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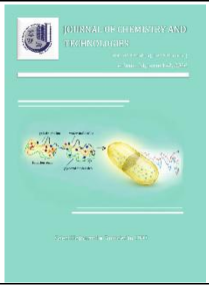

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TECHNOLOGIES FOR REDUCING NITRATE CONTENT IN MEAT PRODUCTS DURING PROCESSING

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Abstract

Nitrites are widely used in the meat industry to stabilise colour and ensure microbiological safety of products; however, potential health risks associated with their use necessitate the search for safer alternatives. This study aimed to evaluate the effectiveness of plant extracts (rosemary, green tea, and pomegranate), containing bioactive compounds with antioxidant properties, in minced meat matrices as factors capable of slowing oxidative processes and influencing microbiological and quality parameters of the products. Pork minced meat samples were treated with aqueous-alcoholic extracts of rosemary, green tea and pomegranate at concentrations of 0.3–0.5 %, stored at +4 °C for 21 days and analysed for microbiological indicators, colour parameters, sensory characteristics and level of lipid oxidation. Among the extracts tested, rosemary (0.5 %) showed the highest efficacy: the number of microorganisms after 21 days was 2.8×10^4 colony-forming units per gram (compared to 3.2×10^4 in the control; $p < 0.05$), the level of malondialdehyde decreased by 33 % (1.2 ± 0.1 mg/kg), and the red hue ($a^* = 9.5 \pm 0.2$) remained stable. Green tea extract (0.3 %) and pomegranate extract (0.4 %) reduced lipid oxidation by 22 % and 11 %, respectively, but had a smaller effect on colour retention. The sensory evaluation results showed that rosemary extract received better scores for aroma (8.7 ± 0.4/10) and overall acceptability (8.9 ± 0.3/10), while pomegranate extract received mixed scores due to its fruity notes. No significant differences in texture were observed among the samples. These results confirm that natural antioxidants – in particular rosemary – can serve as an effective alternative to synthetic nitrates, providing microbiological stability, reducing oxidation and maintaining consumer-acceptable quality attributes. Practical applications include the addition of such extracts to premium meat products and their combined use to enhance the synergistic effect. This study provides a basis for the development of formulations with reduced artificial additives, in line with current trends in health and nutrition.
Keywords: food industry; rosemary extract; malondialdehyde; minced pork; natural antioxidants.

ТЕХНОЛОГІЇ ЗМЕНШЕННЯ ВМІСТУ НІТРАТІВ У М'ЯСНИХ ПРОДУКТАХ ПІД ЧАС ПЕРЕРОБКИ

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Анотація

Нітрити широко застосовуються в м’ясній промисловості для стабілізації кольору та забезпечення мікробіологічної безпечності продукції; однак потенційні ризики для здоров’я, пов’язані з їх використанням, зумовлюють необхідність пошуку безпечніших альтернатив. Метою даного дослідження була оцінка ефективності рослинних екстрактів (розмарину, зеленого чаю та граната), що містять біоактивні сполуки з антиоксидантними властивостями, в системах м’ясного фаршу як факторів, здатних уповільнювати окиснювальні процеси та впливати на мікробіологічні й якісні показники продукції. Зразки свинячого фаршу обробляли водно-спиртовими екстрактами розмарину, зеленого чаю та граната в концентраціях 0.3–0.5 %, зберігали за температури +4 °C протягом 21 доби та аналізували за мікробіологічними показниками, параметрами кольору, сенсорними характеристиками та рівнем окиснення ліпідів. Серед досліджених екстрактів найвищу ефективність продемонстрував розмарин (0.5 %): кількість мікроорганізмів через 21 день становила 2.8×10^4 колонієутворюючих одиниць на грам (порівняно з 3.2×10^4 у контролі; $p < 0.05$), рівень малонового діальдегіду знизився на 33 % (1.2±0.1 мг/кг), а червоний відтінок ($a^* = 9.5 \pm 0.2$) залишився

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стабільним. Екстракт зеленого чаю (0.3 %) та екстракт граната (0.4 %) зменшили окиснення ліпідів на 22 % та 11 % відповідно, але мали менший вплив на збереження кольору. Результати сенсорної оцінки показали, що екстракт розмарину отримав кращі оцінки за аромат (8.7 ± 0.4/10) та загальну прийнятність (8.9 ± 0.3/10), а екстракт граната отримав неоднозначні оцінки через свої фруктові нотки. Текстура залишалася однаковою в усіх зразках. Ці результати підтверджують, що природні антиоксиданти – зокрема розмарин – можуть слугувати ефективною альтернативою синтетичним нітратам, забезпечуючи мікробіологічну стабільність, зменшуючи окислення та зберігаючи якості, привабливі для споживачів. Практичне застосування включає додавання таких екстрактів до м'ясних продуктів преміум класу та їхнє комбіноване використання для посилення синергетичного ефекту. Це дослідження закладає основу для розробки рецептур зі зменшеним вмістом штучних добавок, що відповідає сучасним тенденціям у сфері здоров'я та харчування.
Ключові слова: харчова промисловість; екстракт розмарину; малондіальдегід; свинячий фарш; природні антиоксиданти.

Introduction

Synthetic nitrates and nitrites are major components in the meat industry, where they serve to stabilise colour, inhibit pathogenic microorganisms, and extend the shelf life of the product. However, their ability to form carcinogenic nitrosamines during heat treatment or in the gastric environment poses a significant risk to human health. This problem has prompted both the scientific and industrial communities to search for safer alternatives, as emphasised by O. V. Onoprienko and V. D. Vinyk [1]. This issue has become particularly relevant in light of the growing consumer demand for "clean label" products with a reduced content of artificial additives. Research in the period from 2020 to 2025 is increasingly focusing on natural antioxidants – in particular, plant extracts – that can act as preservatives, colourants, and stabilisers. For example, E. N. Ponnampalam et al. [2] demonstrated that plant-derived polyphenols effectively reduce lipid and protein oxidation in meat products, while R. Kaur et al. [3] reported that rosemary extract exhibits strong antimicrobial properties due to the presence of carnosic acid, which disrupts bacterial membranes. However, much of the existing literature focuses on the individual effects of natural antioxidants, such as their effects on oxidative stability or colour retention, without providing a comprehensive assessment of their potential to fully replace synthetic nitrates. This limitation is highlighted by Y. Zhang et al. [4], who emphasise the need for a broader assessment.

A critical gap in the scientific discussion is the lack of comparative analyses of different natural extracts – such as rosemary, green tea, and pomegranate – on their effects on all key meat quality parameters: microbiological stability, colour, texture, and lipid oxidation. For example, the study by M.V. Shynkaruk and O.O. Baluk [5] highlights the potential use of plant extracts in kraft sausages, but does not establish optimal concentrations for industrial application. Although the authors used extract concentrations ranging from 0.1 % to 0.5 %, their study did not evaluate the stability of these compounds over long storage periods. In addition, there is a significant lack of data on the interaction of natural extracts with meat components during long-term storage, especially under conditions that mimic real industrial processing conditions. This drawback limits the practical implementation of such extracts in large-scale production settings, where standardised protocols and reproducible results are of utmost importance.

Studies by K. Ferysiuk and K.M. Wójciak [6] demonstrated that plant ingredients, such as spinach and beetroot extracts, can reduce nitrite content in meat products by 30–50 %. However, their effects on colour and texture remain poorly understood. The authors noted that certain extracts cause undesirable changes in the appearance of the product, such as surface darkening, which may negatively affect consumer perception. Since visual appeal is a critical factor in product selection, this issue requires further investigation. N. Echegaray et al. [7] developed methodologies for assessing the antioxidant capacity of meat products and emphasized the need for standardization of assessment approaches to ensure reliable comparisons between different extracts. They recommended combining methods in vitro and in vivo tests, such as oxygen radical absorbance capacity (ORAC) and thiobarbituric acid reactive substances (TBARS) assays. However, they noted that integrating these methods into industrial quality control remains challenging due to the lack of standardized testing protocols.

Strategies for improving the quality of meat products proposed by C.Ș. Ursachi et al. [8] involve the use of natural additives; however, these strategies do not consider the issue of optimising extract concentrations for industrial applications. Although dosages ranging from 0.2 % to 0.8 % were recommended, no specific recommendations were given for different types of meat or storage conditions. Similarly, I. Gómez et al. [9] reported that processing techniques such as vacuum packaging can enhance the antioxidant efficacy, but the interaction between these technologies and plant extracts requires further study. In particular, the effect of different oxygen levels in packaging on the long-term stability of polyphenols remains unclear. The microbiological risks associated with the reduction of salt and nitrite have been comprehensively investigated by M.J. Fraqueza et al. [10], who concluded that the combined use of natural antioxidants and protective microbiomes could be an effective strategy for the safe replacement of synthetic preservatives. However, the authors emphasised that the selection of appropriate antagonist bacterial strains should be individual for each type of product, which makes it difficult to develop universal solutions.

An important but understudied area is the influence of plant extracts on the sensory characteristics of meat products. For example, pomegranate extract, rich in anthocyanins, can impart fruity notes that may be undesirable in traditional meat products. This has been confirmed by R. Kaur et al. [3], whose sensory panel described the aroma of such samples as “unusual”. Texture, as a critical quality parameter, is also often ignored in the literature. For example, MJ Fraqueza et al. [10] found that some plant extracts can affect the cohesion of protein fibres, although the mechanisms of this effect remain unclear.

The aim of this study was to evaluate the effectiveness of plant extracts (rosemary, green tea, and pomegranate) containing bioactive compounds with antioxidant properties in minced meat matrices as factors capable of slowing down oxidative processes and influencing microbiological and quality parameters of products.

Experimental part

Materials. The study was conducted at the research laboratory of the Department of Technology of Meat, Fish and Seafood Products of the National University of Life and Environmental Sciences of Ukraine. The experimental process consisted of three main stages: sample preparation, their treatment with plant extracts and subsequent analysis of product quality parameters during a 21-day storage period at a temperature of 4 °C. All experimental conditions were strictly controlled, including storage temperature (maintained at 4 ± 0.5 °C) using a Liebherr refrigerator. GN 1063 (Germany).

The study used minced pork (muscle tissue with a mass fraction of fat of 20 ± 2 %), which is characterised by a high susceptibility to oxidative processes and is widely used in the meat industry, which justifies its use as a model matrix for assessing the effectiveness of bioactive compounds. The raw material was obtained from the certified meat processing enterprise "Antonivskyi meat processing plant". One production batch of raw material was used for the study. The selection criteria included: mass fraction of fat 18–22 % (determined by the Soxhlet method), pH 5.6–5.8 (determined using a pH meter HI99163, Hanna Instruments, Romania), as well as the absence of pre-treatment with preservatives and antibiotics. Additionally, the mass fraction of moisture was controlled, which was determined by drying the product sample to a constant mass at a temperature of 100–105 °C according to DSTU ISO 1442:2005 [11], the mass fraction of protein was determined according to DSTU ISO 937:2005 based on the mass fraction of total nitrogen according to the Kjeldahl method [12], the mass fraction of total fat content was determined by the Soxhlet method, which consists in extracting fat from the sample with a solvent, drying the sample, weighing and by the difference between the weighing of the thimbles before and after extraction according to DSTU 8380:2015 [13].

Four groups of minced meat samples were formed for the experiment. The control group contained sodium nitrite (E250) in an amount of 0.02 % by weight of the raw material, which was used as a traditional functional ingredient for colour stabilisation and microflora suppression. The experimental groups differed in the introduction of plant extracts: group 1 – rosemary extract in an amount of 0.5 % by weight of minced meat (obtained using 70 % ethanol); group 2 – green tea extract in an amount of 0.3 % by weight of minced meat (standardised by the content of epigallocatechin gallate ≥ 60 %, extracted with a water-alcohol solution); group 3 – pomegranate extract in an amount of 0.4 % by weight of minced meat (content of punicalagins ≥ 40 %, extracted with a water-alcohol solution). The selected extracts are characterised by high antioxidant activity and the potential to influence the microbiological stability and sensory properties of the product.

Before application, the extracts were dissolved in water in a ratio of 1 : 10 to ensure uniform distribution in the meat matrix; the amount of added water was taken into account when formulating the recipe in order to minimise the impact on the mass fraction of moisture. It should be noted that the use of water-alcohol extracts can additionally affect microbiological indicators due to residual amounts of ethanol, which was taken into account when interpreting the results. After application of the components, the minced meat was thoroughly mixed, samples weighing 100 ± 2 g were formed, vacuum packed using a Multivac C500 apparatus (Germany) and stored in a refrigerated state.

The choice of plant extract concentrations (0.3–0.5 % by weight of minced meat) is due to the need to achieve a balance between antioxidant and antimicrobial effectiveness and maintaining the proper sensory characteristics of the product. According to scientific research [14], it is in this concentration range that polyphenolic compounds of plant origin are able to effectively inhibit lipid oxidation processes and slow down the development of microflora without the formation of excessively pronounced foreign flavours and aromas. Lower concentrations may be insufficient to demonstrate a stabilising effect, while higher ones may negatively affect organoleptic indicators (in particular, impart bitterness or astringency). In addition, the selected dosage levels are consistent with technological recommendations for the use of plant extracts in meat matrices and provide the possibility of their practical application in industrial production conditions.

Quality assessment was performed at 0, 7, 14 and 21 days of storage – intervals were chosen in accordance with industry standards and to simulate real consumption periods. Microbiological stability was determined according to DSTU EN ISO 4833-1:2014 [15], measuring the total number of mesophilic aerobic microorganisms (in CFU/g). Detection of *Salmonella spp.* and *Listeria monocytogenes* was carried out by PCR using a Bio-Rad thermal cycler T 100 (USA). Colour analysis was performed using a Minolta colourimeter CR -400 (Konica Minolta, Japan) using the CIE system Lab* and cylindrical probe P/36 R (Stable Micro Systems, United Kingdom). Lipid oxidation was assessed using the TBARS method (thiobarbituric acid reactive substances, including malondialdehyde), and the results were expressed in mg malondialdehyde (MDA) per kg of product. Sensory evaluation was conducted by a panel of 15 qualified experts (8 women, 7 men, aged 25–50 years, each with at least 3 years of experience) who rated aroma, texture and overall acceptability on a 10-point scale. The ethical principles of conducting human research in accordance with the World Medical Association Declaration of Helsinki [16] were followed; all participants provided written informed consent, and the data obtained were anonymised.

Statistical analysis. Statistical analysis was performed using IBM SPSS Statistics version 26.0. One-way analysis of variance (ANOVA) with Tukey post hoc correction was used for between-group comparisons, and the Mann–Whitney U test was applied to sensory evaluation results. The significance threshold was set at $p < 0.05$. Normality of distribution was tested using the Shapiro–Wilk test.

Results and discussion

Dynamics of microbiological indicators during product storage. The study of the effect of plant extracts (rosemary, green tea, and pomegranate) containing bioactive compounds with antimicrobial properties in the minced pork matrix revealed significant differences in their effect on the microbiological stability of the product during 21 days of storage. The results obtained indicate that the introduction of these extracts contributes to the inhibition of the growth of mesophilic aerobic and facultative anaerobic microflora compared to the control sample.

The most pronounced antimicrobial effect was observed in samples with the addition of rosemary extract, which may be due to the high content of phenolic compounds capable of disrupting the integrity of the cell membranes of microorganisms and inhibiting their metabolic activity. Green tea and pomegranate extracts also exhibited antimicrobial activity, but their intensity was somewhat lower, which may be explained by differences in the composition and concentration of bioactive components.

Microbiological stability analysis under different processing conditions revealed significant differences between the experimental groups using plant extracts enriched with natural bioactive compounds and the control group. The obtained results confirmed the promising use of such extracts as alternatives to synthetic preservatives (in particular, sodium nitrite, E250).

During the 21-day storage period, a gradual increase in the total number of mesophilic aerobic and facultative anaerobic microorganisms (CFU/g) was observed in all samples, but the rate of this process differed significantly between groups. In the control sample treated with sodium nitrite (E250), a more intensive increase in the

Journal of Chemistry and Technologies, 2026, *34*(2), 512-528

microbial load was recorded after the 14th day, while in the experimental samples with the addition of plant extracts, the growth dynamics were more uniform and slower.

At the beginning of the experiment (day 0), all samples were characterised by a comparable level of microbial contamination, which corresponded to the regulatory values for fresh meat raw materials according to the requirements for microbiological indicators of meat semi-finished products (according to DSTU and sanitary standards). By the 7th day, a more pronounced increase in CFU/g was noted in the control group, while in the experimental samples with the addition of 0.5% rosemary extract, 0.3% green tea extract and 0.4% pomegranate extract, the values were $3.8{\times}10^3$, $4.1{\times}10^4$ and $4.5{\times}10^3$ CFU/g, respectively.

By the 14th day, the differences between the control and experimental groups became statistically significant ($p < 0.05$), indicating a pronounced preservative effect of plant extracts. It is important to note that their effect is associated not only with antioxidant activity, which slows down lipid oxidation, but also with the presence of natural antimicrobial components (polyphenols, tannins, flavonoids), which inhibit the growth of microorganisms. At the final stage (day 21), the control group reached $3.2{\times}10^4$ CFU/g – approaching the upper permissible limit for meat products - while groups 1, 2 and 3 demonstrated slower growth of microorganisms (Table 1). Group 1 demonstrated the most effective antimicrobial effect, and the differences from the control group remained statistically significant. Instead, the differences observed in groups 2 and 3 did not exceed $p = 0.07$, which likely reflects the variation in the mechanisms of action of the respective bioactive components.

Table 1

Dynamics of the total number of mesophilic aerobic microorganisms (CFU/g) in experimental groups during 21 days of storage

Group	0th day	7th day	Day 14	Day 21	p -value (compared to control)
Control (E250)	$1.2{\times}10^2$	$5.2{\times}10^3$	$1.8{\times}10^4$	$3.2{\times}10^4$	–
Group 1 (0.5%)	$1.1{\times}10^2$	$3.8{\times}10^3$	$1.2{\times}10^4$	$2.8{\times}10^4$	0.03
Group 2 (0.3%)	$1.3{\times}10^2$	$4.1{\times}10^3$	$1.5{\times}10^4$	$3.0{\times}10^4$	0.07
Group 3 (0.4%)	$1.0{\times}10^2$	$4.5{\times}10^3$	$1.4{\times}10^4$	$3.1{\times}10^4$	0.08

Note: Data are presented as mean ± standard deviation (n =5); p- values were calculated using one-way analysis of variance (ANOVA) with Tukey's correction.
Source: created by the authors

The effectiveness of plant extracts as natural preservatives in inhibiting the growth of microorganisms is due to the high content of polyphenols, terpenes and other bioactive compounds that interact with the cellular structures of pathogenic microorganisms and disrupt their metabolic processes. Rosemary extract (group 1), containing carnosic and rosmarinic acids, exhibits antimicrobial activity by destabilising the lipid layer of the bacterial cell membrane, which leads to an increase in its permeability and loss of intracellular contents. The ability of these compounds to affect enzyme systems and inhibit the replication and oxidative metabolism of microorganisms has also been established. [17]. Green tea extract (group 2), rich in catechins, in particular epigallocatechin-3-gallate (EGCG), exerts antimicrobial effects by inhibiting bacterial enzymes, disrupting energy metabolism, and reducing the adhesion of microorganisms to the product surface, which prevents the formation of biofilms [18; 19]. Pomegranate extract (group 3), containing punicalagin and other hydrolysed tannins, inhibits the activity of bacterial proteases and enzymes involved in protein and energy metabolism, thereby limiting the growth and reproduction of microorganisms [20; 21].

Polymerase chain reaction (PCR) analysis confirmed the absence of DNA of pathogenic microorganisms, in particular *Salmonella spp.* and *Listeria monocytogenes,* in all test samples, which indicates an adequate level of microbiological safety of the product. The results obtained indirectly indicate the pronounced antimicrobial activity of plant extracts, which contain a complex of biologically active compounds with antioxidant and antimicrobial properties. This property is especially important for meat products that are not heat treated before consumption – such as cold-smoked sausages or raw meat delicacies – where the risk of pathogen contamination is particularly high.

At the same time, it should be noted that the study did not assess the effect of the studied plant extracts on *Clostridium botulinum,* which is one of the key pathogens in the technology of sausage products when nitrites and nitrates are used as

Journal of Chemistry and Technologies, 2026, *34*(2), 512-528

inhibitors of its development. Therefore, the question of the effectiveness of plant extracts against this pathogen remains open and requires further specialised research.

Dynamics of physicochemical parameters during product storage. During storage of the test samples, it was found that the physicochemical parameters (moisture, protein, fat and pH content) changed within the limits typical for meat products with partial dehydration and the use of natural preservative components. In general, a gradual decrease in moisture and a slight increase in the concentration of dry matter were observed, which is a consequence of moisture redistribution and evaporation during storage.

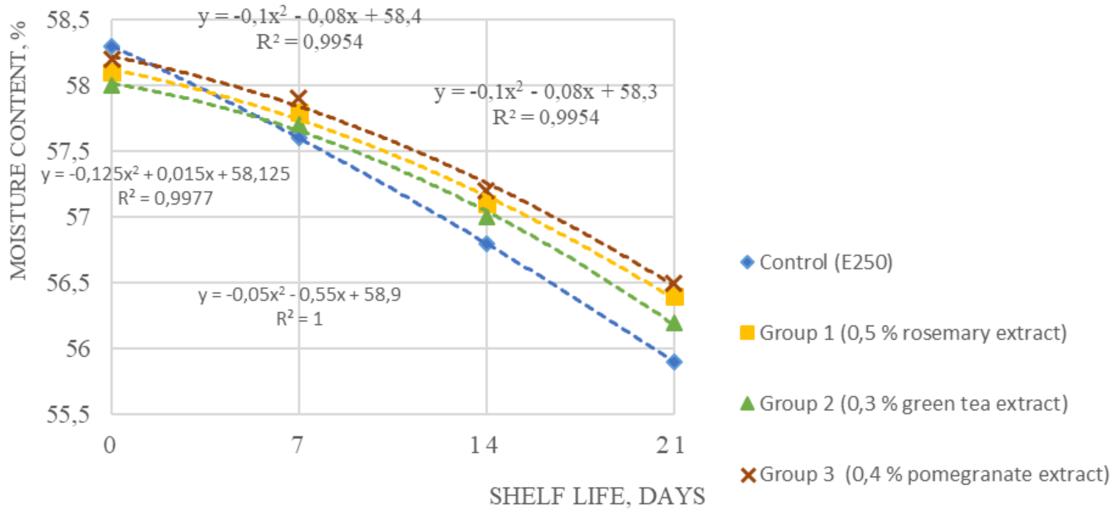

Fig. 1. Dynamics of moisture content during storage of minced meat

It was found that the control sample (E250) had the most intensive decrease in the mass fraction of moisture - from 58.2 % at the beginning of storage to 55.9 % on the 21st day, which indicates active dehydration processes during the studied period. At the same time, in samples with the addition of plant extracts, the rate of moisture reduction was lower, which indicates their stabilising effect.

The highest values of the mass fraction of moisture throughout the entire storage period were recorded in the sample with the addition of 0.4 % pomegranate extract (56.5 % on the 21st day), which may indicate its pronounced moisture-retaining properties. A similar trend was also observed in the samples with the addition of 0.5 % rosemary extract and 0.3 % green tea extract, but the effect was less pronounced.

Analysis of trend dependencies showed that the change in humidity in all groups is adequately described by polynomial equations of the second degree with high coefficients of determination (R^2 = 0.995–1.000), which indicates the stable nature of the dynamics of moisture loss and the correctness of the approximation of experimental data.

The results obtained indicate a positive effect of plant extracts on the preservation of product moisture, which may be associated with their antioxidant and structure-forming properties that slow down dehydration processes during storage.

During storage of the experimental samples for 21 days, it was found that the mass fraction of protein was characterised by high stability and did not undergo significant changes regardless of the processing option. In the control sample (E250), the value of the indicator varied within 18.48–18.53 %, which indicates the absence of intensive processes of hydrolysis of protein substances.

A similar trend was observed in samples with added plant extracts. In the group with rosemary extract (0.5 %), the protein content was 18.50–18.54 %, in the group with green tea extract (0.3%), 18.51–18.59 %, while in the samples with pomegranate extract (0.4 %), slightly higher values were recorded, within 18.54–18.61 % throughout the entire storage period.

The absence of pronounced dynamics of changes in the protein fraction indicates the stability of protein structures in the studied matrix and insignificant activity of proteolytic processes. Minor fluctuations in the indicator are probably due to changes in moisture content and the corresponding concentration of dry matter. Thus, the introduction of plant extracts does not negatively affect the protein composition of the product and ensures the preservation of its nutritional value during storage.

Journal of Chemistry and Technologies, 2026, 34(2), 512-528

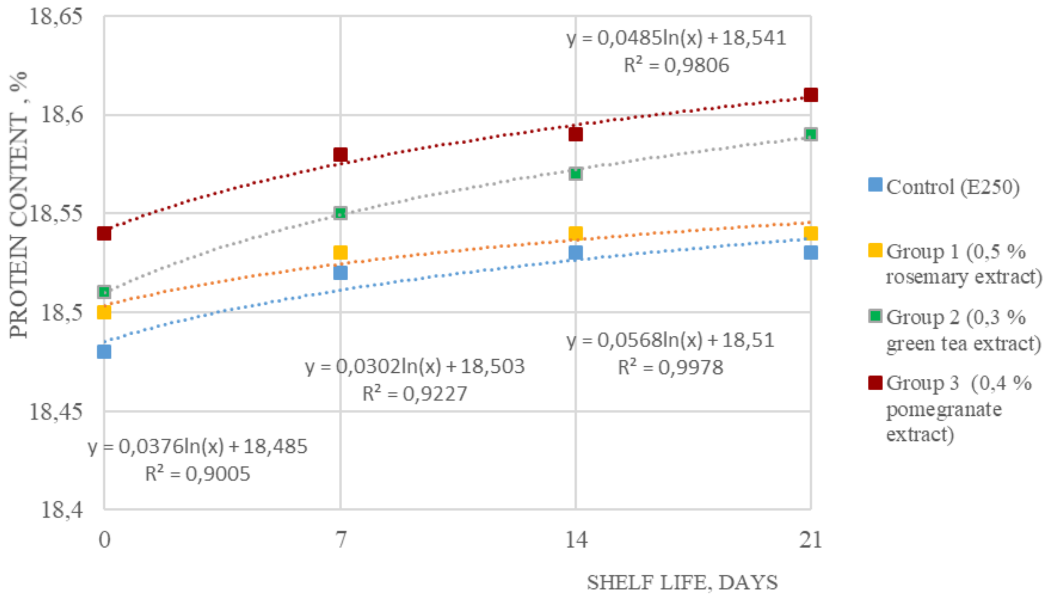

Fig. 2. Dynamics of protein content during storage of minced meat

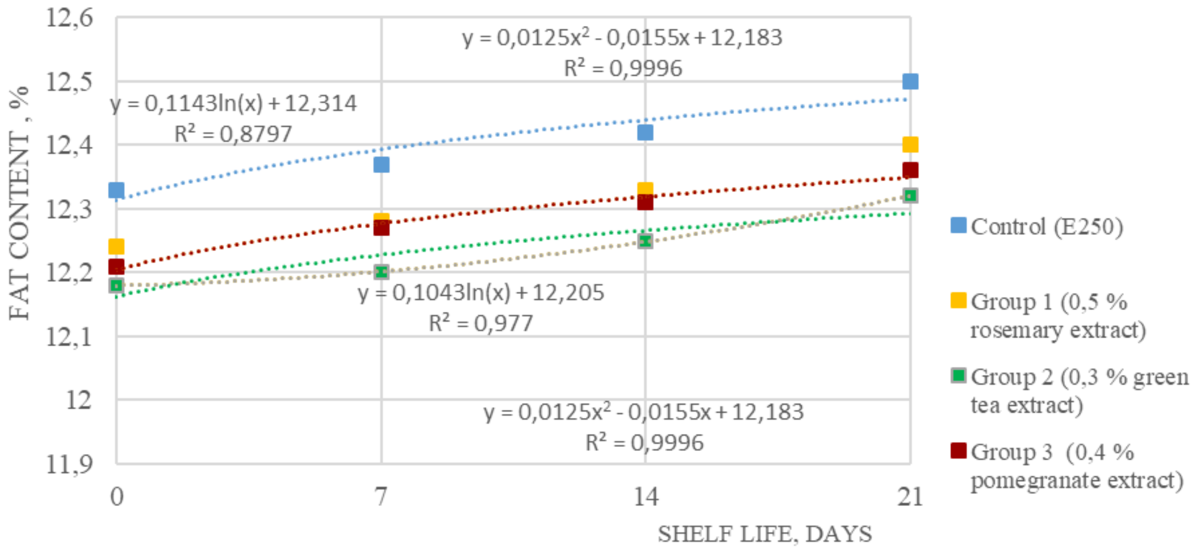

Fig. 3. Dynamics of fat content during storage of minced meat

The study of the dynamics of the mass fraction of fat showed that during the entire storage period, no significant fluctuations in the indicator were observed. In the control sample (E250), the fat content varied within 12.33–12.50 %, which indicates the absence of intensive hydrolytic processes in the lipid fraction.

In the experimental samples with the addition of plant extracts, a similar trend was observed: for the group with rosemary extract (0.5 %), the indicator was 12.24–12.40 %, for green tea extract (0.3 %) – 12.18–12.32 %, and for pomegranate extract (0.4%) – 12.21–12.36 %. The differences between the variants are insignificant and do not exceed the error of the determination method.

It should be emphasised that the observed increase in the mass fraction of fat is relative and is primarily due to a decrease in moisture content in the matrix, and not to the accumulation of lipids or the course of lipolytic processes. This is consistent with the data obtained on the decrease in moisture content during storage.

Thus, the addition of plant extracts does not have a destabilising effect on the lipid component of the product.

Journal of Chemistry and Technologies, 2026, *34*(2), 512-528

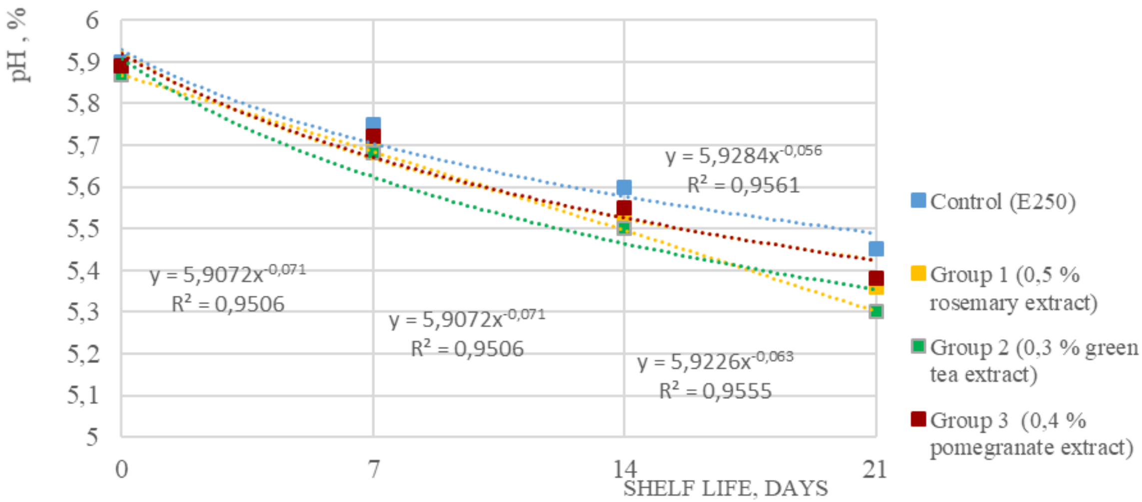

Fig. 4. Change in pH during storage of minced meat

The dynamics of the pH of the studied minced meat samples during refrigerated storage are characterised by a clearly pronounced tendency to a gradual decrease in the indicator in all variants, which is typical for raw meat matrices and reflects the course of post-biochemical and microbiological processes.

At the initial stage, the pH values in all samples were within 5.87–5.90, which corresponds to the normal values of fresh pork after autolysis. During further storage in the control sample (E250), a gradual decrease in pH was noted to 5.75 on day 7, 5.60 on day 14 and 5.45 on day 21. Such dynamics is due to the accumulation of low-molecular acid metabolites (lactic, acetic and other organic acids), which are formed as a result of the development of psychrotrophic microflora and enzymatic cleavage of muscle tissue substrates.

In the experimental samples with the addition of plant extracts, a similar pattern is observed, but with a slightly pronounced increase in the decrease in pH. In particular, in the group with rosemary extract (0.5 %), the indicator decreased from 5.88 to 5.36, in the samples with green tea extract (0.3 %) – from 5.87 to 5.30, and in the group with pomegranate extract (0.4 %) – from 5.89 to 5.38 for 21 days of storage. The most intense decrease in pH was observed for samples with green tea extract, which may be due to the presence of polyphenolic compounds of an acidic nature in its composition, as well as their effect on the metabolic activity of the microbiota.

It should be noted that plant extracts, on the one hand, exhibit antimicrobial properties, limiting the development of certain groups of microorganisms, and on the other hand, they can promote the selective growth of acid-producing microflora, which causes a more pronounced accumulation of organic acids. An additional factor is the inherent acidity of the extracts, which also affects the initial and current pH values of the matrix. Therefore, the use of plant extracts as an alternative to sodium nitrite does not violate the natural kinetics of changes in pH, while slightly modifying its intensity, which must be taken into account when predicting shelf life and assessing product quality.

The effect of natural antioxidants on the colour of meat products. Colour stability analysis using the CIE system Lab* revealed significant differences between the groups treated with natural antioxidants and the control group, highlighting the importance of these extracts in maintaining the visual appeal of meat products. The parameter a*, which reflects the intensity of the red hue, is particularly important because it is directly related to the stabilisation of oxymyoglobin, the pigment responsible for the characteristic pink-red colour of fresh meat. After 21 days of storage, the a* value in the control group (treated with sodium nitrite) was 9.8 ± 0.3, while in the group with rosemary extract, it remained close to this value, at 9.5 ± 0.2. Although the difference between these values was not statistically significant ($p > 0.05$), the stability of a* in the rosemary group suggests the effectiveness of its bioactive compounds – such as carnosic acid – in inhibiting the oxidation of iron in the heme group of myoglobin [22]. This inhibition prevents the formation of metmyoglobin, which causes the undesirable grey-brown discolouration commonly associated with meat spoilage.

Pomegranate extract, rich in anthocyanins and ellagic acid, caused a slight darkening of the meat surface, as reflected in a decrease in the L* (brightness) value to 42.1 ± 0.4 compared to 44.5 ± 0.5 in the control. This effect is likely due to the interaction of polyphenols with meat proteins, leading to the formation of complexes that absorb light in the visible spectrum [23]. Despite this darkening, sensory evaluation did not reveal a negative impact on consumer acceptability, as the colour change was uniform and not associated with spoilage. On the contrary, some panellists described the appearance as "natural", indicating the potential marketing benefits of such products.

Minced meat with the addition of green tea extract demonstrated intermediate values of the L* index (43.0 ± 0.3), which were lower than the control, but higher compared to the sample with pomegranate extract (Table 2). The decrease in brightness in this case is reasonably associated with the presence of catechins, which, in addition to their antioxidant effect, are able to interact with proteins and lipids of the meat matrix, affecting its optical properties [24]. Similar to the samples with pomegranate extract, the detected changes did not have a negative impact on the overall sensory evaluation, which confirms the technological feasibility of using green tea extract as a functional ingredient in the production of meat products.

Table 2

Colour parameters (CIE Lab) of meat products treated with natural antioxidants after 21 days of storage*

Group	Day 0 (L*)	Day 21 (L*)	Day 0 (a*)	Day 21 (a*)
Control group (E250)	50.2±0.4	44.5±0.5	12.1±0.2	9.8±0.3
Group 1 (0.5 %)	49.8±0.3	44.0±0.3	12.0±0.1	9.5±0.2
Group 2 (0.3 %)	50.1±0.5	43.0±0.3	11.9±0.3	9.1±0.4
Group 3 (0.4 %)	49.9±0.2	42.1±0.4	11.8±0.2	8.9±0.3

Notes: L* is brightness (0=black, 100=white), a* is hue from green (-60) to red (+60). Data are presented as mean ± standard deviation (n =5)
Source: created by the authors

It was found that the decrease in the a* parameter (the red colour index in the CIE Lab* system, which reflects the intensity of the red hue and is directly related to the content of oxymyoglobin) correlated with the increase in the levels of malondialdehyde (TBARS) in all experimental groups ($r = -0.82$, $p < 0.01$), which confirms the close relationship between the processes of lipid oxidation and the degradation of meat pigments. It is known that the accumulation of secondary products of lipoperoxidation promotes the oxidation of myoglobin to metmyoglobin, which is accompanied by the loss of the characteristic red colour.

At the same time, in samples with the addition of plant extracts, the indicated correlation was less pronounced ($r = -0.61$), which indicates a protective effect of bioactive compounds on the stability of both lipids and meat pigments. In particular, in the group with rosemary extract, the intensity of lipid oxidation was lower by 33 %, and the decrease in the a value was by 15 % compared to the control group, which indicates the effectiveness of phenolic components in inhibiting oxidative processes.

L* values were observed in the pomegranate and green tea extract groups; the lack of statistically significant deterioration in a* confirms the potential of these antioxidants for use in premium meat products, where consumer demand favours natural ingredients. It should be noted that this work is not aimed at completely eliminating sodium nitrite, but at partially replacing it and reducing its potentially negative impact by using plant extracts rich in antioxidant compounds. In this context, combining plant extracts with reducing agents such as ascorbic acid, which is able to reduce metmyoglobin to oxymyoglobin and act synergistically with polyphenols, increasing colour stability, is promising.

Lipid oxidation and the effect of natural antioxidants. The intensity of lipid oxidation was assessed by the content of secondary peroxidation products, in particular malondialdehyde (MDA), determined by the TBARS (thiobarbituric acid reactive substances) method. It should be noted that, in this case, the discussion concerns lipid oxidation rather than lipid hydrolysis, as the former is accompanied by the formation of secondary products that adversely affect the sensory properties and safety of meat products.

At the beginning of storage (day 0), the MDA content in all experimental samples did not exceed 0.2 ± 0.05 mg/kg, which corresponds to the indicators of fresh raw materials. During storage, a significant increase in the intensity of oxidation was found in the control sample: already on the 7th day, the MDA content reached 0.8 ± 0.1 mg/kg. At the same time, in samples with the addition of plant extracts, this indicator remained significantly lower.

On the 14th day of storage, the MDA concentration in the control sample increased to

1.4 ± 0.2 mg/kg, while in the experimental samples it was within 0.9–1.1 mg/kg, and the differences were statistically significant ($p < 0.01$). By the 21st day in the control sample, the MDA value approached the maximum permissible level for meat products, which indicates an intensive course of oxidative processes. (Table 3). Among the experimental groups, the most pronounced inhibitory effect on lipid oxidation was found for the sample with the addition of rosemary extract, where the MDA content was 33 % lower compared to the control. In samples with green tea and pomegranate extracts, the decrease was 22 % and 11 %, respectively, which reflects the different antioxidant activity of the studied plant components.

Table 3

Malondialdehyde levels in groups

	Day 0	Day 7	14th day	21st day
Control (E250)	0.2±0.05	0.8±0.1	1.4±0.2	1.8±0.1
Group 1 (0.5%)	0.2±0.03	0.5±0.1	0.9±0.1	1.2±0.1
Group 2 (0.3%)	0.2±0.04	0.6±0.1	1.0±0.2	1.4±0.1
Group 3 (0.4%)	0.2±0.05	0.7±0.1	1.1±0.1	1.6±0.2

Source: created by the authors

Statistical analysis confirmed high levels of antioxidant activity in the groups receiving rosemary and green tea extracts, with differences from the control group reaching statistical significance ($p < 0.001$). Although pomegranate extract demonstrated a relatively lower efficacy, it still significantly reduced lipid oxidation compared to the control group ($p < 0.05$).

The powerful antioxidant properties of rosemary extract are explained by the high concentration of carnosic and rosmarinic acids. These compounds neutralise free radicals, thereby interrupting oxidative chain reactions, and also form chelates with metal ions (Fe^{2+}, Cu^{2+}), which catalyse the breakdown of lipids. [25]. Green tea extract, rich in catechins – particularly epigallocatechin gallate – acts by forming stable complexes with peroxide radicals, thereby reducing the accumulation of hydroperoxides, which are key intermediates in the oxidation process [26]. Pomegranate extract, which consists mainly of punicalagins, exerts its protective effect through a different mechanism: it stimulates the synthesis of endogenous antioxidant enzymes, such as superoxide dismutase, which enhances the intrinsic defence mechanisms of muscle cells and reduces oxidative stress at the molecular level [27].

A pronounced negative correlation was also established between the MDA level and the lightness of the samples (L^*) ($r = -0.75$), which indicates a significant influence of lipid oxidation processes on the colour characteristics of the product. Lipid oxidation is accompanied by the formation of reactive carbonyl compounds that interact with muscle proteins, in particular with proteins of the myoglobin complex, which leads to a change in their redox state and a decrease in the lightness (L^*) of the meat matrix.

In addition, the group with the addition of rosemary extract, which was characterised by the lowest MDA values, also demonstrated higher stability of the a^* index (red hue), which is explained by the slowdown of myoglobin oxidation and the preservation of oxymyoglobin in a more stable form. This indicates that the inhibition of lipid oxidation indirectly contributes to the stabilisation of the red colour of the meat product, which confirms the complex protective effect of rosemary extract on both oxidative processes and colour quality parameters.

Sensory characteristics and texture analysis of meat products. Evaluation of the sensory properties of minced meat enriched with natural antioxidant extracts revealed pronounced differences in the perception of aroma, texture and overall acceptability between the experimental groups. Expert sensory evaluations showed that samples with the addition of rosemary extract (group 1) received the highest scores for both aroma and overall acceptability, which can be explained by its characteristic spicy notes that complement traditional meat flavours. Samples with the addition of pomegranate extract (group 3) provided a moderate fruity aroma, which caused an ambiguous reaction from the participants: 60 % described the aroma as “original”, while 40 % perceived it as “excessively sweet”. Samples with the addition of green tea extract (group 2) were evaluated as having a neutral aroma, probably due to the low volatility of catechins. Importantly, the texture of this group did not differ significantly from the control, indicating that the structural integrity of the product was maintained.

Statistical analysis using the Mann–Whitney U test showed statistically significant differences in aroma perception between group 1 and the other experimental groups ($p < 0.01$), while no

Journal of Chemistry and Technologies, 2026, *34*(2), 512-528

significant differences were found for textural parameters (hardness, elasticity, and cohesiveness) ($p > 0.05$). This indicates that the addition of natural antioxidant extracts can significantly affect the sensory perception of the aroma of minced meat, but does not change its structural and mechanical characteristics.

Instrumental studies of textural properties, in particular hardness and elasticity, were carried out by the Texture Profile Analysis (TPA) method using a texture analyser (specify the model of the device). The hardness, elasticity and cohesiveness indicators were evaluated, which characterise the resistance of the sample to deformation and the ability to restore the structure after loading. No statistically significant differences were found between the study groups for the specified parameters ($p > 0.05$).

The stability of the obtained results may be due to the conditions of experimental storage of samples, which was carried out at a temperature of 4 ± 1 °C for 21 days in hermetic packaging. Such conditions limited the influence of oxygen and external factors, which in turn contributed to the preservation of the structural and mechanical characteristics of meat matrices at a stable level.

These results are consistent with the existing literature on the preservation of meat microstructure in the presence of polyphenolic compounds. The lack of changes in elasticity (ranging from 8.5 to 8.7 mm for all samples) indicates that natural extracts do not affect the cohesion of protein fibres (Table 4).

Table 4

Sensory evaluations and textural characteristics

Parameter	Control (E250)	Group 1 (rosemary)	Group 2 (green tea)	Group 3 (pomegranate)
Aroma	8.5±0.3	8.7±0.4	6.8±0.6	7.2±0.5
Texture	8.1±0.3	8.0±0.2	7.9±0.2	7.8±0.3
General acceptability	8.6±0.4	8.9±0.3	7.5±0.5	7.3±0.6

Note: The rating was based on a scale from 0 (worst) to 10 (best)
Source: created by the authors

A strong positive correlation was found ($r = 0.89$, $p < 0.001$) between aroma ratings and overall acceptability, which highlights the key role of aroma in shaping consumer preferences. In particular, samples from group 2, characterised by a neutral aroma, received lower overall acceptability values, despite satisfactory textural indicators. In the case of group 3, the presence of «fruity aromatic notes» caused heterogeneity in sensory perception: while some tasters considered them innovative, others considered them inappropriate for traditional meat products.

For premium product lines, rosemary extract is an optimal choice, combining high antioxidant efficacy with a familiar, classic aroma that matches consumer expectations well. Pomegranate extract may be suitable for use in experimental or niche product lines, although its use should be approached with caution due to the potential for mixed consumer reactions. Combined use of natural Antioxidants such as rosemary and green tea may provide a balanced solution that provides oxidative stability while simultaneously softening the flavour intensity, increasing overall product acceptability. These findings provide a scientific basis for the development of new formulations of meat products with reduced nitrite content, meeting today's consumer demands for clean-label, health-oriented foods.

The results obtained in this study suggest that rosemary extract can be considered as a promising natural alternative to nitrites in minced pork. The obtained results are partially consistent with the findings of E.R.B. Bellucci et al. [28], who demonstrated that rosemary polyphenolic compounds are capable of inhibiting lipid and protein oxidation in meat matrices, particularly through the scavenging of free radicals and the chelation of metal ions. In their study, the use of rosemary extracts allowed for the preservation of the organoleptic characteristics of meat products during 30 days of storage, which confirms their stabilising effect over time.

At the same time, our study found that the most pronounced antioxidant effect was observed at a concentration of 0.5 % rosemary extract. In contrast to the work of E.R.B Bellucci et al. [28], where lower concentrations (0.1–0.3 %) were effective, the differences obtained may be due to the specifics of the minced pork formulation, in particular the higher content of the lipid fraction and, accordingly, the increased susceptibility to oxidation. This indicates a matrix-dependent nature of the effectiveness of plant antioxidants in meat matrices. The observed decrease in MDA levels by 33 % in the rosemary group also confirms the findings of Šojić et al. [29], who reported a 25–40 % reduction in lipid oxidation in pork sausages when using tomato extract. Although *Šojić et al.* reported improved flavour characteristics of meat matrices with the combined use of tomato extract and peppermint oil, in this study, rosemary extract demonstrated efficacy as a standalone functional additive without the need for combination with other plant components. Such differences may be due to the different composition of bioactive substances and the peculiarities of their interaction with the meat matrix.

In particular, rosemary phenolic diterpenes provide multifunctional antioxidant protection, which allows for effective inhibition of lipid oxidation processes in different phases of their development. This may explain the preservation of the organoleptic properties of the product even when using rosemary extract as the only functional ingredient.

Regarding microbiological stability, the results for the rosemary group (2.8×10^4 CFU/g) are consistent with *those of L. Martínez-Zamora et al.* [30], who used a spice blend in Spanish *chorizo* and observed a comparable reduction in microbial load. Although L. Martínez-Zamora et al. [30] reported a synergistic antimicrobial effect of a combination of garlic and paprika extracts, in this study, rosemary extract as an individual ingredient demonstrated pronounced antimicrobial activity. This may indicate a high biological activity of its phenolic components, in particular carnosic acid and related compounds, which are able to inhibit the growth of microorganisms in meat matrices without the need for combination with other plant extracts. The results regarding colour stability ($a^* = 9.5 \pm 0.2$) partially disagree with the observations of L. Martínez et al. [31], who noted the effective preservation of the brightness of meat products when using pomegranate extracts, which was associated with a high content of anthocyanins and their antioxidant activity. In the mentioned work, colour stabilisation was also indirectly associated with the use of nitrite systems, which contribute to the formation of the stable colour of meat products. In our study, pomegranate extract provided only partial colour retention, which may be due to the absence of nitrite curing component and less pronounced stabilisation of meat pigment matrices. At the same time, sensory evaluation showed that minor changes in colour intensity did not negatively affect the overall consumer acceptability of the product, which is consistent with the results of *S. Smaoui et al.* [32], who noted the compensatory effect of the natural appearance of the product in forming a positive consumer perception.

The aromatic characteristics of pomegranate, which elicited mixed sensory responses in the present study, are consistent with the findings of A.M. Awad et al. [33], who reported lower sensory scores for açaí and pomegranate extracts in traditional meat products due to their distinctive fruity notes. Awad et al. concluded that such extracts are more suitable for use in innovative or non-traditional products, highlighting the importance of targeted marketing strategies. In this study, 60 % of respondents described the fruity flavour as “original”, indicating its potential for use in niche premium products targeting consumers seeking new sensory experiences.

The observed inhibition of the growth of mesophilic aerobic microorganisms in the antioxidant-treated groups is consistent with the findings *of G. Manessis et al.* [34], who demonstrated that plant polyphenols disrupt the structural integrity of bacterial membranes. The increased antimicrobial activity of rosemary extract in the conditions of this study may be associated with the presence of phenolic diterpenes, in particular carnosic acid, which, according to *M. Efengberger-Schmechtig et al.* [35], is able to affect the viability of pathogenic microorganisms by disrupting key cellular processes, including the replication of genetic material. It should be noted that the mechanisms of action of bioactive compounds may be multifactorial and depend on the conditions of the food matrix.

At the same time, the observed relatively lower antimicrobial activity of pomegranate extract ($p = 0.08$) differs from the results of *F. Pini et al.* [36], who reported a pronounced antibacterial effect in fermented sausages. Such discrepancies may be due to differences in the type of food matrix: in this study, fresh minced pork with an increased moisture content was used, which could affect the distribution and stability of phenolic compounds, as well as reduce their local concentration in microbiologically active areas of the matrix.

MDA levels by 33 % in the group with the addition of rosemary extract compared to the control sample confirm the findings of G. Manessis et al. [34], who emphasised the key role of terpene and phenolic compounds in inhibiting the chain reactions of lipid oxidation. Conversely, the weaker antioxidant protection observed with the use of pomegranate extract contradicts the findings of N. Khatib et al. [37], who reported a 45 % reduction in lipid oxidation when punicalagins were combined with nanotechnology. This suggests that concentration optimisation or synergistic formulation may be necessary to achieve comparable efficacy. The stabilisation of the a* parameter (red hue) in all experimental groups is consistent with the findings of H. I. Yong et al. [38], who demonstrated that natural antioxidants can mimic nitrite, maintaining the stability of oxymyoglobin. However, the observed decrease in brightness (L*) in samples with the addition of pomegranate and green tea extract is different from the results of *S. Melios* et al. [39], who found no significant changes in the L* parameter when using similar plant extracts in cold-smoked sausages. This discrepancy may be due to differences in the interaction of polyphenolic compounds with the protein matrix of fresh minced meat compared to fermented meat matrices.

The high consumer acceptance of the rosemary-treated group highlights its added value as a flavouring agent, confirming the findings of S. Melios et al. [39], in which spicy notes were identified as “familiar” and preferred by the majority of consumers. In contrast, the mixed perception of pomegranate extract in this study reflects the results reported *by N. Khatib et al.* [36], where fruit flavours elicited polar responses. These findings highlight the importance of the cultural and sensory preferences of the target consumer group when developing new meat products.

The antimicrobial effects observed in the rosemary and pomegranate groups are consistent with the findings *of J. Shi et al.* [40], who confirmed the efficacy of plant extracts in inhibiting the development of pathogens. Their study also highlighted the increased efficacy of combining several bioactive components, which may explain the variability in antimicrobial activity observed among the extracts in this study. Similarly, the work of S. J. Konteles et al. [41] on the use of rose and rosemary processing wastes to reduce nitrite in meat products supports the current findings on colour stability, in particular the preservation of the a* parameter in rosemary-treated samples. However, the variation in brightness effects (L*) may be due to differences in the product matrix, highlighting the need to adapt formulations to specific meat matrices.

Research by A. S. Rodrigues et al. [42] on the use of banana flower extract as a natural antioxidant in meat products illustrates the broader potential of non-traditional plant sources. Although this study focused on rosemary, green tea and pomegranate, all extracts share a common mechanism of action, namely the inhibition of lipid oxidation. Rodríguez et al. [42] also highlighted the importance of raw material availability and economic feasibility as key factors for the industrial implementation of natural antioxidants in the meat industry. MP Totaro et al. [43] demonstrated that olive leaf extract, which also belongs to the polyphenolic plant antioxidants, can effectively replace nitrite systems in sausage products without compromising physicochemical and sensory parameters.

The results obtained are partially consistent with the data on rosemary extract, since both types of extracts are characterised by a high content of bioactive phenolic compounds capable of stabilising oxidative processes and maintaining the organoleptic properties of the product, in particular aroma and textural characteristics.

At the same time, in contrast to the results of *Totaro et al.*, a decrease in lightness values (L*) was observed in this study, which may be due to the characteristics of the fresh meat matrix, in particular, the absence of fermentation processes and the greater availability of protein groups for interaction with polyphenolic compounds, in contrast to dried or fermented sausage systems.

The study by M. Hadidi et al. [44] describes the mechanisms by which plant-derived antioxidants regulate protein and lipid oxidation processes in food systems. The authors note that the effectiveness of such compounds is largely determined by the synergistic interaction between different classes of bioactive substances, as well as their concentration and matrix conditions of application.

Their conclusions regarding the dependence of antioxidant activity on the composition and ratio of phenolic components are partially consistent with the results of this study, since the effectiveness of extracts in meat matrices also varied depending on their nature and composition.

In particular, in our study, pomegranate extract showed a relatively lower antioxidant effect compared to rosemary extract, which may be due to differences in the profile of phenolic compounds and their interaction with the components of minced pork, as well as their stability characteristics in this food matrix. Similarly, a study by *M.A. Andrade* [45] on active packaging containing extracts of algae, plants and fruit processing by-products demonstrates the potential of bioactive compounds in preserving the quality of food products. Andrade showed that

Journal of Chemistry and Technologies, 2026, *34*(2), 512-528

such extracts can inhibit both lipid oxidation and microbial growth, which is consistent with current data on the reduction of malondialdehyde levels and the inhibition of the growth of mesophilic aerobic microorganisms in the groups treated with rosemary and pomegranate. However, differences in matrix composition – namely, fresh minced pork in this study versus packaging systems in *Andrade's work* – may explain the observed differences in colour stabilisation parameters. A recent review by *A.I. Osman et al.* [46] highlights the novel application of green nanotechnology to enhance the functional properties of natural antioxidants. In particular, encapsulation of polyphenols has been shown to improve bioavailability and stability, potentially explaining the high efficacy reported in studies where synergy of components was achieved. Such approaches may be a promising direction for enhancing the efficacy of pomegranate extract, which, in this study, demonstrated a relatively lower antioxidant capacity.

In conclusion, the results of this study are supported by the current literature, which demonstrates the feasibility of using plant extracts as an alternative to nitrites. Differences in their effects on specific quality parameters can be explained by differences in product matrices, types of extracts or concentrations used. These factors should be carefully considered when developing and optimising future formulations.

Conclusions

Studies on the replacement of nitrites with natural antioxidant extracts, including rosemary, green tea, and pomegranate extracts in minced pork, have confirmed their effectiveness in maintaining the quality, safety, and consumer acceptability of meat products. Rosemary extract was the most promising alternative: it not only reduced the growth of mesophilic aerobic microorganisms to 2.8×10^4 CFU/g at day 21 (compared to 3.2×10^4 CFU/g in the control group), but also ensured the stability of the red hue ($a^* = 9.5 \pm 0.2$), which is an important indicator of the visual appeal of the meat product.

This effect is due to the action of phenolic diterpenes of rosemary, which inhibit the oxidation processes of myoglobin and slow down the formation of metmyoglobin, thus stabilising the colour system of meat.

Analysis of the dynamics of physicochemical indicators during 21 days of storage confirmed the stabilising effect of plant extracts on the meat matrix. It was established that the loss of moisture in the experimental samples occurred more slowly compared to the control: at the end of storage, its content was 56.2–56.5%, while in the control sample – 55.9 %, which indicates an improvement in the water-holding capacity of the product. The obtained dependences of the change in humidity are characterised by high coefficients of determination at the level of R^2 = 0.995–1.000, which confirms the stable and predictable nature of the dehydration processes. The mass fraction of protein remained practically unchanged and varied within 18.48–18.61 %, which indicates the absence of intensive proteolysis, while a slight increase in the mass fraction of fat to the level of 12.18–12.50 % is relative and is due to a decrease in moisture content. PH during storage naturally decreased from initial values of about 5.90 to 5.30–5.45 at the end of the study, which reflects the course of post-biochemical and microbiological processes and does not go beyond the limits typical for chilled meat products. Taken together, the results obtained indicate that the use of rosemary, green tea and pomegranate extracts provides stabilisation of physicochemical parameters, slowing down degradation changes and maintaining product quality throughout the entire storage period, which justifies their use as an effective alternative to traditional nitrite additives in the technology of meat products.

Lipid oxidation, assessed by TBARS, showed that rosemary extract reduced malondialdehyde levels by 33%, indicating its higher antioxidant activity compared to green tea and pomegranate extracts. A strong correlation was found between pigment degradation and lipid oxidation levels ($r = -0.82$; $p < 0.01$), highlighting the relationship between oxidative processes in the lipid and pigment fractions and the need for an integrated approach to stabilising the quality of meat matrices. Sensory evaluation further confirmed the advantages of rosemary extract, whose characteristic spicy aroma and high overall acceptability outperformed the other groups. Although pomegranate extract provided fruity notes, they caused mixed reactions among the tasters, limiting its suitability for traditional meat products. Texture remained stable in all groups, indicating preservation of structural integrity throughout the storage period. From a practical perspective, rosemary extract is recommended for use in premium product lines due to its balanced antimicrobial, antioxidant and sensory properties. In addition, combining extracts — such as rosemary and green tea – can enhance overall efficacy and provide additional product differentiation.

Limitations of the study, including the exclusive use of ground pork and the lack of heat treatment, highlight the need for further research. Future studies should examine the effects of these antioxidants on different types of meat, incorporate different processing methods, and evaluate long-term storage outcomes. Special emphasis should be placed on optimising formulations and exploring potential synergies between different bioactive compounds. These efforts will contribute to the development of standardised protocols for the industrial application of plant-derived additives in the meat industry.

Conflict of interest

None.

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