

DEVELOPMENT AND STABILITY OF COLOUR IN DRY-CURED MEAT PRODUCTS PRODUCED WITH PLANT-BASED SOURCES OF NITRATES

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Abstract: This study aims to investigate the effect of Swiss chard powder, as a natural source of nitrates, in combination with the starter culture *BactoFerm Rosa*, on the development and stability of colour in dry-cured pork neck produced under industrial conditions. Five experimental groups were analysed: NC - negative control (sodium chloride and dextrose); PC - positive control (nitrite curing salt and dextrose); NS - nitrite curing salt, dextrose and starter culture; SCF - sodium chloride, dextrose, Swiss chard powder (from the first producer) and starter culture; and SCS - sodium chloride, dextrose, Swiss chard powder (from the second producer) and starter culture. Colour parameters (L^* , a^* , b^* , h° , C^*) were monitored on fresh cut surfaces at three stages of the production process: day 0 (12 hours after salting), after smoking (before onset of ripening), and at the end of production. The results revealed statistically significant differences ($p \leq 0.05$) among the examined groups at all analysed stages. The most intense and stable red colour was observed in samples treated with nitrite curing salt in combination with the starter culture. In contrast, the negative control group exhibited the lightest and least saturated colour. The groups supplemented with Swiss chard powder and starter culture showed moderate but stable red colour development, significantly better than the negative control, but with lower intensity than the nitrite-treated groups. These findings indicate that natural plant-based sources of nitrates, in combination with nitrate-reducing starter cultures, can provide moderate and stable colour formation in dry-cured meat products and represent a promising partial alternative to conventional nitrite curing in the production of clean-label meat products.

Keywords: clean label, starter culture, nitrates, nitrites, plant-based sources, colour

1. INTRODUCTION

Dry-cured meat products represent an important segment of the meat processing industry, characterized by distinctive sensory attributes and extended shelf life. Among these products, dry-cured pork neck has gained increasing consumer acceptance due to its characteristic texture, flavour profile, and visual appearance, which strongly influence purchasing decisions. In particular, colour is considered a primary quality indicator, as it directly affects consumer perception of freshness and overall product quality (Kolev et al., 2022).

The development of the typical reddish-pink colour in cured meat products is primarily associated with the use of nitrites. Nitrites play a crucial technological role by stabilising meat pigments, inhibiting lipid oxidation, and contributing to microbiological safety (Premi et al., 2024; Škrlep et al., 2022; Tahmouzi et al., 2025). Their interaction with myoglobin leads to the formation of nitrosylmyoglobin, which is responsible for the stable red colour characteristic of cured meat products (Flores & Toldrá, 2021). Owing to these multiple technological functions, nitrites remain widely applied in the meat industry (Zhang et al., 2023).

However, mounting scientific evidence has raised concerns about the potential health risks of nitrite consumption. These risks are mainly associated with the formation of N-nitroso compounds, which may occur during processing and digestion (Bak et al., 2025; Nardin et al., 2025; Sheng et al., 2025). As a result, regulatory authorities and consumers alike have become more cautious regarding the use of synthetic curing agents in food products.

In parallel, contemporary consumers increasingly favour foods perceived as natural, minimally processed, and free from artificial additives. This shift has spurred the development of so-called clean-label meat products, characterised by simplified ingredient lists composed of recognizable, naturally derived components (Roobab et al., 2021; Inguglia et al., 2023; Kim et al., 2025).

Recent studies have explored the potential of nitrate-rich vegetables such as celery, Swiss chard, beetroot, leek, and radish as natural curing agents. These plant-based sources are typically used in combination with starter cultures containing nitrate-reducing bacteria, which convert nitrate to nitrite during fermentation and ripening (Kim et al., 2019; Yong et al., 2020; Shakil et al., 2022; Eleiwa et al., 2025). This approach allows for the development of cured meat colour while complying with clean-label requirements. Nevertheless, regulatory limitations in the European Union restrict the use of pre-fermented nitrate extracts, making direct application of plant powders in combination with starter cultures a more acceptable strategy (Silovska Nikolova et al., 2023).

This study builds upon our previous research on dry-cured pork loin (Silovska Nikolova et al., 2023) by extending the investigation to dry-cured pork neck, a muscle with different structural and technological characteristics. The main objective was to evaluate the feasibility of replacing synthetic nitrites with Swiss chard powder, used as a

natural nitrate source in combination with a nitrate-reducing starter culture, in order to ensure stable colour development under industrial production conditions.

2. MATERIALS AND METHODS

Materials

The experiment was conducted under industrial conditions at the meat processing plant Rimes MS Group (North Macedonia). The experimental design and technological procedure were adapted from our previously published study on dry-cured pork loin (Silovska Nikolova et al., 2023), with specific modifications related to the raw material and ripening conditions for dry-cured pork neck. The company's standard production protocol for dry-cured pork neck served as the basis for the experiment and was optimized according to the objectives of this study.

Production was performed in three independent batches (replications). Within each batch, five experimental groups were prepared:

- **NC (negative control):** table salt (4%) and dextrose (0.5%)
- **PC (positive control):** nitrite curing salt (4%) and dextrose (0.5%)
- **NS:** nitrite curing salt (4%), dextrose (0.5%), and starter culture (0.025%)
- **SCF:** table salt (4%), Swiss chard powder (producer 1) (0.25%), dextrose (0.5%), and starter culture (0.025%)
- **SCS:** table salt (4%), Swiss chard powder (producer 2) (0.25%), dextrose (0.5%), and starter culture (0.025%)

The starter culture used was *BactoFerm Rosa* (Chr. Hansen, Denmark), which contained the nitrate-reducing bacteria *Staphylococcus vitulinus* and *Staphylococcus xylosus*.

Frozen pork neck was used as raw material. Thawing was carried out under dry conditions. After thawing, the pieces were manually trimmed and shaped to obtain uniform samples with typical product characteristics.

Dry curing was performed by evenly distributing the curing mixture on the surface of each piece. The samples were placed on racks and transferred to a cooling chamber, where salting was carried out for 21 days at 0-4 °C and 85–90% relative humidity. During this period, the samples were turned every third day to ensure uniform salt diffusion.

After salting, cold smoking was performed in a smoking chamber at 22 °C and 82% relative humidity. Smoking lasted one day, with smoke application every three hours for 40 minutes.

Following smoking, the samples were transferred to a climate-controlled chamber for fermentation and ripening. At the beginning of this phase, the temperature was maintained at 22 °C and the relative humidity at 82%. During ripening, the temperature was gradually reduced to 12 °C, while the relative humidity was decreased to 72%. The ripening process lasted 45 days.

Methods

Instrumental colour analysis was performed at the following stages: on day 0 (12 hours after salting), after smoking (before onset of ripening), and at the end of production.

Colour was measured on a fresh cut surface using a Dr Lange spectrophotometer. Ten parallel measurements were performed for each sample. Measurements were conducted at room temperature (20 °C) with a maximum temperature deviation of ± 2 °C. From the obtained L^* , a^* , and b^* values, the following colour parameters were calculated using mathematical formulas: hue angle (h°) and colour saturation (C^*).

The hue angle (h) was calculated using the following formula:

$$h^\circ = \tan^{-1} (b^* / a^*)$$

Colour saturation (C^*) was calculated using the following formula:

$$C^* = \sqrt{(a^{*2} + b^{*2})}$$

For each sample, the mean of 10 instrumental measurements was calculated and used for statistical analysis. Descriptive statistics (mean values and standard deviations) were determined for all colour parameters (L^* , a^* , b^* , h° , and C^*). The effects of treatment group and production batch on colour parameters were evaluated using a general linear model (GLM) according to the equation:

$$Y_{ijk} = \mu + G_i + P_j + \varepsilon_{ijk}$$

where Y_{ijk} represents the observed colour parameter, μ is the overall mean, G_i is the fixed effect of treatment group (NC, PC, NS, SCF, SCS), P_j is the random effect of production batch ($j = 1, 2, 3$), and ε_{ijk} is the residual error.

Statistical analyses were performed separately for each production stage (day 0 (12 hours after salting), after smoking (before onset of ripening), and at the end of production). Differences among mean values were determined using Duncan's multiple range test at a significance level of $p \leq 0.05$.

All statistical analyses were performed using IBM SPSS Statistics, version 23 (IBM Corp., 2015).

3. RESULTS AND DISCUSSION

Table 1 presents the colour values of the analysed dry-cured pork neck groups 12 hours after salting on a fresh cut surface, where clear and statistically significant differences among the groups were observed ($p \leq 0.05$). In the NC group, 12 hours after salting, the highest L^* value (48.36) and h° value (67.80°), as well as the lowest a^* value (2.60) and C^* value (6.74), were recorded, indicating the lightest, least saturated colour and minimal development of the red component. This result is expected, considering that the samples were cured exclusively with table salt.

In the PC group, a relatively high L^* value (47.70) was observed, along with a significantly higher a^* value (5.13) than in the NC group, indicating the initial development of red colour following nitrite salt application. The NS group, which included a starter culture in addition to nitrite salt, showed the highest a^* value (7.22) and C^* value (10.61), as well as the lowest h° value (45.32°), indicating the most intense and saturated red colour. This may result from enhanced nitrite reduction and faster pigment stabilisation under the influence of the starter culture. In groups supplemented with Swiss chard powder in combination with starter culture (SCF and SCS), moderate a^* values (4.70 and 4.27) and C^* values (8.87 and 8.84) were observed, indicating moderate red colour development and saturation compared to the nitrite-treated groups.

Table 1. L^* , a^* , b^* , h° , C^* values on a fresh cut surface of dry-cured pork neck on day 0 (12 hours after salting) (Duncan's test, $\alpha = 0.05$)

Colour parameters	Groups of dry-cured pork neck				
	NC	PC	NS	SCF	SCS
	$\bar{x} \pm SD$				
L^*	48.36 ± 2.03^a	47.70 ± 2.37^{ba}	46.49 ± 3.65^{cb}	44.53 ± 2.38^d	45.08 ± 3.79^{dc}
a^*	2.60 ± 0.88^d	5.13 ± 0.77^b	7.22 ± 1.29^a	4.70 ± 1.17^{cb}	4.27 ± 0.88^c
b^*	6.40 ± 0.84^b	5.65 ± 0.94^c	7.39 ± 0.91^a	7.12 ± 1.25^a	7.31 ± 1.08^a
h°	67.80 ± 9.33^a	47.07 ± 9.61^c	45.32 ± 9.39^c	56.71 ± 9.90^b	59.32 ± 8.93^{ba}
C^*	6.74 ± 0.96^c	7.88 ± 0.89^c	10.61 ± 0.98^a	8.87 ± 1.41^b	8.84 ± 1.06^b

\bar{x} – mean value; SD – standard deviation; mean values marked with different letters within the same row are statistically significantly different ($p \leq 0.05$).

Source: Author's own research

After completion of smoking, i.e., before the onset of ripening, statistically significant differences in colour values on the fresh cut surface were observed among the analysed dry-cured pork neck groups ($p \leq 0.05$) (Table 2), indicating different degrees of colour development and stability. As expected, in the NC group, due to the absence of nitrites, the lowest a^* value (3.04) and C^* value (5.97) were recorded, along with the highest hue angle (h°) value (53.04°), indicating a weakly expressed, poorly saturated red colour.

Table 2. L^* , a^* , b^* , h° , C^* values on a fresh cut surface of dry-cured pork neck after completion of smoking, before the onset of ripening (Duncan's test, $\alpha = 0.05$)

Colour parameters	Groups of dry-cured pork neck				
	NC	PC	NS	SCF	SCS
	$\bar{x} \pm SD$				
L^*	38.90 ± 0.56^b	41.69 ± 1.17^a	41.15 ± 1.28^a	34.20 ± 0.70^c	41.11 ± 1.41^a
a^*	3.04 ± 0.63^d	11.06 ± 1.11^b	11.83 ± 0.95^a	7.19 ± 1.20^c	6.94 ± 1.05^c
b^*	4.09 ± 0.72^c	5.64 ± 1.00^a	5.50 ± 1.10^a	4.82 ± 0.69^b	4.71 ± 0.86^b
h°	53.04 ± 11.00^a	27.16 ± 6.10^{cb}	24.16 ± 7.60^c	34.00 ± 7.18^b	34.90 ± 7.97^b
C^*	5.97 ± 0.81^d	12.00 ± 1.24^b	13.66 ± 0.87^a	8.96 ± 1.15^c	8.70 ± 1.09^c

\bar{x} – mean value; SD – standard deviation; mean values marked with different letters within the same row are statistically significantly different ($p \leq 0.05$).

Source: Author's own research

In the PC group, significant increases in a^* (11.06) and C^* (12.00) values were observed, accompanied by a pronounced decrease in h° (27.16°), indicating the stable development of red colour resulting from nitrite salt application. The most pronounced colour development was recorded in the NS group, where the highest a^* value (11.83) and C^* value (13.66), as well as the lowest h° value (24.16°), were registered, indicating the most intense and most saturated red colour among all analysed groups, as a result of the synergistic effect of nitrite salt and starter culture. In the groups supplemented with Swiss chard powder in combination with starter culture (SCF and SCS), the a^* values (7.19 and 6.94) and C^* values (8.96 and 8.70) were statistically significantly higher compared to the NC group, indicating that natural sources of nitrites contribute to improved colour development, although with lower intensity compared to the nitrite-treated groups.

Table 3 presents the colour values on the fresh cut surface of dry-cured pork neck at the end of the production process, where clear and statistically significant differences among the analysed groups were again observed ($p \leq 0.05$). In the NC group, as in the previous stages, the highest L^* value (36.22) and h° value (45.76°), together with the lowest a^* value (4.08) and C^* value (5.82), were recorded, indicating the lightest, least saturated, and weakly expressed red colour. This result is expected, considering that only table salt was used in this group, resulting in limited development and stability of red colour. In the PC group, a significantly lower L^* value (33.59) and a pronounced increase in a^* value (11.61) and C^* value (12.04) were observed, accompanied by a significant decrease in h° value (21.56°), indicating a well-developed, intense, and stable red colour as a result of the conventional use of nitrite curing salt. The most pronounced final colour development was recorded in the NS group, where the lowest L^* value (30.41), the highest a^* value (12.85), and C^* value (13.22), as well as the lowest h° value (20.04°), were registered. These results indicate the darkest, most intense, and most saturated red colour among all analysed groups, which can be attributed to the synergistic effect of nitrite curing salt and starter culture, particularly during the ripening stages. In the groups supplemented with Swiss chard powder in combination with starter culture (SCF and SCS), moderate but stable a^* values (9.33 and 8.72) and C^* values (10.92 and 9.15) were observed, which were statistically significantly higher compared to the NC group but lower than those of the PC and NS groups. This indicates that natural sources of nitrites ensure acceptable, relatively stable development of red colour in the final product, although with slightly lower intensity than in the groups cured with nitrite salt. The obtained results are consistent with literature data (Zhang et al., 2023; Kim et al., 2025; Kim et al., 2019; Silovska Nikolova et al., 2023). Differences between the SCF and SCS groups also suggest that the plant source's origin and composition may affect the final colour parameters.

Table 3. L^* , a^* , b^* , h° , C^* values on a fresh cut surface of dry-cured pork neck at the end of the production process (Duncan's test, $\alpha = 0.05$)

Colour parameters	Groups of dry-cured pork neck				
	NC	PC	NS	SCF	SCS
	$\bar{x} \pm SD$				
L^*	36.22 ± 1.24 ^a	33.59 ± 1.17 ^b	30.41 ± 0.97 ^c	30.97 ± 1.47 ^c	33.18 ± 1.47 ^b
a^*	4.08 ± 0.97 ^e	11.61 ± 1.08 ^b	12.85 ± 0.84 ^a	9.33 ± 0.69 ^c	8.72 ± 0.68 ^d
b^*	4.10 ± 0.75 ^c	4.67 ± 1.12 ^{ba}	4.69 ± 0.96 ^{ba}	4.83 ± 1.09 ^a	4.25 ± 0.85 ^{cb}
h°	45.76 ± 11.35 ^a	21.56 ± 6.30 ^{dc}	20.04 ± 5.15 ^d	27.90 ± 7.79 ^b	26.65 ± 7.43 ^{cb}
C^*	5.82 ± 0.91 ^e	12.04 ± 1.11 ^b	13.22 ± 0.79 ^a	10.92 ± 0.73 ^c	9.15 ± 0.58 ^d

\bar{x} – mean value; SD – standard deviation; mean values marked with different letters within the same row are statistically significantly different ($p \leq 0.05$).

Source: Author's own research

Overall, the negative control group (NC) was, as expected, characterised by a light, poorly saturated, and insufficiently developed red colour at all production stages and at the end of processing due to curing with table salt. In contrast, the groups supplemented with nitrite curing salt (PC and especially NS) exhibited a significantly more intense and more stable red colour. A more pronounced effect was observed in the group of dry-cured pork neck treated with nitrite curing salt in combination with starter culture, which is consistent with literature data and confirms that starter cultures significantly promote nitrite reduction and pigment stabilisation in meat products (Zhang et al., 2023; Kolev et al., 2022; Silovska Nikolova et al., 2023). In the groups supplemented with Swiss chard powder in combination with starter cultures (SCF and SCS), a moderate and stable development of red colour was observed compared to the negative control group (NC), but with lower intensity compared to the groups of dry-cured pork neck treated with nitrite curing salt (PC and NS). Natural plant-based sources of nitrates, combined with starter cultures, may represent an alternative to synthetic nitrites.

4. CONCLUSION

Based on the results, it can be concluded that Swiss chard powder, in combination with the starter culture *BactoFerm Rosa*, contributes to the development of a moderate and stable colour in dry-cured pork neck. Natural plant-based nitrate sources, combined with starter cultures containing nitrate-reducing bacteria, may partially replace synthetic nitrites for colour development, although with lower intensity than conventional nitrite curing. Given that the study was conducted under industrial conditions, these findings provide practical insight into the potential application of clean-label strategies in dry-cured meat production.

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