

POSSIBILITIES FOR PHOSPHATE AND NITRITE REDUCTION AND REPLACEMENT IN MEAT PRODUCTS THROUGH CLEAN-LABEL APPROACHES

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Abstract: Food additives are widely used in processed meat production because they provide important technological functions and contribute to product quality and safety. Nitrites contribute to microbiological safety, colour formation and oxidative stability and are also involved in the development of the characteristic flavour of cured meat products. Phosphates are primarily added to improve water-holding capacity, emulsion stability and texture. Potential health effects associated with the use of these additives have also received increasing attention. Consumer interest in meat products with cleaner labels and fewer synthetic additives has increased in recent years. In response to these expectations, the meat industry is developing alternative approaches that can reduce the use of conventional additives while maintaining product quality and safety. This paper reviews the role of phosphates and nitrites in meat products, the reasons for reducing their use, and the possibilities for replacing them. Their complete replacement remains challenging because both additives perform several important technological functions and contribute to the sensory characteristics and microbiological stability of meat products. For this reason, natural functional ingredients may be used in combination with carefully controlled processing conditions. Such an approach may help to maintain acceptable sensory properties and product safety while allowing the production of meat products with a cleaner label.

Keywords: phosphates, nitrites, meat products, clean label, natural replacements, functional ingredients.

1. INTRODUCTION

Meat products represent complex food systems in which quality, stability and sensory acceptability depend on the composition of the raw material, the additives used and the technological process applied. In the meat industry, phosphates and nitrites are of particular importance, as they contribute to improvements in texture, juiciness, colour, oxidative stability and microbiological safety. Phosphates are most commonly associated with improved water-holding capacity, extraction of myofibrillar proteins and stability of meat emulsions, whereas nitrites are important for the formation of the characteristic pink-red colour, inhibition of certain microorganisms and retardation of lipid oxidation (Yasui et al., 1964; Trout & Schmidt, 1986; Honikel, 2008; Glorieux et al., 2017).

Despite their technological importance, the use of these additives is increasingly being re-evaluated for health, regulatory and market-related reasons. Excessive intake of inorganic phosphates may contribute to an increased total phosphorus intake, while the use of nitrites is associated with the possible formation of N-nitroso compounds under certain processing and storage conditions. These concerns have encouraged the meat industry to reduce the use of synthetic additives and develop products with cleaner labels that are more acceptable to consumers (Bedale et al., 2016; Delgado-Pando et al., 2021; Molina et al., 2023; Silovska Nikolova & Belichovska, 2024).

The regulatory aspect is particularly important in relation to nitrites and nitrates, as their use in meat products is strictly controlled in order to maintain a balance between microbiological safety and the reduction of the risk of N-nitroso compound formation. In the European Union, the use of food additives is regulated by Regulation (EC) No 1333/2008, while Commission Regulation (EU) 2023/2108 further amends the conditions of use for nitrites (E 249–250) and nitrates (E 251–252), by reducing permitted levels and introducing stricter requirements for residual amounts in certain categories of meat products. These regulatory changes confirm the need to develop technologically controlled strategies for reducing nitrites and nitrates without compromising the safety, stability and sensory quality of meat products (European Commission, 2023; European Parliament and Council, 2008).

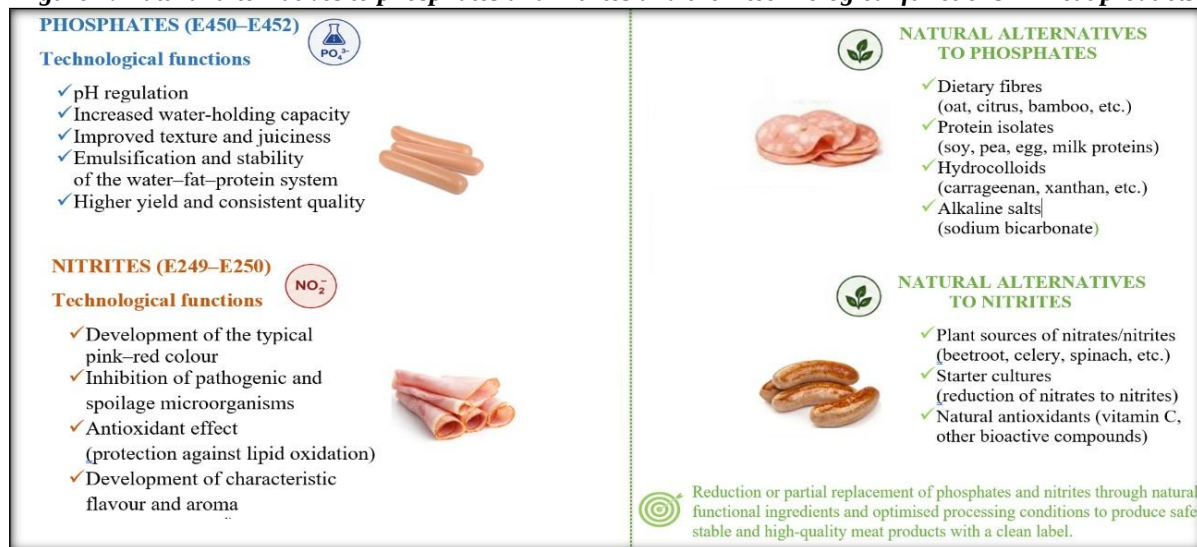
The clean-label approach does not simply involve removing phosphates and nitrites from the formulation; rather, it requires the application of alternative ingredients and technologies capable of preserving product functionality, safety and sensory quality. Dietary fibres, protein isolates, hydrocolloids, alkaline salts and advanced physical treatments have been investigated as possible phosphate replacers, whereas nitrite reduction or replacement is most commonly based on nitrate-rich plant sources, nitrate-reducing starter cultures and natural antioxidants (Goemaere et al., 2021; Silovska Nikolova & Belichovska, 2021; Yoon et al., 2023; Premi et al., 2024).

Nevertheless, the replacement of phosphates and nitrites is a complex process, as these additives exert multiple technological effects and cannot be fully replaced by a single ingredient. In practice, combining functional

ingredients with natural sources of bioactive compounds and controlled processing conditions may provide a more effective approach (Molina et al., 2023; Pinton et al., 2024; Kim et al., 2026).

The aim of this paper is to review the technological role of phosphates and nitrites in meat products and the reasons for reducing or replacing them. Natural and functional alternatives are also considered in relation to their practical use in clean-label meat products. Some of these approaches have greater potential for industrial application, whereas others are still mainly investigated under laboratory conditions. Complete replacement is not always technologically justified and may also affect product safety. Figure 1 summarises the principal technological functions of phosphates and nitrites and the main clean-label alternatives discussed in this review.

Figure 1. Natural alternatives to phosphates and nitrites and their technological functions in meat products.



Source: Author's own elaboration

2. FUNCTIONAL SYSTEMS FOR PHOSPHATE REDUCTION AND REPLACEMENT IN MEAT PRODUCTS

Phosphates are among the most widely used functional additives in the meat industry, as they simultaneously influence pH, ionic strength, myofibrillar protein solubility, water-holding capacity, emulsion stability, texture and product yield. Their action is associated with shifting the pH away from the isoelectric point of proteins, increasing electrostatic repulsion between myofibrillar filaments and creating greater space for water immobilisation. Phosphates are particularly important in heat-treated and emulsified meat products, where the stability of the water-fat-protein system is closely linked to product quality and technological yield (Yasui et al., 1964; Trout & Schmidt, 1984, 1986; Glorieux et al., 2017; Kim et al., 2026).

Phosphates also improve the extraction of myofibrillar proteins, especially in the presence of sodium chloride. This supports the formation of the protein network during heat treatment. This effect is important in emulsified meat products, where functional proteins stabilise the fat phase and reduce the separation of water and fat, but also in whole-muscle meat products, where they contribute to cohesiveness and binding between meat pieces. Studies on beef, turkey and chicken meat confirm that the effect of phosphates depends on their type and concentration, salt level and method of preparation, indicating that their replacement must be considered according to the specific product type rather than as a universal solution (Yasui et al., 1964; Prusa & Bowers, 1984; Trout & Schmidt, 1984, 1986; Knipe et al., 1985; Young & Lyon, 1986; Young et al., 1987; Glorieux et al., 2017; Goemaere et al., 2021).

Phosphates also have an indirect antioxidant effect, related to their ability to chelate metal ions that can catalyse lipid oxidation. This effect is important in products with a higher fat content, as it contributes to the preservation of colour, odour, taste and sensory acceptability during storage (Glorieux et al., 2017; Kim et al., 2026).

Replacing phosphates is difficult because they perform several technological functions simultaneously. Current replacement strategies mainly focus on combined systems that include functional ingredients and complementary technological approaches (Molina et al., 2023).

Dietary fibres, such as citrus, bamboo, wheat and oat fibres, are used because of their ability to bind water and stabilise the matrix. They can reduce cooking losses and improve texture, but they do not directly improve the extraction of myofibrillar proteins. They are more effective when combined with other functional ingredients, such as protein isolates or hydrocolloids. In more recent formulations, Pinton et al. (2024) showed that a combination of bamboo fibre, pea protein and mushroom powder can be used to produce mortadella with reduced sodium content and without phosphates, with the aim of preserving the technological, oxidative and

sensory properties of the product. However, the reformulation also reduced several texture-profile parameters, changed instrumental colour and caused small increases in lipid and protein oxidation.

Protein isolates represent another important group of potential replacers. Soy, pea, egg and milk proteins, blood plasma and other protein ingredients can improve emulsion stability, participate in gel-network formation and contribute to better retention of water and fat. Goemaere et al. (2021) showed that blood plasma and soy proteins had the strongest effect in phosphate-free cooked sausages, with certain parameters such as firmness, cooking yield and stability being comparable to products containing phosphates. Egg and pea proteins also showed a positive effect, although to a lesser extent. This indicates that the choice of protein ingredient must be linked to the product type, formulation and technological process applied.

Hydrocolloids, such as carrageenan, xanthan, guar gum, gum arabic, konjac mannan and other polysaccharides, play an important role in stabilising the aqueous phase, increasing viscosity and improving texture. They can reduce syneresis and improve juiciness. Their main effect is the physical binding of water rather than the activation of meat proteins. Hydrocolloids are most suitable as part of combined systems with proteins, fibres or starches (Molina et al., 2023; Kim et al., 2026). Alkaline salts, particularly sodium bicarbonate, have been investigated as a possible partial replacement for phosphates, as they can increase the pH of the meat system and thereby partially imitate the pH-related effect of phosphates. Zhou et al. (2024) showed that partial replacement of complex phosphates with sodium bicarbonate affects the aggregation, conformation and gel properties of myofibrillar proteins in a mixed beef, pork and chicken meat system. Excessive use of alkaline salts may produce an undesirable alkaline taste, so the amount used needs to be adjusted to the product and its formulation (Zhou et al., 2024).

Beyond ingredient-based approaches, advanced technological treatments can also improve meat protein functionality and reduce the need for added phosphates. High pressure, ultrasound, vacuum massaging/tumbling and improved control of salt concentration and temperature can enhance myofibrillar protein extraction and water retention in the meat system. These technologies do not represent a complete replacement for phosphates, but they may form an important part of combined strategies for their reduction, particularly when applied together with functional ingredients such as fibres, protein isolates, hydrocolloids or alkaline salts (Kim et al., 2026).

In practice, phosphate replacement usually requires a combination of ingredients because the available alternatives act through different technological mechanisms. For industrial application, partial replacement or reduction of phosphates through a combination of fibres, protein ingredients, hydrocolloids and an optimised technological process appears more practical than complete removal without prior validation (Goemaere et al., 2021; Molina et al., 2023; Pinton et al., 2024).

3. FUNCTIONAL SYSTEMS FOR NITRITE REDUCTION AND REPLACEMENT IN MEAT PRODUCTS

Nitrites represent one of the most important groups of additives in the meat industry. They are most commonly used in the form of sodium nitrite, and their technological role is associated with the formation and stabilisation of the characteristic pink-red colour, inhibition of certain undesirable microorganisms, retardation of lipid oxidation, and development of the typical taste and odour of cured meat products (Honikel, 2008; Bedale et al., 2016; Silovska Nikolova & Belichovska, 2020; Kim et al., 2025).

The technological action of nitrites is related to their transformation into nitric oxide, which reacts with myoglobin in meat and participates in the formation of a stable pinkish-red colour. During curing, nitrosomyoglobin is formed, while heat treatment leads to the formation of a more stable pigment, nitrosylhaemochrome, which is responsible for the typical pink colour of meat products. The development and stability of colour in meat products have a significant influence on sensory acceptability, visual appearance and product recognition (Honikel, 2008).

Nitrites also have important antimicrobial and antioxidant effects. Their antimicrobial activity is particularly important in the control of *Clostridium botulinum* in meat products, but it depends on several factors, including pH, salt concentration, water activity, storage temperature, heat treatment and the presence of other functional ingredients. Nitrites should be considered as part of a broader technological system that supports microbiological stability, oxidative protection and sensory quality of the product (Honikel, 2008; Sebranek & Bacus, 2007; Delgado-Pando et al., 2021).

Despite their technological importance, the use of nitrites is increasingly being restricted and re-evaluated because of the possible formation of N-nitroso compounds, particularly nitrosamines, which may form under certain processing, storage or high-temperature exposure conditions. This concern, together with the increasing demand for meat products with fewer additives, is directing the meat industry towards the development of alternative strategies for reducing or replacing directly added sodium nitrite. The health aspects associated with the use of nitrites in meat products emphasise the need for controlled application, compliance with permitted concentrations and the development of safer technological solutions (Bedale et al., 2016; van Breda et al., 2021; Silovska Nikolova & Belichovska, 2024).

Contemporary clean-label strategies are most commonly based on the use of nitrate-rich plant sources, such as celery, radish, Chinese cabbage, spinach, beetroot and Swiss chard. Naturally occurring nitrates must be reduced to nitrites by nitrate-reducing microorganisms. In this way, the formation of nitric oxide in the meat system and the development of a typical cured colour can be achieved without the direct addition of synthetic sodium nitrite. The use of plant-derived nitrate sources in indirect curing systems is considered a possible approach for producing meat products with a more acceptable label and reducing the use of synthetic additives (Sebranek & Bacus, 2007; Silovska Nikolova & Belichovska, 2021; Premi et al., 2024).

The use of starter cultures is of particular importance in natural curing systems, as they enable the reduction of plant-derived nitrates to nitrites. Nitrate-reducing bacteria are especially important, among which coagulase-negative staphylococci play an important role in colour development, formation of the cured pigment and product stability. The effectiveness of this approach depends on the type of plant source, nitrate content, starter culture activity, pH, temperature and incubation time (Premi et al., 2024).

In practice, standardised plant sources of nitrates/nitrites can be combined with nitrate-reducing starter cultures under controlled processing conditions (Sebranek & Bacus, 2007; Silovska Nikolova & Belichovska, 2021; Premi et al., 2024).

Recent studies show that plant powders can be successfully used as natural sources of nitrates or nitrites in meat products. Bae et al. (2023) showed that nitrate-rich fermented dongchimi powder, used together with a nitrate-reducing starter culture, could serve as an indirect curing ingredient in emulsion-type pork sausages. Amounts above 0.35% provided satisfactory curing efficiency and colour formation. However, the naturally cured sausages showed higher lipid oxidation than the sausages containing synthetic nitrite. Gwak et al. (2024) showed that Chinese cabbage and radish powders can be used as potential nitrite replacers in cured pork sausages, with the preparation method of the plant powder having a significant influence on its functionality. Natural sources of nitrates/nitrites may be useful, although their application requires standardisation of the raw material and precise control of technological conditions (Bae et al., 2023; Gwak et al., 2024). These solutions show potential, but they cannot yet be considered fully validated for industrial use; microbiological safety, oxidative stability, residual nitrite and sensory acceptability still need to be assessed across different product categories.

Reducing agents such as ascorbate can promote the conversion of nitrite to nitric oxide and support the development and stability of cured colour. Polyphenol-rich extracts primarily contribute to oxidative stability and may reduce the formation of undesirable oxidation products. Some phytochemical-rich ingredients may also reduce exposure to N-nitroso compounds. Their effectiveness depends on the dose, composition, processing method and interaction with the meat matrix (van Breda et al., 2021; Kim et al., 2025).

The main strategies for phosphate and nitrite reduction and replacement, together with their principal limitations, are summarised in Table 1.

Table 1. Main strategies for phosphate and nitrite reduction and replacement in meat products

Additive	Main technological role	Possible clean-label alternatives	Main limitation
Phosphates	Improvement of water-holding capacity, emulsion stability, texture and product yield	Dietary fibres, protein isolates, hydrocolloids, alkaline salts and physical treatments	No single ingredient can fully replace all phosphate functions
Nitrites	Formation of characteristic cured colour, antimicrobial protection, antioxidant effect and typical cured flavour	Plant sources of nitrates/nitrites, starter cultures and natural antioxidants	Control of residual nitrite, microbiological safety and oxidative stability is required
Combined approach	Preservation of quality, safety and sensory acceptability	A combination of functional ingredients and controlled technological conditions	Product-specific validation is required

Source: Author's summary based on Honikel (2008), Sebranek and Bacus (2007), Goemaere et al. (2021), Molina et al. (2023), Yoon et al. (2023), Premi et al. (2024), Kim et al. (2025) and Kim et al. (2026).

Some recent studies have also examined the simultaneous replacement of several additives in meat products. Yoon et al. (2023) investigated the replacement of nitrite and phosphate in minced pork products using a clean-label approach, which is particularly important because, in real industrial formulations, additives do not act in isolation but interact with one another. Reducing synthetic additives requires a balance between colour, texture, water-holding capacity, oxidative stability and sensory acceptability (Yoon et al., 2023; Kim et al., 2025).

Reducing or replacing nitrites requires a controlled technological approach rather than simply removing the additive from the formulation. Natural sources of nitrates/nitrites, starter cultures and antioxidants can contribute to the development of clean-label products, but their application requires standardisation of raw materials,

control of technological conditions and verification of microbiological safety, oxidative stability, residual nitrite and sensory acceptability (Silovska Nikolova & Belichovska, 2022; Premi et al., 2024).

4. CONCLUSION

Phosphates and nitrites have an important technological role in meat products, particularly in relation to water-holding capacity, emulsion stability, texture, colour, oxidative stability and microbiological safety. Owing to their multiple functions, their replacement cannot be considered as a simple substitution with a single alternative ingredient. For phosphate reduction, combined functional systems based on dietary fibres, protein ingredients, hydrocolloids and alkaline salts appear to be the most practical option, although their effectiveness varies with product type and processing conditions. In the case of nitrites, natural sources of nitrates/nitrites, starter cultures and antioxidants represent promising solutions, but they do not automatically provide the same level of safety and stability as conventional nitrites. Complete replacement of phosphates and nitrites without prior technological, microbiological, oxidative and sensory validation is not justified. For industrial use, controlled reduction or partial replacement appears more practical than complete removal, provided that product safety, stability and sensory quality are maintained.

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