NITRITE REDUCTION IN PROCESSED MEAT PRODUCTS: PLANT-DERIVED NITRATE/NITRITE SOURCES, STARTER CULTURES AND HURDLE TECHNOLOGIES

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Abstract: Nitrites remain among the most important additives in processed meat products because they contribute simultaneously to cured colour development and stability, lipid oxidative protection, microbiological safety, and the formation of characteristic sensory attributes. However, growing concern about the potential formation of *N*-nitrosamines has intensified research into strategies to reduce nitrite use without compromising product quality and safety. This paper reviews current approaches to nitrite reduction in meat products, with particular emphasis on plant-derived nitrate and nitrite sources, nitrate-reducing starter cultures, and hurdle technologies as complementary tools within clean-label reformulation strategies. Particular attention is given to vegetables with high nitrate-accumulating potential, such as celery, parsley, spinach, chard, beetroot, radish, and Chinese cabbage, as well as to the importance of ingredient format, including juice, concentrate, powder, and fermented vegetable systems. The reviewed evidence indicates that such ingredients can provide a curing effect and, in some cases, quality characteristics comparable to those obtained with conventional nitrite addition. Nevertheless, their performance is strongly influenced by raw-material variability, agronomic and seasonal factors, processing conditions, and the efficiency of nitrate-to-nitrite conversion within the product matrix. The review also highlights the growing relevance of hurdle concepts, in which reduced nitrite levels are supported by synergistic combinations of plant ingredients, starter cultures, antioxidants, packaging systems, and non-thermal processes such as high-pressure processing, pulsed electric fields, cold plasma, and ultrasound-assisted treatments. Overall, nitrite reduction in processed meat products appears technologically feasible, but successful application depends on formulation standardisation, product-specific optimisation, and systematic monitoring of residual nitrite/nitrate levels, oxidative stability, microbiological status, and the possible formation of *N*-nitrosamines.
Keywords: Nitrites, Nitrates, Plant-based sources, Starter cultures, Clean label

1. INTRODUCTION

Humans have, since earliest times, sought to extend the shelf life of surplus meat to ensure a continuous food supply during seasonal fluctuations, limited availability, and the absence of refrigeration. The earliest meat-preservation techniques emerged from practical experience and were later scientifically validated and refined. Today, the modern manufacture of processed meat products commonly relies on preservatives (Silovska Nikolova & Belichovska, 2022).

The most commonly used preservatives are nitrites and nitrates, which are authorised for use and considered safe when used within legally permitted limits and in accordance with good manufacturing practice. Their use is strictly regulated by law and precisely defined, with clearly established conditions and justified reasons for application, the categories of processed meat products in which they are permitted, and maximum allowable levels (Silovska Nikolova & Belichovska, 2020). From a technological perspective, they are important for the development and stability of the red colour in processed meat products; they limit lipid oxidation and thereby contribute to the development of more acceptable sensory properties, including aroma (Kureljušić et al., 2025; Silovska Nikolova & Belichovska, 2021; Stoica et al., 2022; Shakil et al., 2022; Zhang et al., 2023).

Despite these technological benefits, nitrite use may also pose certain health risks to consumers. During thermal processing - particularly at higher temperatures - and during nitrosation reactions with compounds containing amino groups, N-nitrosamines may form; these compounds are regarded as carcinogenic and mutagenic (Bak et al., 2025; Silovska Nikolova & Belichovska, 2024; Xie et al., 2023).

Owing to the “dual” role of nitrites - on the one hand, technologically essential compounds, and on the other, additives that raise concerns regarding potential health risk - research into their reduction without compromising the safety and quality of processed meat products has intensified markedly over approximately the past five decades (Alahakoon et al., 2015; Delgado-Pando et al., 2021). The practical challenge arises from the fact that nitrites simultaneously contribute to colour stability, limit lipid oxidation, participate in the development of characteristic sensory properties, and support the microbiological stability of the product (Alahakoon et al., 2015; Munekata et al., 2021). Consequently, a single “replacement” most often cannot fulfil all functions; instead, combined (hurdle) approaches are more commonly applied, in which multiple measures and functional ingredients synergistically compensate for the reduced nitrite level (Alahakoon et al., 2015; Kim, Bae, et al., 2025). Within current trends, "clean-label" strategies are particularly prominent, including the use of natural sources with nitrate/nitrite potential (e.g., plant extracts/powders) in combination with ingredients with antioxidant and/or antimicrobial activity, in order to maintain product stability and achieve a more consumer-acceptable label declaration (Delgado-Pando et al., 2021; Munekata et al., 2021; Kim, Bae, et al., 2025).

This paper presents a narrative review of nitrite-reduction strategies in processed meat products, with particular emphasis on nitrate-rich plant ingredients used in combination with nitrate-reducing starter cultures as a clean-label curing approach, and on hurdle technologies that support product safety and quality in reduced-nitrite systems. Special attention is given to plant-ingredient variability and standardisation, processing conditions affecting nitrate-to-nitrite conversion, and the effects of these strategies on colour development, oxidative stability, microbiological safety, sensory quality, residual nitrite/nitrate levels, and the potential formation of *N*-nitrosamines.

2. NITRITE REDUCTION THROUGH PLANT-DERIVED SOURCES OF NITRATES AND NITRITES

Nitrates (NO_3^-) naturally accumulate in plants as part of nitrogen metabolism, and their concentration in vegetables varies markedly depending on species/cultivar, agronomic practices (particularly nitrogen fertilisation), light intensity, season, and storage conditions. The highest levels are most often found in leafy vegetables (lettuce, spinach, rocket/arugula, chard/Swiss chard) and in certain stem/herb species (celery, parsley). Practical literature commonly reports an approximate range of 1000-2500 mg/kg fresh weight, while substantially higher values may also be observed in rocket (Hosseini et al., 2023; Dodocioiu et al., 2025).

In contrast to nitrates, nitrites (NO_2^-) in fresh, intact vegetables are generally low, since nitrite is a reactive intermediate and typically does not accumulate as a stable storage form (Luetic et al., 2023; Dodocioiu et al., 2025). However, an important limitation is that mechanical processing (chopping/puréeing) and subsequent storage, especially at ambient temperature, may promote microbial reduction of nitrates to nitrites, leading to a substantial increase in nitrite levels within the processed matrix (Clayton-Cuch et al., 2025).

From the perspective of botanical groupings, "nitrate accumulators" are most frequently identified among vegetables belonging to families that include typical leafy and stem species: Apiaceae (celery, parsley), Asteraceae (lettuce), Brassicaceae (rocket, Chinese cabbage, etc.), and Amaranthaceae (formerly Chenopodiaceae) (spinach, chard, beetroot) (Santamaria, 2006; Hosseini et al., 2023).

In practice, for technological purposes (including "clean-label" meat products), vegetables are often categorised according to nitrate content (mg/kg fresh weight) as follows (Santamaria, 2006; Dodocioiu et al., 2025):

- > 2500 mg/kg: celery, rocket, lettuce, spinach, chard, radish, beetroot, etc.
- 1000-2500 mg/kg: celeriac, Chinese cabbage, endive, leek, parsley, etc.
- 500-1000 mg/kg: cabbage, Savoy cabbage, turnip, etc.
- 200-500 mg/kg: carrot, cucumber, pumpkin, broccoli, etc.
- < 200 mg/kg: potato, tomato, onion, mushrooms, asparagus, etc.

When vegetables are used as juice, concentrate, or powder, water removal and concentration result in a higher "nitrate potential" per unit mass, which is practically relevant for formulations in which plant ingredients are applied as natural nitrate sources (Munekata et al., 2021; Kim, Bae, et al., 2025).

Within "clean-label" technologies for meat products, nitrates from plant sources can be controllably reduced to nitrites by nitrate-reducing microorganisms in starter cultures (e.g., *Staphylococcus carnosus*, *S. xylosus*), under appropriate incubation/processing conditions. This principle ($NO_3^- \rightarrow NO_2^-$) underpins so-called indirect/"natural" curing and is described in both review papers and more recent experimental studies using vegetable powders and starter cultures (Eisinaitė et al., 2020; Munekata et al., 2021; Kim, Bae, et al., 2025; Kos et al., 2025).

Sugita et al. (1993), in research on nitrite-free systems, used radish extract (1% and 3%) in combination with sodium ascorbate, obtaining products with a characteristic colour and flavour similar to those of heat-treated and cured meat products.

Riel et al. (2017) evaluated parsley extract powder as an alternative to the direct addition of sodium nitrite in mortadella-type sausages and showed that, particularly at higher inclusion levels, it reduced Listeria monocytogenes growth, maintained redness comparable to the nitrite-cured control up to day 21, and achieved overall acceptance comparable to the conventional control.

Celery, similarly to parsley, accumulates substantial amounts of nitrates and is therefore frequently used in natural curing systems. In this context, Sindelar et al. (2007) investigated the effects of vegetable juice powder and incubation time on several quality-related parameters of ready-to-eat uncured ham, including colour, residual nitrate and nitrite, pigment characteristics, pH, and trained sensory attributes. Their findings supported the view that vegetable-derived curing systems can contribute to the development of properties associated with conventionally cured meat products.

Likewise, Magrinyà et al. (2009) evaluated celery concentrate as an alternative nitrate source in dry-cured sausages and showed that its effects should be interpreted within the specific formulation tested, particularly with regard to colour stability, residual nitrate/nitrite behaviour, and overall product acceptability.

Horsch et al. (2014) examined the effect of pH and nitrite concentration from celery juice concentrate on the growth of Listeria monocytogenes in broth and on ham slices, and also evaluated the influence of these factors on selected ham quality attributes. Their results indicated that the antimicrobial performance of celery juice concentrate depends strongly on formulation conditions, particularly pH and nitrite concentration.

Golden et al. (2014) investigated the inhibition of Listeria monocytogenes in deli-style turkey breast formulated with cultured celery powder and/or cultured sugar-vinegar blend during storage at 4°C. Their study showed that such formulations can contribute to microbial control in poultry products cured alternately.

In dry fermented sausages, Eisinaitė et al. (2016) applied 3% freeze-dried celery, celery juice, parsley, parsnip, and leek and observed no adverse effects on the technological process; sausages produced with celery products showed more stable colour, while samples with celery juice were additionally characterised by higher lightness and lower hardness at the end of ripening.

Jin et al. (2018) similarly reported that cooked sausages containing 0.8% celery powder developed a red colour and acceptable sensory characteristics, with no significant deterioration in quality during storage.

Madentzidou et al. (2012) reported that salt-stressed fresh-cut leek enhanced microbial activity and product stability and shortened the storage time required for the development of quality characteristics in traditional Greek sausages.

Choi et al. (2017) reported that pre-converted nitrite from red beet used in combination with ascorbic acid improved redness relative to the negative control and produced quality characteristics comparable to those of the nitrite-containing treatment.

Hwang et al. (2018) used pre-converted nitrite from spinach, lettuce, celery, and red beet in raw and cooked pork sausages and found that spinach-derived nitrite produced the highest redness in cooked samples among the natural-source treatments.

Kim et al. (2019a) showed that the combination of fermented spinach-derived nitrite and sodium nitrite improved quality characteristics of cured pork loin, indicating that partial replacement may be more effective than complete substitution.

Kim et al. (2019b) used pre-converted nitrite from frozen chard powder and reported the highest CIE a* value (9.08) and the best lipid oxidative stability in semi-dry cured pork loin produced with chard powder.

In fermented dry sausages, Ozaki et al. (2021) showed that radish and beetroot powders (0.5–1.0%) can promote nitrite formation during ripening, with changes in moisture/mass loss and aw, and measurable effects on colour and oxidative stability observed. The authors identified 1% radish as the most promising option within their study design.

Gwak et al. (2024) examined Chinese cabbage and radish powders prepared using different processes (filtered-juice powder versus “crushed” powder) in ground pork sausages. They reported that the type of vegetable powder (and its preparation method) influenced redness and curing-related parameters, indicating that selecting the vegetable species alone is insufficient; the powder-production technology is critical for achieving a consistent curing effect.

Sheng et al. (2025) explicitly compared organic and conventional vegetable-based curing ingredients and monitored their effects on the quality and sensory attributes of frankfurters. Studies of this type are important because, in practice, market ingredients are processed differently and may therefore behave differently within the meat matrix.

Overall, the more recent literature (2021–2025) indicates that vegetable nitrate sources (radish/beetroot/Chinese cabbage/celery, as well as fermented vegetable powders) can provide a curing effect (colour development/pigment formation/residual nitrite) across different categories of meat products; however, outcomes are strongly dependent on standardisation of the plant raw material, the preparation approach (powder/juice/“crushed”), and processing conditions (incubation, starter culture, reducing agents). A recurring limitation is the need for improved control of oxidative stability and systematic monitoring of nitrosamines, particularly in thermally processed or complex products (Bernardo et al., 2021; Kim, Bae, et al., 2025; Zhang et al., 2023).

3. HURDLE TECHNOLOGIES FOR NITRITE REDUCTION: SYNERGY BETWEEN NATURAL INGREDIENTS AND NOVEL PROCESSES

The concept of hurdle technology (the combination of multiple “barriers” to ensure safety and stability, rather than relying on a single measure) is increasingly regarded as the most realistic route for nitrite reduction, because nitrite performs multiple functions (colour development and stability, oxidative protection, microbiological stability, and characteristic sensory attributes), and a single “straightforward” substitute rarely replicates all these effects. Within clean-label approaches (formulations based on “natural”/consumer-acceptable ingredients with fewer synthetic additives), Kim, Bae, et al. (2025) emphasise that the most successful formulations are synergistic systems (e.g., nitrate-rich plant sources + nitrate-reducing starter cultures that convert nitrate to nitrite/NO during processing, together with antioxidants and well-controlled processing conditions), rather than the isolated replacement of a single additive.

In this context, Andrade et al. (2025) provide a systematic review of non-thermal technologies (processes that are not conventional thermal pasteurisation/sterilisation) as processing "hurdles" for partial or complete nitrite replacement, focusing on the balance between antimicrobial efficacy and potential effects on N-nitrosamines (compounds that may form through nitrosation and are considered a potential health concern), as well as the risk of changes in product stability and sensory quality. The authors indicate that technologies such as high-pressure processing (HPP), pulsed electric fields (PEF), and cold plasma (a low-temperature ionised gas with antimicrobial activity) may serve as useful additional barriers in the "reformulation" of reduced-nitrite products.

The practical value of the hurdle approach is evident in studies where reduced nitrite + processing technology + packaging/storage operate together. For example, Molina et al. (2025) report that in cooked ham it is feasible to reduce nitrite to 40 mg kg^{-1} and apply HPP (600 MPa/3 min) without significant deterioration of colour, odour, and texture during storage. The authors also highlight that the packaging system (e.g., vacuum packaging or modified-atmosphere packaging, MAP) can strongly influence odour and oxidative changes.

In fermented sausages, Lopez et al. (2021) demonstrate the need for a multi-step barrier strategy in nitrite-free and low-nitrite systems. They employ acidification and ripening (as natural barriers through pH reduction and decreased water activity) and add HPP as an additional hurdle to control indicator microorganisms such as Salmonella spp. (multiple species within the genus Salmonella) and Listeria innocua (a non-pathogenic model organism frequently used to indicate the behaviour of Listeria).

Beyond microbiological control, hurdle strategies must also address colour, which is often the main limitation when nitrite is eliminated. Molina et al. (2024) propose combining natural colourants (e.g., betanin/plant extracts) with PEF as a pre-treatment to provide stronger technological support for the desired effect within the product matrix.

Another promising direction is the development of non-traditional nitrite sources for controlled application. Marcinkowska-Lesiak et al. (2024) optimise plasma-activated egg white (material treated with cold plasma to generate a functional "nitrite profile") to produce powders that can serve as a nitrite source, while proposing a practical inclusion limit (maximum 2%) to maintain stability and controlled functionality.

Finally, not every processing hurdle produces uniformly positive outcomes across different product matrices. For instance, Kim, Kim, et al (2025) evaluate pre-converted natural nitrite (nitrite generated from nitrate in the raw material/ingredient prior to addition to the product) in combination with ascorbic acid (vitamin C as a reducing/antioxidant agent) and ultrasound marination (ultrasound to enhance uptake and processing effects). Their findings indicate that synergy must be optimised on a product-specific basis (composition × process × conditions).

4. CONCLUSION

Reducing nitrite levels in processed meat products is feasible, provided that the product's key technological functions are maintained, particularly colour development and stability, lipid oxidative stability, microbiological stability, and acceptable sensory quality. Nitrate-rich plant sources, combined with nitrate-reducing starter cultures, represent a promising clean-label alternative that delivers a curing effect and quality attributes comparable to those of conventional formulations. However, outcomes vary considerably and depend on the standardisation of the plant raw material (species/cultivar, seasonal and agronomic influences), the ingredient format (juice, concentrate, or powder), and the precise control of processing conditions that determine nitrate-to-nitrite conversion and stability within the meat matrix. Therefore, systematic monitoring of residual nitrite/nitrate and the assessment of potential *N*-nitrosamine formation - particularly in thermally processed products, where nitrosation conditions may be more favourable - are essential to ensure consistent quality, safety, and reproducible industrial performance.

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