasound treatment at 40 kHz and 300 W for 45 min, followed by vacuum tumbling at 1 kPa for 45 min	The shear force was reduced by 87.12 %, the cooking loss was decreased to 11.67 %, and the moisture content was increased to 71.65 %.	[168]

Intelligent Active Packaging Technology	Shrimp	Aronia melanocarpa anthocyanins as pH-sensitive indicator, tea polyphenol as anthocyanin stabilizer	Extended shrimp shelf life by 12 h, enabled real-time visual freshness monitoring.	[169]
	Shrimp, Pork	Packaged with CP-Cur150 film, shrimp stored at 25 °C for 5 days, pork stored at 4 °C for 7 days	PPH free radical scavenging rate of 87 % and an ABTS free radical scavenging rate of 98 %, *Staphylococcus aureus* and *E. coli* were reduced by 2.7 and 1.3 Log10 CFU/mL.	[170]
Ultrasound Technology	Cured sea bass	300 W ultrasound for 60 min	Significantly increased NaCl transfer rate, reduced hardness and chewiness, improved water retention.	[171]
	Beef (*E. coli* and harmless *listeria monocytogenes)*	US: 33 + 20 kHz, 1 h, stored at 4 °C and 10 °C for 60 days	25 % reduction in sodium and a major drop in microbial count.	[172]
	Chicken, breast meat	24.5 kHz, 300 W, 10 min	Cooking loss reduced by 28.78%, enhanced moisture retention, reduced hardness, chewiness, and gumminess.	[173]

3.2.1 Antioxidants

Antioxidants are food additives that prevent or delay the oxidation of food and extend its shelf life. The oxidation of meat can lead to changes in color, taste, and odor, as well as the production of secondary metabolites harmful to human health[124]. Therefore, the use of antioxidants in meat processing is particularly important. However, since the in vivo and in vitro toxicity of synthetic antioxidants has been confirmed, the use of antioxidant compounds from natural sources can meet consumer demand for clean label foods, which are perceived as more natural and safer[125].

Phenolic compounds are the most commonly used clean label antioxidant alternatives in the meat industry[126]. Natural phenolic compounds are primarily found in plant tissues and are natural bioactive molecules. They contain one or more hydroxyl groups and can disrupt oxidation chain reactions through hydrogen atom transfer and electron transfer mechanisms[125, 127, 128]. Manzoor et al.[129] observed that mango peel extract, rich in phenolic compounds, significantly enhanced the lipid oxidation stability, antioxidant activity, and DPPH radical scavenging capacity of chicken sausages when added at different concentrations. Chernukha et al.[130] added varying volumes of onion husk ethanol extract to meat paste and found that quercetin and glycosides, abundant in yellow onion skins, reduced oxidative spoilage and increased total antioxidant capacity by more than 1.5 times. This indicates that onion skin extract can enhance the functionality of meat products, contributing to the development of clean label foods free from synthetic antioxidants. Terpenoids such as monoterpenes and carotenoids also exhibit significant antioxidant effects [131]. The primary sources of carotenoids include carrots, spinach, red peppers, tomatoes, parsley, and red watermelon, with their antioxidant activity attributed to functional groups and the number of double bonds interacting with carotenoid radicals[132]. Cadariu et al.[133] added processing byproducts of large tomatoes (DLTB) and cherry tomatoes (DCTB) as natural antioxidants to nitrite-free sausages, finding that DCTB and DLTB, at polyphenol compound levels of at least 180 mg GAE/kg (DCTB) and 270 mg GAE/kg (DLTB), showed potential to replace sodium nitrite. Haraf et al.[134] incorporated different proportions of kiwifruit pulp into marinades and found that beef marinated with 30% kiwifruit pulp significantly improved FRAP and ABTS antioxidant activity metrics.

3.2.2 Antimicrobial Agents

Antimicrobial agents are substances added to materials to impart antibacterial properties, capable of inhibiting the growth of bacteria and fungi, with their antibacterial effects lasting for an extended period. Clean label alternatives to antimicrobial agents in meat include animal-derived lactoferrin and lysozyme, as well as lactic acid bacteria and their metabolites[135].

Lactoferrin derived from milk is a glycoprotein that binds iron to protein[136]. It binds to iron, thereby depriving bacteria such as Listeria monocytogenes, Salmonella, Escherichia coli, Bacillus stearothermophilus, Shigella, and Bacillus subtilis of the iron necessary for their growth[137], making it an effective natural antimicrobial agent. Del et al.[138] demonstrated that lactoferrin and its derivatives exhibited the highest sensitivity to *Listeria monocytogenes* in vitro, moderate resistance to *Staphylococcus aureus*, and high resistance to *Enterococcus faecalis* when added to chicken breast.

Lysozyme is a natural protein with antimicrobial properties[139]. To date, egg white lysozyme is the only lysozyme permitted for use in the food industry. Its antimicrobial activity mechanisms are divided into lytic and non-lytic actions. The lytic mechanism involves lysozyme hydrolyzing the β-1,4-glycosidic bonds of peptidoglycan, leading to the destruction of the mucin layer and a reduction in the mechanical strength of bacterial cell walls, ultimately causing bacterial death. The non-lytic mechanism is attributed to structural factors, cationic properties, and hydrophobic characteristics[140]. Cho et al.[141] used a combination of ε-poly-L-lysine and lysozyme to treat *Listeria monocytogenes* biofilms on beef surfaces, reducing the biofilm by 3.3 to 4.2 log CFU/g. Additionally, the combined treatment significantly inhibited the expression of genes related to bacterial virulence. Li et al.[142] investigated the inhibitory effects of lysozyme and Chinese liquor on the growth and enterotoxin production of *Staphylococcus aureus*. The data showed that the combined use of lysozyme and liquor significantly reduced the total *Staphylococcus aureus* count in sausages to approximately 2.1 log CFU/g and suppressed enterotoxin concentration. These findings provide a potential natural antimicrobial alternative for enhancing the safety and quality of meat products.

Essential oils (EOs) are complex mixtures of low-molecular-weight compounds synthesized by plants, possessing antimicrobial properties[143]. Their effectiveness in meat preservation is primarily due to the presence of bioactive compounds, which can modulate bacterial activity by limiting the penetration of hydrophobic components through the outer membrane of Gram-negative bacteria[144]. However, the strong odor produced by the volatilization of EOs can reduce the overall acceptability of minced meat[145], necessitating careful control of dosage. Ghabraie et al.[146] demonstrated that EOs from red thyme, red bergamot, Ajowan, summer savory, and Chinese cinnamon exhibit significant antimicrobial effects against foodborne pathogens and spoilage bacteria in solid, liquid, and gaseous environments. Chinese cinnamon EOs showed the lowest minimum inhibitory concentration against *Staphylococcus aureus* and *Escherichia coli* in liquid environments, reaching 470 ppm. Additionally, combinations of EOs at concentrations below

0.05% were sensorially acceptable in cooked minced meat. Mantzourani et al.[144] investigated the antimicrobial activity of ethanol pomegranate extract combined with oregano EOs on pork slices. The results showed that the combined marinade significantly reduced the counts of microbial communities such as *Enterobacteriaceae*, *Pseudomonas spp.*, *Staphylococcus spp.*, and Lactic Acid Bacteria, extending the shelf life of the meat without negatively affecting its color, tenderness, flavor, or juiciness. These findings suggest that EOs and their combinations may play an important role in the field of food preservation, particularly in enhancing food safety and extending shelf life.

3.2.3 Humectants

Inorganic phosphates are the most commonly used humectants in meat products, enhancing water-holding capacity by increasing pH, ionic strength, chelating metal ions, dissociating myosin, and inducing more protein structural changes[147, 148]. The U.S. Food and Drug Administration generally recognizes inorganic phosphates as safe and permits their use as effective food additives in various processed foods, including meat, ham, sausages, and canned fish [149, 150]. Although the maximum allowable levels of phosphates are regulated and controlled to ensure they do not pose health risks, their use conflicts with consumer preferences for "natural" foods. Therefore, finding natural alternatives to phosphates has become a trend. To date, various natural ingredients have been evaluated as substitutes for inorganic phosphates with varying degrees of success, such as plant-based components (e.g., starch, fiber, or seeds), fungal components (e.g., mushrooms and mushroom extracts), algal components, animal-derived materials (e.g., meat/seafood, dairy, or egg products), and inorganic compounds (minerals). The addition of natural products can improve the water-holding capacity of meat to some extent; however, completely replacing phosphates in meat with alternative ingredients may negatively affect appearance, texture, and other key product characteristics[150]. Xu et al.[151] added different proportions of natural aromatic extracts from black tea (NAEBT) to pork mince. The results showed that NAEBT reduced cooking loss from 23.95% to 18.30%, improved color stability and elasticity, effectively mitigated protein oxidative damage, increased β-sheet structure content, and restricted the mobility of water molecules in pork mince. These effects provide strong scientific support for the application of clean labels in meat products. Choe et al.[152] evaluated the potential of winter mushroom powder (WMP) as a phosphate substitute by adding it to pork emulsified sausages at different ratios. The results indicated that adding 1.0% or more WMP increased sausage pH, inhibited lipid oxidation, and enhanced water and fat retention due to its dietary fiber properties. A 1.0% WMP addition effectively replaced phosphates without affecting sensory quality. Weigel et al.[153] studied the addition of freeze-dried vegetable powders (e.g., kale, red pumpkin, sweet corn) to cooked sausage meat. They found that sausages with 1.6% dehydrated kale or red pumpkin showed similar weight gain (7.0%) and comparable softness and tenderness to those containing 0.6% phosphate additives. These results support the feasibility of natural ingredients as phosphate substitutes in meat processing. However, the color of vegetables significantly impacts the sensory attributes of the final product, a factor that must be considered during product development.

Despite various efforts to replace inorganic phosphates with suitable natural ingredients, these components cannot fully replicate the role of phosphates in meat. An alternative approach to address these shortcomings is to combine these natural ingredients with new processing technologies, such as ultrasound, HPP, and PEF technologies[149, 154-156]. These innovative methods may help bridge the gap left by the absence of phosphates, enhancing the functional properties of meat products while maintaining consumer acceptance.

3.2.4 Color Stabilizers

Nitrates and nitrites are the most commonly used color stabilizers in meat products. When nitric oxide (NO), a volatile compound produced by the degradation of nitrates, binds to the heme iron in myoglobin, it forms another type of myoglobin that gives cured meat its characteristic pink color[12], thereby maintaining a stable red color in meat. However, nitrites can lead to the formation of nitrosamines, some of which are known carcinogens. Therefore, in addition to traditional curing with nitrites, it is recommended to incorporate various natural colorants or stabilizers to achieve a stable red color, such as chili, red yeast rice (Monascus), cochineal, and certain microorganisms (e.g., lactic acid bacteria, micrococci) [157, 158]. Su et al.[159] investigated the interaction between betanin red (BR) and myoglobin using multiple spectroscopic methods, isothermal titration calorimetry, and molecular docking techniques, as well as its dual effect on meat color protection. The experiments showed that adding 0.2% BR to beef increased redness by 27.65%, improved sensory acceptance by 9.35%, and reduced lipid oxidation by 15.34%. Ozaki M et al.[160] used radish powder in a nitrite-free formulation and found that it effectively promoted color development, reduced mesophilic bacterial counts, and maintained water activity and pH within suitable ranges. Szymanski P et al.[161] explored the application of *Limosilactobacillus fermentum* S8, isolated from organic acid whey, in the processing of uncured cooked meat products. The results showed that treatment with *L. fermentum* S8 significantly increased the concentration of nitroso pigments and redness (a*), while reducing pH and redox potential and enhancing antioxidant capacity. These studies are significant for developing healthier meat products that align with the "clean label" trend.

Furthermore, it is important to note that the applicability of clean-label technologies and natural additives may vary across different meat types due to differences in muscle composition, microstructure, fat content, and susceptibility to oxidation or microbial spoilage. For instance: Poultry meat (e.g., chicken, turkey), with its relatively higher surface-area-to-volume ratio and milder flavor, is particularly suitable for CAP and ultrasound-assisted marination, which effectively enhance surface decontamination and flavor penetration without compromising texture. Pork, often richer in fat and more prone to lipid oxidation, benefits greatly from HPP and natural antioxidants (e.g., plant extracts rich in polyphenols), which improve lipid stability and inhibit off-flavors. Beef cattle, with its dense muscle structure, responds well to PEF, which improve tenderness and protein digestibility without excessive use of phosphates.

Therefore, the selection of processing technologies and additives should be tailored to the specific meat type to maximize efficacy and maintain product quality.

4. Conclusion

In recent years, consumer demand for clean-label meat products has grown significantly, with many high-income and highly educated consumers particularly willing to pay a premium for such offerings; thus, to expand acceptance from high-end to price-sensitive segments, producers must reduce costs through process optimization, scaling up, and supply-chain integration while clearly communicating added value. Concurrently, governments and industries should bolster consumer trust and awareness through certifications such as "additive-free" or "animal welfare," thereby paving the way for the commercialization of clean-label meat products.

The adoption of clean-label principles in meat production and processing has become an inevitable industry trend, playing a crucial role in improving meat quality and safety while meeting rising consumer expectations for healthier food options. However, clean-label meat products still represent a relatively small market share, indicating that broader adoption will require a gradual, sustained effort across the supply chain. To fully realize the potential of clean-label meat, implementation must begin at the farming stage. Enhancing animal welfare, optimizing diet formulations, improving breeding conditions, and minimizing stress during transportation and slaughter are essential steps to ensure high-quality, safe raw materials for processing. At the production level, advanced technologies—such as high-pressure processing, ultrasound, and pulsed electric fields—can mitigate quality degradation associated with conventional methods while extending shelf life. Moreover, replacing synthetic additives like nitrates and artificial antioxidants with natural alternatives, including plant extracts and probiotics, aligns with consumer preferences for clean, health-conscious foods while improving market appeal.

Despite progress in clean-label meat research, further advancements are needed in multiple areas, including sustainable farming practices, novel processing techniques, functional product development, and robust traceability systems. Strengthening collaboration between industry, academia, and research institutions will be vital to accelerate innovation and translate scientific findings into practical applications. Such efforts will not only enhance the meat industry's competitiveness but also support evolving consumer trends and drive long-term sector growth. Beyond its benefits for food quality and safety, clean labeling is deeply intertwined with sustainability. For instance, reducing chemical additives decreases pollution from agricultural runoff and waste, protecting soil and aquatic ecosystems. Improved farming methods, such as optimized feeding with natural additives and lower stocking densities, enhance animal welfare and contribute to ecological balance by reducing the environmental footprint per unit of meat produced. The adoption of clean-label practices in meat production positively impacts environmental conservation, resource efficiency, and socioeconomic outcomes. For instance, reducing chemical additives decreases pollution from agricultural runoff and waste, protecting soil and aquatic ecosystems. Improved farming methods, such as optimized feeding with natural additives and lower stocking densities, enhance animal welfare and contribute to ecological balance by reducing the environmental footprint per unit of meat produced. Future research should further investigate how clean-label meat production contributes to sustainable development, particularly its mechanisms and impacts in environmental protection, resource management, and socioeconomic progress. Such evidence-based findings will offer actionable frameworks for implementing sustainability initiatives throughout the meat value chain.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the earmarked fund for CAR-43, the National Modern Agricultural Industrial Technology System, Sichuan Innovation Team Construction Project (SCCXTD-2024-8).

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