ЛУЦЬКИЙ НАЦІОНАЛЬНИЙ ТЕХНІЧНИЙ УНІВЕРСИТЕТ

ТОВАРОЗНАВЧИЙ ВІСНИК

Том 18, № 2

Заснований у 2009 році
Видається два рази на рік

Луцьк
2025

ISSN 2310-5283
e-ISSN 3041-1432

DOI: 10.62763/cb/2.2025

Видавець:
Луцький національний технічний університет

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Луцького національного технічного університету
(протокол № 7 від 26 грудня 2025 р.)

Свідоцтво про державну реєстрацію
друкованого засобу масової інформації:
Національна рада України з питань телебачення та радіомовлення (Рішення № 40 від 11.01.2024).
Ідентифікатор медіа – R30-02530.

Науковий журнал включено до категорії «Б» Переліку наукових фахових видань України, у яких можуть публікуватися результати дисертаційних робіт на здобуття наукових ступенів доктора та кандидата наук зі спеціальностей: 076 – Підприємництво та торгівля; 132 – Матеріалознавство; 181 – Харчові технології; 182 – Технології легкої промисловості (наказ МОН України № 886 від 02.07.2020 р.)

Журнал представлено у міжнародних наукометричних базах даних,
репозитаріях та пошукових системах: Google Scholar, Crossref,
Національна бібліотека України імені В. І. Вернадського, Dimensions, UC Santa Barbara Library,
University of Oslo Library, OUCI (Open Ukrainian Citation Index), EuroPub, Ulrich's Periodicals Directory, Sherpa/
Romeo, ScienceOpen, Litmaps, J-Gate, WorldCat

Контактна адреса:
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
E-mail: info@c-bulletin.com.ua
https://c-bulletin.com.ua/uk

LUTSK
NATIONAL
TECHNICAL
UNIVERSITY

COMMODITY BULLETIN

Volume 18, No. 2

Year of foundation: 2009
Frequency: 2 issues per year

Lutsk
2025

ISSN 2310-5283
e-ISSN 3041-1432

DOI: 10.62763/cb/2.2025

Publisher:
Lutsk National Technical University

Recommended for printing and distribution
via the Internet by the Academic Council
of Lutsk National Technical University
(Minutes 7 of December 26, 2025)

Certificate of state registration of the print media:
National Council of Ukraine on Television and Radio Broadcasting (Decision No. 40 of 11.01.2024).
Media identifier – R30-02530.

The scientific journal is included in category "B" of the List of scientific specialized publications of Ukraine,
in which can be published the results of dissertations for obtaining the scientific degrees of doctor and
candidate of sciences in specialties: 0416 – Wholesale and retail sales;
0788 – Interdisciplinary programmes and qualifications involving engineering, manifacturing and construction;
0721 – Food processing; 0723 – Textiles (clothes, footwear and leather)
(Order of the Ministry of Education and Science of Ukraine No. 886 of 02.07.2020)

**The journal is presented international scientometric databases, repositories
and scientific systems**: Google Scholar, Crossref, Vernadsky National Library of Ukraine,
Dimensions, UC Santa Barbara Library, University of Oslo Library, OUCI (Open Ukrainian Citation Index),
EuroPub, Ulrich's Periodicals Directory, Sherpa/Romeo, ScienceOpen,
Litmaps, J-Gate, WorldCat

Address for contacts:
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
E-mail: info@c-bulletin.com.ua
https://c-bulletin.com.ua/en

ТОВАРОЗНАВЧИЙ ВІСНИК
Journal homepage: https://c-bulletin.com.ua/en
Том 18, № 1, 2025

Редакційна колегія

COMMODITY BULLETIN
Journal homepage: https://c-bulletin.com.ua/en
Vol. 18, No. 2, 2025

Editorial Board

ЗМІСТ

Content

COMMODITY BULLETIN
Journal homepage: https://c-bulletin.com.ua/en
DOI: 10.62763/cb/2.2025.09

Article's History: Received: 21.08.2025 Revised: 18.11.2025 Accepted: 26.12.2025 Published: 02.01.2026

ISSN 2310-5283; e-ISSN 3041-1432 Vol. 18, No. 2, 2025, 9-19

UDC 641.1:613.2.032.33]:613.98

Commodity evaluation of decorative and applied art objects

Volodymyr Indutnyi*
Doctor of Geological and Mineralogical Sciences, Professor, Associate Professor
State University of Trade and Economics
02156, 19 Kioto Str., Kyiv, Ukraine
https://orcid.org/0000-0001-6676-7472

Nina Merezhko
Doctor of Technical Sciences, Professor
State University of Trade and Economics
02156, 19 Kioto Str., Kyiv, Ukraine
https://orcid.org/0000-0003-3077-9636

Kateryna Pirkovich
PhD in Technical Sciences, Associate Professor
State University of Trade and Economics
02156, 19 Kioto Str., Kyiv, Ukraine
https://orcid.org/0000-0002-1461-0235

Nina Kaluha
PhD in Chemistry, Associate Professor
State University of Trade and Economics
02156, 19 Kioto Str., Kyiv, Ukraine
https://orcid.org/0000-0002-0901-5052

Valentyna Tkachuk
Doctor of Technical Sciences, Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0001-5793-5227

Abstract. The purpose of this study was to examine the patterns of pricing in the modern Ukrainian market of decorative and applied art objects and to build a mathematical model for predicting the estimated value using the example of products made of wood and metals, as well as to determine the level of financial losses resulting from the destruction or loss during hostilities. Decorative and applied art objects were represented by everyday objects that have become symbols of the material culture of mankind, ethnic and national characteristics. Such works were made of various materials and are widely distributed on the market. The study created a source database, which included 115 samples made of wood and metal: interior wall decorations, mini-sculptures and decorative household items. The value indicators of the samples were distributed from the smallest to the largest and logarithmised to the base 2. As a result, three intervals of distribution of value indicators in the source database were identified. In the second interval, the logarithmic value indicators increased linearly, which made it possible to build a mathematical model for predicting the estimated value in the context of the issue of determining the level of possible losses resulting from the destruction and loss.

Suggested Citation:
Indutnyi, V., Merezhko, N., Pirkovich, K., Kaluha, N., & Tkachuk, V. (2025). Commodity evaluation of decorative and applied art objects. *Commodity Bulletin*, 18(2), 9-19. doi: 10.62763/cb/2.2025.09.

**Corresponding author*

Also, ranges of permissible predicted value indicators were determined for items from the source database. The article provides 3 examples of calculating the estimated value of decorative and applied art objects and compares these prices with the prices offered by sellers. It was found that an interior decoration made of wood was offered for sale at an abnormally low price (79 UAH), an inlaid rachva for jewellery – at an abnormally high price (2,500 UAH), a metal wall panel – at a slightly inflated price (1,500 UAH), but within the regulatory liquidity. The more useful information was published when describing decorative and applied art objects, the higher the sociocultural value and estimated value became. The results of the study showed that decorative and applied art objects made of wood and metals had a market value that was determined by the financial capabilities of potential buyers

Keywords: decorative and applied art objects; wooden products; metal products; value forecasting; value indicators

Introduction

Decorative and applied art objects are cultural monuments and, at the same time, commodities presented on the modern global market in a wide range – personal, interior, exterior and garden decorations, amulets, amateur painting and sculpture, painted household items, clothing, embroidery, ceramics, furniture and home accessories, dishes, ceremonial items, household tools, etc. In addition to the utilitarian purpose, decorative and applied art objects serve as symbols that satisfy people's humanitarian needs in the involvement in ideas about beauty, the work of individual masters, beliefs, the way of social organisation, as well as national traditions professed by individual families, communities, and peoples. The market for decorative and applied art objects has become the object of research by many scientists. Thus, I. Hrabynskyi (2021) considered the methodological problems of analysing the world market for works of art, antiquities, and antiques and considered the valuation to be an important problem, which the author proposed to derive from the sale price at the last auction of such or similar items.

L. Demydchuk (2023) analysed the problems of the market for folk art and souvenir products in Ukraine and noted that very little attention was paid to these local markets. The author noted that organisations and individual masters of folk art often did not have the opportunity to properly organise sales, marketing, trade and educational activities. Also, L. Demydchuk (2021) considered the classification, manufacturing features and commodity valuation of souvenirs and folk art products. L. Bogaychuk *et al.* (2024) noted the underestimation of the market for contemporary art in Ukraine, in particular for objects of decorative and applied art of Ukrainian production, which was found out by the authors based on the results of a survey. Scientists O. Dmytriyeva *et al.* (2023) pointed out that not only the classical art school of the academic tradition has been preserved in Ukraine, but also numerous crafts. For example, Petrykivka and Kyiv painting, wood carving, hand weaving, artistic fabric painting and ceramics exist and are developing. The authors emphasised that the art market in general and the market for objects of decorative and applied art are a window of opportunity for the economy and business.

O. Kalashnykova (2022) noted that art has increasingly become a significant segment of the market of the most profitable goods, and art auctions have become platforms that oppose illegal art business. M. Zinchenko (2023) considered the auction as a cultural and economic phenomenon of the modern artistic process. The concept of the market for art and antiques was considered in two meanings: as the purchase and sale of objects that had artistic value, and as the sphere of commodity and monetary relations that arose between legal entities and individuals regarding the purchase and sale of art and antiques. The author noted that pricing on the art market depended not only on the cost of the created cultural and artistic product, but also on a number of sociocultural factors. M. Besaha (2025) investigated the impact of digital technologies on art historical support of auctions and identified key digitalisation trends that contributed to the modernisation of mechanisms for identifying, evaluating, and promoting works of art. Virtual exhibitions, online auctions, and digital platforms expanded access to the art market, attracting a new audience. The study revealed the potential for the development of new forms of interactive communication between experts, buyers, and sellers, which allowed for a more open and dynamic bidding system. Zh. Denysiuk (2025) noted the importance of art projects of modern decorative and applied arts in shaping the cultural brand and image of Ukraine. Such projects served not only as a means of aesthetic representation, but also as a tool of cultural diplomacy, which contributed to improving the international image of the state. A. Kravets (2025) noted that effectively planned and successfully implemented art projects became ambassadors of Ukrainian art, spreading its unique and inimitable image. Art projects formed trust and interest in Ukrainian decorative and applied art.

Decorative and applied art objects had a complex and diverse specific nature, which allowed for a differentiated analysis of the world market for these objects based on the involvement in the work of outstanding masters, utilitarian purpose, complexity of the execution technique, materials, and manufacturing technologies used, age and region of origin. At the same time, many years of research into the patterns of market pricing indicated the expediency of ignoring the specific nature and the appropriateness of conducting predictive research based on the study of the permanent distribution of financial capabilities of potential buyers within a given market. The aim of the study was to study the patterns of price formation in the market of decorative and applied art objects in Ukraine and to create a mathematical model for predicting the value, in particular, using the example of products made of wood and metal. Also, within the framework of the study, the task was set to assess the financial losses from the loss of such products as a result of military operations. The study was based on the hypothesis that, based on the analysis of value indicators for decorative and applied art objects exhibited on the open market, it is possible to develop a mathematical model for scientifically substantiated and effective determination of the predicted estimated value of such items.

Materials and Methods

The methodology for studying the market of decorative and applied art monuments involved three main stages of the expert's work. The first stage consisted of creating a database of initial data on a certain type of cultural monuments, as well as on the value. For this purpose, information was used from the Internet sources Violity (n.d.), Rozetka (n.d.), Temu (n.d.) and Prom (n.d.), using data such as a photo of the object, its brief description (dimensions, weight, material, manufacturing technique, author), source of information and cost (or price) at which it was offered to the buyer (Resolution of the Cabinet of Ministers of Ukraine No. 1440, 2003). The number of objects entered into the source database had to ensure a representative sample and contain at least one hundred samples. Therefore, a source database was created, which included 115 samples made of wood and metal: interior wall decorations, mini-sculptures and decorative household items. The total cost of the goods described in the source database was 122586.6 hryvnias. An interior decoration made of wood – a painted duck, about which no information was indicated on the website, except for its dimensions, was evaluated. Also, another product made of wood – an inlaid box for decorations and trinkets, made by the master Vasyl Grepinyak, was considered and a decorative and household decoration made using the laser cutting technique of metal – a wall panel "Zebra of Happiness" was evaluated.

The second stage consisted of the procedure of sorting the source database in order of increasing the value indicators indicated in it. This work allowed displaying the distribution of value indicators on the graph and establish the number of cheap and expensive goods on the market and the ratio. The third stage of the work involved testing the hypothesis of the implementation of the basic law of pricing and building a regression mathematical model to predict value indicators taking into account data on the distribution of financial capabilities of potential buyers on the market. Also, data from the works of V. Indutnyi (2022) and V. Indutnyi *et al.* (2024) were taken into account, where possible losses arising from damage or loss of cultural values were considered and assessed. As examples, the authors of these works took precious stones, rocks, and minerals from museums, graphics, iconography and painting, mosaic works, other types of jewellery. The assessment was based on the results of research into the markets of various cultural monuments and the proposed mathematical models for predicting value. To assess the correlation between the observed and theoretically calculated indicators of the predicted estimated value of works of decorative and applied art, the Pearson correlation coefficient (R^2) was calculated, which allowed assessing the accuracy of the developed mathematical model.

Results and Discussion

Decorative and applied art was distinguished by its devotion to traditions, the preservation of its forms and decorative elements developed and polished over the centuries. At the same time, there was a constant process of expanding the subject, using new materials, and improving production techniques (Zapasko, 2000). The analysis of the market for decorative and applied art objects was carried out on the basis of studying the combined distribution of value indicators of decorative and applied art objects made of wood and metals. The first interval of value indicators of objects presented for sale (from the first to the 12^{th} sample) was 10.43% of the entire sample and corresponded to value indicators from 3 to 100 hryvnias per sample. The second interval – from 13 to 42 samples – was 26.09% of the entire sample of decorative and applied art objects, with a cost from 101 to 250 hryvnias. The third interval – from 43 to 68 samples – accounted for 22.61% of the entire sample and was valued at 250 to 500 hryvnias per sample. The fourth interval – from 69 to 84 samples – accounted for 13.91% of the total number of samples in the source database and had value indicators in the range from 500 to 1000 hryvnias. The fifth interval – from 85 to 101 samples – accounted for 14.78% and had value indicators in the range from 1000 to 2000 hryvnias. Moreover, the interval from the first to 101 samples, which recorded a cost level of up to 2000 hryvnias, described 87.82% of the entire sample. The sixth interval included 14 samples with a cost of more than 2000 hryvnias (12.17% of the sample). It was impractical to highlight the remaining intervals, as these intervals covered a very small number of figurative points (Fig. 1).

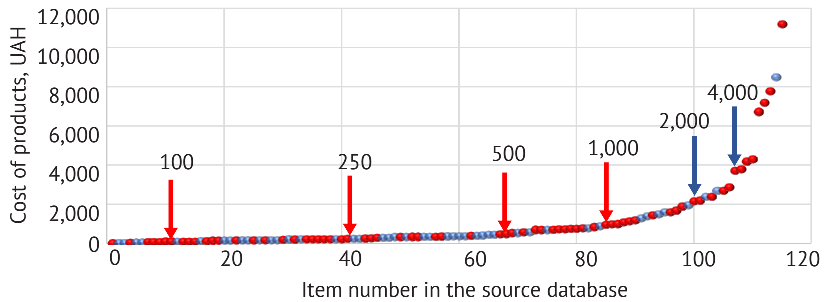

Figure 1. *Polygon of distribution of value indicators for decorative and applied art objects, built on the basis of the source database created on 10.08.2025*
Note: *red dots indicate products made of wood, blue dots indicate products made of metals: iron, bronze, nickel silver and cast iron*
Source: *based on Violity (n.d.), Rozetka (n.d.), Temu (n.d.), Prom (n.d.)*

The polygon of distribution of value indicators showed that the market value indicators of wooden and metal products in the space of the graph were distributed evenly, covering the range from the smallest to the largest values recorded in the source database. This meant that the potential buyer did not consider it necessary to divide decorative and applied art objects by material, execution technique or manufacturing complexity. The potential buyer's attention was drawn to the possibility of purchasing things that were most suitable for satisfying the potential buyer's own humanitarian needs and within the available financial capabilities. Decisions were made individually, taking into account the aesthetic impressions from observing the objects, the authorship of the presented works, as well as the availability of particularly valuable materials, for example, mahogany and ebony, bronze or silver. Figure 1 showed the financial capabilities of people to purchase decorative and applied art objects on the Ukrainian market, since the cost of the objects was formed freely in the interaction of sellers and buyers. It can be stated that 87.82% of potential buyers were ready to acquire goods valued at no more than 2,000 hryvnias per sample (or 41.428 euros) (as of 10.08.2025 the euro exchange rate was 48.276 hryvnias) (MinFin, 2025).

Also, buyers were ready to purchase cheaper goods if these goods were suitable for satisfying the buyers' humanitarian needs. Having information on the number of goods sold in each of the selected intervals (such information was confidential for many market participants), it became possible to assess the liquidity, but only goods with a value of up to 2,000 hryvnias should be considered liquid by regulation. It is worth noting that the sellers were well-informed about the needs of potential buyers and were interested in carrying out trading operations with maximum benefit for the sellers. Thus, the polygon of value indicators reflected the market for works of decorative and applied art, taking into account value indicators and the number of buyers. The construction of a mathematical model for predicting the value of decorative and applied art objects assumed compliance with the law of pricing, which linked the estimated value of the object and the amount of information about it in bits (Indutnyi, 2022). The formula for determining the predicted estimated value will be as follows:

$$C = \alpha * 2^N, \quad (1)$$

where C is the predicted estimated value; α is the estimation base; N is the amount of information in bits; 2^N is the integrated quality indicator, which is measured in exbits (exb).

From formula (1), it is clear that for an empirical study of the relationship between the value of objects C and the amount of information about those objects N, it is necessary to logarithmise the value indicators described by the ordinate axis to the base 2 in order to observe this polygon in values proportional to N – the amount of information about those objects (Fig. 2).

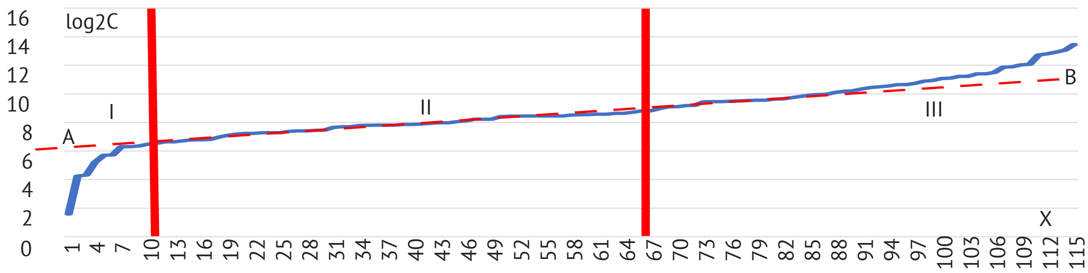

Figure 2. *Distribution of item value indicators after logarithmisation, built on the basis of the original database*
Note: *the ordinate axis is the logarithmised base 2 cost (log_2C); the abscissa axis is the item number (X) in the original database. The vertical lines divide the entire polygon of indicators into 3 intervals. The line AB approximates the trend of cost growth within the second interval*
Source: *based on Violity (n.d.), Rozetka (n.d.), Temu (n.d.), Prom (n.d.)*

V. Indutnyi (2022) presented a protocol for accounting for the amount of known information about an item, which contained a list of criteria for evaluation in bits. The most important criteria for evaluating decorative and applied art objects were: "Relationship of the monument to cultural traditions", "Reproduction", "Age of the monument", "Level of recognition of the author", "Relationship of the monument to outstanding manufactories and schools" and "Level of technical perfection". The protocol provided a ranking of the evaluation criteria. After evaluation by individual criteria, a general indicator was determined by multiplication, which reflected the amount of positive information about the object and was used in further modelling. In the first interval (I) in Figure 2 (1-12 samples) there were abnormally low indicators, for which the distribution was characterised by a rapid increase in specific value indicators. Underestimation by sellers of the starting price at auctions became thoughtful actions that were associated with the desire to interest a larger number of buyers. Low value indicators can be explained by the fact that there is no demand for some items at the time of sale, but sellers want to sell these items. Also, unprofessional manufacturing of the item, violation of characteristic stylistic features and carrying out rough restoration work reduces the value of works of decorative and applied art. Given the variety of reasons for undervaluation of decorative and applied art, which was observed in the first interval in Figure 2, meaningful prediction of value based on the law of pricing is impossible. At the same time, abnormally low indicators were useful, because these indicators allowed having an idea of the minimum levels of liquidation value (Indutnyi *et al.*, 2024). In the second interval (II) (from 13 to 67 samples) logarithmic value indicators increased linearly and proportionally to the available information about the monument, and also in full accordance with the law of pricing, this trend was reflected in the graph. So, it is worth calculating the parameters of the linear regression equation that described this trend:

$$C = 2^{0.038 * x + 6.33} = 86.39 * 2^{0.038 * x}, \quad (2)$$

where C is the indicator of the predicted estimated value; x is the sample number in the table of initial data.

The value 86.39 indicated the point of intersection of the approximating function of the ordinate axis and was a mathematically modelled "evaluation base" ("α") (Resolution of the Cabinet of Ministers of Ukraine No. 1440, 2003), which was determined in hryvnias, and at the same time the minimum theoretically justified value of a work of decorative and applied art, which was put up for sale in the auction mode. There was no positive information for such a work. The point was in the first interval of abnormally low value indicators. In the second interval, forecasting value indicators based on the pricing law became appropriate, which was reflected in Figure 3 and the Pearson correlation coefficient (R^2).

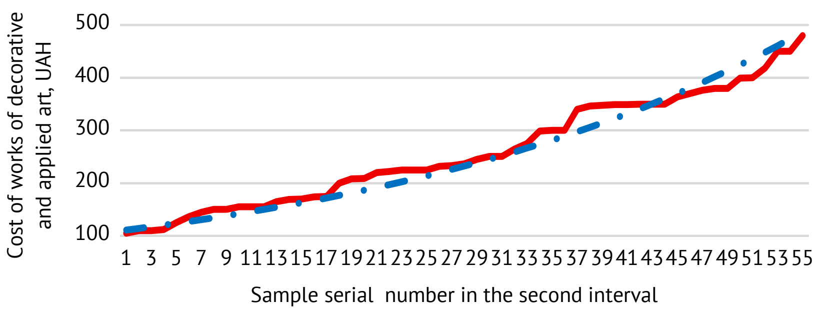

Figure 3. *Distribution of value indicators for decorative and applied art objects in the second interval*
Note: *the solid line represents the recorded value indicators. The dash-dotted line reflects the theoretical dependence. Pearson correlation coefficient (R^2) = 0.98*
Source: *based on Violity (n.d.), Rozetka (n.d.), Temu (n.d.), Prom (n.d.)*

The third interval (III) of the distribution of value indicators in the source database – from 68 to 115 samples – was described by an increasing uncertain function and did not demonstrate compliance with the law of pricing. At the same time, if the figurative points from the third interval are moved to the right, arbitrarily increasing the own numbers in the source database (along the abscissa axis), then the points will lie on the theoretical straight line AB, described by the regression equation in the second interval. Thus, by performing these operations, it is possible to virtually supplement the number of samples in the source database and determine the imaginary number of the sample, based on the described regression equation and the amount of useful information about it in bits. This method simulated the process of artificial expansion of the source data distribution polygon along the "X" axis. For example, if a sample of a decorative and applied vase, indicated as number 110 in the source database (flare "Kosiv", 28 × 19 cm), had a declared cost of 4300 hryvnias (Kosiv painted ceramics, 2025), then its new virtual number in the database – "X", calculated based on the regression formula (2), can be found by solving the equation:

$$4{,}300 = 86.39 * 2^{0.038*x} \rightarrow 49.774 = 1.027^{x} \rightarrow x = = \log_{1.027}(49.774) = 146.667 \text{ or } x \approx 147. \quad (3)$$

The sample number is an integer, so rounding was performed. The estimated cost of this work of decorative and applied art, calculated on the basis of the new virtual number, will be 4149.7 hryvnias and will differ from the price declared by the seller by only 3.5%. This is a good indicator of the reliability of the forecast and justifies the calculation of the virtual number. If making an extrapolation assumption about the inclusion of numerous imaginary samples in the source database, then for items from the third interval it is possible to calculate new virtual numbers, while the implementation of the pricing law will be observed within all intervals described in Figure 2. The forecasted value indicators in the third interval will differ slightly from those recorded due to rounding in the calculations of the value "X". In this case, abnormally low value indicators will be replaced by new ones – forecasted ones. The application of extrapolation assumptions is possible provided that the pricing law is implemented in the second interval.

The observed value indicators in the third interval should be considered anomalous (Indutnyi *et al.*, 2024), since these indicators were not directly described by the law of pricing and, accordingly, were considered unsuitable for creating reasoned predictive conclusions, because in expert work it is worth using only mathematical models that can be verified by third-party experts. At the same time, the price recorded at the auction was also partially justified, although it depended on the action of emotional factors. Determining the influence of emotional factors on the formation of market value became a separate task that required theoretical development and concerned the explanation of the phenomenon of unmotivated increase in value indicators during auction trading. At the same time, unmotivated underestimation of value was not considered at all due to the lack of such a need. The emotional factor present during the competitive struggle of potential buyers was indirectly determined by the difference between the predicted and market value, which could also be described by the amount of information about the emotional state of the seller, associated with the seller's intuitive premonitions about the presence of an interested and financially capable buyer on the market. For the already described conditional example of a decorative and applied vase, the amount of additional information that described the emotional state of the seller or potential buyers during the auction trade can be determined in bits (Goleman, 2005). If C1 is the predicted value of the product, C2 is the market value declared by the seller or formed as a result of auction trading, and C1 < C2, then the amount of emotional information (N) for the decorative and applied vase under number 110 will be:

$$N = \log_2(C2/\alpha) - \log_2(C1/\alpha) = \log_2(4{,}300/86.39) - \log_2(4{,}149.7/86.39) = 0.051. \quad (4)$$

Since the result N = 0.051 bits is a value less than one, it is reasonable to assume that information about the influence of the emotional factor on trading is absent or insignificant. Therefore, the proposed approach to forecasting value indicators in the third interval, which is associated with ignoring the influence of the emotional factor and calculating the virtual number, is fully justified. The mathematically predicted and market indicators of specific value are distinguished. The difference between these indicators does not require explanation – it is unmotivated and intuitively formed. Fulfilment of the condition when $N \geq 1$ bit should be considered as a criterion for the presence of a significant influence of the emotional factor on pricing. This situation arises only in the conditions of selling an item in the auction trading mode. In addition, the description of the emotional factor of influence is not described by any criteria, since it is based on the intuition of market participants.

It is worth noting that the final auction prices for decorative and applied art objects cannot be used in calculating losses, pledges and investments, since such prices depend on permanent trading circumstances and are not subject to theoretical justification. However, the Order of the Ministry of Culture and Arts of Ukraine No. 325 (1998) recommends the use. Knowing the value "C", predicted by the extrapolation method, and the "assessment base" – "α", it is possible to calculate the amount of positive information in bits, which is theoretically necessary to substantiate the estimated value according to the Resolution of the Cabinet of Ministers of Ukraine No. 1440 (2003) for each of the samples of decorative and applied art objects presented in the source database:

$$C = \alpha * 2^{N} \rightarrow C/\alpha = 2^{N} \rightarrow N = \log_2(C/a). \quad (5)$$

The calculation yielded real numbers, however, only integers were used to determine the amount of information (in bits) (Shannon, 1948; Cruces, 2019), so it was necessary to round off. Therefore, the predicted estimated value of the studied objects belonged to the information interval {(N – 1);(N + 1)}. The permissible error of the expert was ±1 bit of information in the protocol to account for the amount of known information about the object. The range of permissible predicted indicators expanded in accordance with the increase in the level of information security of the object of assessment (Fig. 4).

Depending on the content of the expert task, the result of predicting the value of decorative and applied art objects can be either the average value of the estimated value or the interval of values {min(C) – max(C)}. In this case, the interval increases with the increase in the predicted value of the works, i.e. a more valuable item has a less unambiguous estimate. The more likely price after the auction is ΣC, the justified level of liquidation value is min (C), and the highest justified price is max (C). Therefore, when carrying out expert activities, it is worth noting possible (non-anomalous) indicators and providing explanations for anomalous indicators in case these indicators are achieved during the bidding process. Figure 4 shows justified value indicators for works of decorative and applied art. Since the sale of objects is influenced by many factors, it is possible to encounter anomalous value indicators associated with the action of emotional factors. The total number of objects in the first and third intervals determines decorative and applied art objects with anomalous value indicators. In this study, 60 such samples were used, which amounted to 52.17% of the total number of decorative and applied art objects described in the source database. Therefore, it was important to show the possibility of making the forecasting procedures used by the expert fully substantiated and suitable for independent audit. Figure 5 shows the first example of forecasting the cost of a work of decorative and applied art, namely an interior decoration made of wood, put up for sale on the Apricot website. There is no information about the availability of useful information about the work. The price of the work from the seller is 79 hryvnias.

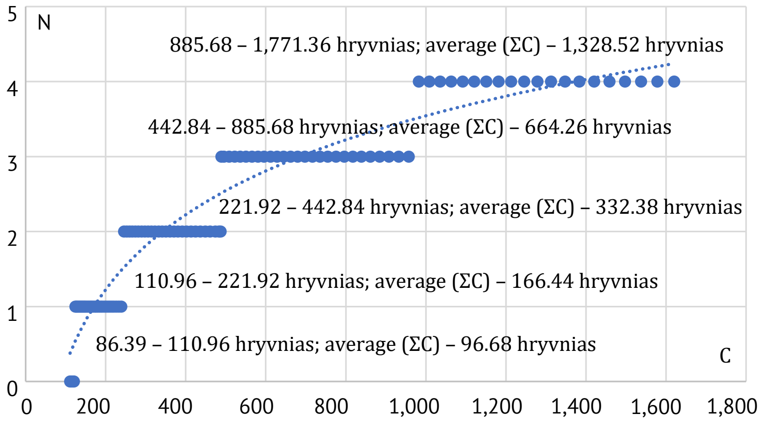

Figure 4. *Projected value indicators for decorative and applied art objects from the source database*
Note: *the ordinate axis is the number of positive information in bits (N), and the abscissa axis is the predicted value indicators for decorative and applied art objects (C). The dotted curve indicates the trend of growth of the average (ΣC) values of the estimated value of decorative and applied art products on the Ukrainian market*
Source: *developed by the authors*

Figure 5. *Painted wooden duck (10.5 × 6 × 5 cm)*
Source: *Apricot Opt (n.d.)*

Given the absence of any positive information about the quality of this item (N = 0), the predicted estimated value will be: C = 86.39 × 20 = 86.39 hryv nias. This indicator exaggerates the price offered by the seller, therefore, the value of this work of decorative and applied art on the market should be recognised as abnormally low. The average estimated value of this item is 98.68 hryvnias. This indicator can also be used in expert forecasting the estimated value. The second example is an inlaid rachva for jewellery and trinkets, put up for sale on the Chichka website. Material: pear wood, mother-of-pearl, beads. Size: 17 × 6 cm. Hand-made by a craftsman from the village of Richki, Vasyl Grepinyak. The current price of the work from the seller is 2,500 hryvnias (Fig. 6).

Figure 6. *Inlaid rachva for decoration*
Source: *Chichka (n.d.)*

The estimated value, which is calculated based on the protocol for assessing the sociocultural significance of a cultural monument, which takes into account information about the subject's involvement in folk traditions and the level of recognition of the craftsman at the national level (N = 4), is determined as follows: C = 86.39 × 24 = 1,382.24 hryvnias. This figure is significantly lower than the price offered by the seller, therefore, the value of this work of decorative and applied art on the market is declared abnormally high – more than 2,000 hryvnias, which are more affordable for a potential buyer. The third example (Fig. 7) is the wall panel "Zebra of Happiness" – a decorative and applied decoration made using the laser cutting technique of metal and presented on the Ekans website. The price of the work, declared by the seller, is 1,500 hryvnias.

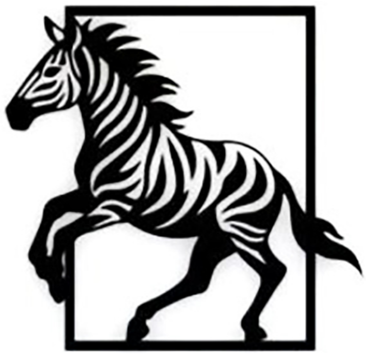

Figure 7. *Wall panel "Zebra of Happiness"*
Source: *Ekans (n.d.)*

The estimated value of this work was calculated based on the protocol for assessing the sociocultural significance of a cultural monument, which took into account useful information about the high technical perfection and relatively large dimensions of the work (N = 4), and is determined as follows: C = 86.39 × 24 = 1,382.24 hryvnias. Therefore, the price offered by the seller on the website is slightly overstated, but is within the regulatory liquidity of 2,000 hryvnias. Thus, the developed mathematical model for predicting the estimated value of decorative and applied art objects made of wood and metal allowed determining the value based on the accounting of known useful information. In addition, this model can be used to analyse the prices for these goods set by sellers – whether the prices are justified or not.

Other scholars have also dealt with the issues of predicting the value of works of art and antiques. O. Kalashnykova (2006) presented a fundamental work on the basics of art historical expertise and valuation of cultural values, which was referred to by many scholars. An important feature of the book was the coverage of methods for attribution and expertise of objects of historical and cultural significance, as well as modern methods for determining the value of works of art. B. Platonov (2013) reviewed the existing approaches, principles, and methods of evaluation, which were considered classics of evaluation and the features of the application in the assessment of cultural values, special attention was paid to the consideration of cost and comparative approaches to evaluation. V. Karpov & Zh. Denysiuk (2020) described expert activities in Ukraine related to the study of movable monuments of history and culture, and presented a methodology for determining the estimated value of museum objects. A. Dmytrenko (2024) revealed the essence and practical use of the state methodology for the examination of cultural values, in particular, determining the insurance value of museum objects, and provided a brief analysis of the author's methods for conducting an appraisal examination. O. Vagonova *et al.* (2022) proposed to improve the conduct of commodity appraisal of antiques and collectibles, presenting a formula for calculating the predicted market price and a list of parameters for determining the collector's premium. Thus, the mathematical model presented in the study for predicting the estimated value of decorative and applied art objects expanded the existing base of scientific research, in particular for products made of wood and metal.

Conclusions

Thus, decorative and applied art objects made of wood and metals had a market value that was determined by the financial capabilities of potential buyers, the cost of the materials from which those works were made, and the manufacturer's overhead costs. When predicting the estimated value of decorative and applied items, it is advisable to use a single valuation base – 86.39 hryvnias per sample. The results of these calculations were reasonable and corresponded to the mathematical model built on the basis of the law of pricing. The quality of forecasting the estimated value of decorative and applied items was high and was briefly assessed by the correlation index between the observed and theoretically calculated indicators at the level of 0.98 according to K. Pearson.

The nature of the distribution of value indicators for decorative and applied items on the open market indicated the possibility of distinguishing separate groups of goods according to the liquidity level, as well as determining the upper limit of price indicators favourable for the rapid sale of goods. 87.82% of potential buyers on the Ukrainian market were ready to purchase decorative and applied art objects worth up to 2000 hryvnias per sample. The high level of sociocultural significance of decorative and applied art objects contributed to the manifestation of emotional factors of potential buyers, which allowed sellers to reasonably increase the value and liquidity. The more useful information was taken into account when describing decorative and applied art objects, the higher the sociocultural value became and the wider the range of theoretically justified predictive indicators of estimated value. The estimated value of decorative and applied art objects presented on the Ukrainian market should be determined as an average indicator in the range of possible predicted values. 3 examples of the evaluation of decorative and applied art objects were given, and it was established that an interior decoration made of wood – a painted duck – was offered for sale at an abnormally low price (79 UAH), an inlaid rachva for decorations – at an abnormally high price (2,500 UAH), a wall panel made of metal – at a slightly inflated price (1,500 UAH), but within the limits of regulatory liquidity. Final auction prices for decorative and applied items cannot be used when calculating losses, pledges and investments, since these prices depend on permanent circumstances of the auction and are not subject to theoretical justification. The prospect of further research is to consider other types of decorative and applied items, create a database of initial data and build a mathematical model to predict the estimated value.

Acknowledgements
None.

Funding
None.

Conflict of Interest
None.

References

[1] Apricot Opt. (n.d.). *Painted wooden duck (10.5 × 6 × 5 cm) (BUR120SE)*. Retrieved from https://apricot.com.ua/utka-derevyannaya-raspisnaya-105kh6kh5-smbur120se/.
[2] Besaha, M. (2025). The impact of digital technologies on art historical support of auctions: Challenges and prospects. *Fine Art and Culture Studies*, 1, 247-255. doi: 10.32782/facs-2025-1-36.
[3] Bogaychuk, L., Dmitriyeva, O., Kryzhevska, S., & Kotova, O. (2024). Underestimating the contemporary art market in Ukraine. *Collection of Scientific Papers «ΛΌГOΣ»*, 464-465. doi: 10.36074/logos-24.05.2024.106.
[4] Chichka. (n.d.). *Kosiv painted ceramics*. Retrieved from https://chichka.in.ua/shop/cat/kosivska-keramika.
[5] Cruces, S., Martin-Clemente, R., & Samek, W. (2019). Information theory applications in signal processing. *Entropy*, 21(7), article number 653. doi: 10.3390/e21070653.
[6] Demydchuk, L. (2021). *Commodity science of souvenirs and folk arts and crafts products*. Lviv: Lviv University of Trade and Economics Publishing House.
[7] Demydchuk, L. (2023). Handicrafts and souvenirs as components of the local production, retail and hospitality markets. *Herald of Khmelnytskyi National University. Economic Sciences*, 316(2), 112-116. doi: 10.31891/2307-5740-2023-316-2-16.
[8] Denysiuk, Zh. (2025). Art projects of contemporary decorative and applied arts in forming the cultural brand and image of Ukraine. *Current Issues of the Humanities*, 1(92), 175-181. doi: 10.24919/2308-4863/92-1-23.
[9] Dmytrenko, A. (2024). *Methods of evaluation of cultural values*. Lutsk: Lesya Ukrainka Volyn National University.
[10] Dmytriyeva, O., Bogaychuk, L., & Rudoy, V. (2023). Decorative and applied arts of Ukraine are a window of opportunity in times of crisis. *Collection of Scientific Papers «ΛΌГOΣ»*, 126-127. doi: 10.36074/logos-03.03.2023.39.
[11] Ekans. (n.d.). *Wall decor (panel) "Zebra of happiness" (laser cut)*. Retrieved from https://ekans.com.ua/product/dekor-na-stinu-panno-zebra-shhastya-lazerna-porizka.
[12] Goleman, D. (2005). *Emotional intelligence: Why it can matter more than IQ*. New York: Bantam.
[13] Hrabynskyi, I. (2021). Methodological problems of analysing the world market for works of art, antiquities and antiques. *Grail of Science*, 10, 41-44. doi: 10.36074/grail-of-science.19.11.2021.004.
[14] Indutnyi, V. (2022). Universal unit for measurement of quality for accounting and evaluation procedures in museum practice. In *14th international scientific and practical conference "Science, innovations and education: Problems and prospects"* (pp. 55-64). Tokyo: CPN Publishing Group.
[15] Indutnyi, V., Merezhko, N., & Pirkovich, K. (2024). Abnormal and normative cost indicators in the painting market. *Commodity Science. Technologies. Engineering*, 52(4), 35-48. doi: 10.31617/2.2024(52)03.
[16] Kalashnykova, O. (2006). *Fundamentals of art historical expertise and valuation of cultural values*. Kyiv: Znannia.
[17] Kalashnykova, O. (2022). New art formats: The auction experience. In *Multidisciplinary academic research, innovation and results. Proceedings of the XXII international scientific and practical conference* (pp. 134-136). Prague, Czech Republic.
[18] Karpov, V., & Denysiuk, Zh. (2020). *Formation of art collections: Determining the estimated value of museum objects*. Kyiv: NAKKKiM.
[19] Kravets, A. (2025). Art projects of Ukrainian decorative and applied arts in the context of their image-building mission. *National Academy of Managerial Staff of Culture and Arts Herald*, 3, 194-199. doi: 10.32461/2226-3209.3.2025.344383.
[20] MinFin. (2025). *NBU dollar exchange rate on August 10, 2025*. Retrieved from https://minfin.com.ua/ua/currency/nbu/usd/2025-08-10/.
[21] Order of the Ministry of Culture and Arts of Ukraine No. 325 "On Approval of the Instruction on the Procedure for Determining the Appraised and Insurance Value of Objects of the Museum Fund of Ukraine". (1998, July). Retrieved from https://zakon.rada.gov.ua/laws/show/z0496-98#Text.
[22] Platonov, B. (2013). *Fundamentals of evaluation activity*. Kyiv: NAKKKiM.

[23] Prom. (n.d.). Retrieved from https://prom.ua.
[24] Resolution of the Cabinet of Ministers of Ukraine No. 1440 "On Approval of National Standard No. 1 "General Principles of Property and Property Rights Valuation". (2003, September). Retrieved from https://zakon.rada.gov.ua/laws/show/1440-2003-п#Text.
[25] Rozetka. (n.d.). Retrieved from https://rozetka.com.ua.
[26] Shannon, C.E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, 27, 379-423.
[27] Temu. (n.d.). Retrieved from https://www.temu.com/ua.
[28] Vagonova, O., Chornobayev, V., & Nesterova, L. (2022). Improvement of approaches for carrying out product expertise on the example of assessment of antique and collectible items. *Economic Space*, 180, 9-15. doi: 10.32782/2224-6282/180-1.
[29] Violity. (n.d.). Retrieved from https://violity.com/ua.
[30] Zapasko, Ya. (Ed.). (2000). *Decorative and applied arts. Dictionary* (Vol. 1). Lviv: Afisha.
[31] Zinchenko, M. (2023). Auction as cultural and economic phenomenon of contemporary art process. *National Academy of Managerial Staff of Culture and Arts Herald*, 1, 191-196. doi: 10.32461/2226-3209.1.2023.277662.

Товарознавча оцінка творів декоративно-ужиткового мистецтва

Володимир Індутний
Доктор геолого-мінералогічних наук, професор, доцент
Державний торговельно-економічний університет
02156, вул. Кіото, 19, м. Київ, Україна
https://orcid.org/0000-0001-6676-7472
Ніна Мережко
Доктор технічних наук, професор
Державний торговельно-економічний університет
02156, вул. Кіото, 19, м. Київ, Україна
https://orcid.org/0000-0003-3077-9636
Катерина Пірковіч
Кандидат технічних наук, доцент
Державний торговельно-економічний університет
02156, вул. Кіото, 19, м. Київ, Україна
https://orcid.org/0000-0002-1461-0235
Ніна Калуга
Кандидат хімічних наук, доцент
Державний торговельно-економічний університет
02156, вул. Кіото, 19, м. Київ, Україна
https://orcid.org/0000-0002-0901-5052
Валентина Ткачук
Доктор технічних наук, професор
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0001-5793-5227

Анотація. Метою цього дослідження було вивчити закономірності ціноутворення на сучасному українському ринку декоративно-ужиткових предметів та побудувати математичну модель для прогнозування їх оціночної вартості на прикладі виробів, створених з дерева і металів, а також визначити рівень фінансових збитків від їх втрати в ході воєнних дій. Твори декоративно-ужиткового мистецтва представлені предметами побуту, які стали символами матеріальної культури людства, етнічних та національних особливостей. Вони виготовлялися з різноманітних матеріалів і широко розповсюджені на ринку. У дослідженні було створено базу вихідних даних, до якої було внесено 115 зразків, виготовлених з дерева та металу: інтер'єрні настінні прикраси, міні-скульптури та декоративні побутові речі. Вартісні показники зразків були розподілені від найменшого до найбільшого та логарифмовані за основою 2. В результаті було виділено три інтервали розподілу вартісних показників в базі вихідних даних. В другому інтервалі логарифмовані вартісні показники зростали лінійно, це дозволило побудувати математичну модель для прогнозування їх оціночної вартості в контексті питання про визначення рівня можливих збитків від їх втрати. Також, для предметів з бази вихідних даних було визначено діапазони допустимих прогнозованих вартісних показників. В статті наведено 3 приклади розрахунку оціночної вартості декоративно-ужиткових предметів і здійснено порівняння із цінами, запропонованими продавцями. Встановлено, що інтер'єрна прикраса з дерева пропонувалася до продажу за аномально низькою ціною (79 грн), інкрустована рахва для прикрас – за аномально високою ціною (2500 грн), настінне панно з металу – за незначно завищеною ціною (1500 грн), але в межах нормативної ліквідності. Чим більше корисної інформації було опубліковано при описі декоративно-ужиткових предметів, тим вищою стала їх соціально-культурна цінність та оціночна вартість. Результати дослідження показали, що твори декоративно-ужиткового мистецтва з дерева та металів мали ринкову вартість, яка визначалася фінансовими можливостями потенційних покупців

Ключові слова: декоративно-ужиткові предмети; вироби з дерева; вироби з металів; прогнозування вартості; вартісні показники

COMMODITY BULLETIN
Journal homepage: https://c-bulletin.com.ua/en
DOI: 10.62763/cb/2.2025.20

Article's History: Received: 30.07.2025 Revised: 04.11.2025 Accepted: 26.12.2025 Published: 02.01.2026

ISSN 2310-5283; e-ISSN 3041-1432

Vol. 18, No. 2, 2025, 20-29

UDC 679.86

Operational properties of film materials for bio-packaging

Oleksandra Krykhovets *
PhD in Chemistry, Associate Professor
Lviv Polytechnic National University
79013, 12 Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0002-2603-0991
Vyacheslav Repeta
Doctor of Technical Sciences, Professor
Lviv Polytechnic National University
79013, 12 Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0003-3204-1512
Olha Hulai
Doctor of Pedagogical Sciences, Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-1120-6165

Abstract. The development of environmentally safe packaging materials has become one of the key requirements for 2026. Across various segments of the modern market, there has been a clear and steady increase in interest in biopolymer materials produced from renewable raw materials and capable of biodegradation. The aim of this work was to investigate the performance characteristics of films based on polyvinyl alcohol, maize starch, glycerine and sodium tetraborate, as well as to assess their potential for use as environmentally safe packaging materials. During the study, the films were produced by solution casting onto a glass substrate with heat treatment at temperatures of 393 K and 423 K. Samples of various thicknesses were produced: in the range of 0.0552-0.0616 mm, as well as thicker films – from 0.1953 to 0.2240 mm. The physical and mechanical properties of the materials were determined using a universal tensile testing machine. It was found that the experimental tensile strength values for the obtained film materials increased with an increase in the sodium tetraborate content – from 18.79 N to 66.2 N. The tensile strength reached 30.5 MPa at a sodium tetraborate content of 10% and a film stabilisation temperature of 423 K. The relative elongation at break gradually decreased at higher sample stabilisation temperatures. The increase in tensile strength for films containing 10% sodium tetraborate made this composition effective for producing films with improved strength. Film materials with a thickness of 0.0612-0.0734 mm exhibited the best performance characteristics in terms of the "material strength-film thickness" ratio. The results of the study of the performance characteristics of film materials formed on the basis of polyvinyl alcohol, water-soluble maize starch and glycerine with varying sodium tetraborate content allowed for the consideration of their potential use for food packaging and the encapsulation of fresh vegetables and fruit

Keywords: biodegradable materials; physico-mechanical properties; biopolymers; polyvinyl alcohol; tensile strength

Suggested Citation:
Krykhovets, O., Repeta, V., & Hulai, O. (2026). Operational properties of film materials for bio-packaging. *Commodity Bulletin*, 18(2), 20-29. doi: 10.62763/cb/2.2025.20.

*Corresponding author

Introduction

Packaging has played a key role in ensuring the effective sale of goods, as it combines functional, logistical, marketing and informational aspects, whilst guaranteeing the physical, chemical, microbiological and barrier safety of goods. The rapid growth in packaging volumes, and consequently in the amount of plastic waste, has had a negative impact on the environment. In modern market segments, there has been a steady trend towards growing demand for biopolymer materials derived from renewable raw materials, which have found practical application particularly in food packaging. S. Kumar *et al.* (2022) highlighted the advantages of using biopolymers as materials for food packaging. The use of biodegradable materials, weight reduction and optimisation of packaging structure had a positive impact on companies' image and expanded opportunities for entering environmentally-oriented markets. Polyvinyl alcohol (PVA)-based film materials exhibited satisfactory gas barrier properties under conditions of low relative humidity and were used as a base for the production of environmentally safe packaging films. One of the main strategies for modifying PVA-based films involved the introduction of inorganic nanofillers (in particular, ZnO and TiO_2), which, according to research by Y. Xie *et al.* (2024), enhanced antimicrobial activity, provided UV protection and strengthened the mechanical structure of the film. Thanks to these properties, PVA films have been actively used to create modern packaging solutions in the pharmaceutical industry and as biocompatible coatings for medical devices. The method for producing PVA-based composite films proposed by C. Wang *et al.* (2024) enabled the production of strong materials with the potential to impart antimicrobial properties. A study by R. Hussain *et al.* (2023) established the antimicrobial activity of biodegradable PVA films in combination with ascorbic acid and glutaraldehyde.

PVA-based composite films demonstrated enhanced functional capabilities, making them promising for various technological applications. V. Krasinskyi *et al.* (2021) used montmorillonite as a filler in polyvinyl films, which enabled the formation of a homogeneous cross-linked structure, reduced the degree of crystallinity, and increased the thermal stability of the nanocomposites. X. Li *et al.* (2021) developed a packaging film based on polyvinyl alcohol containing Fe^{3+} ions, which optimised food storage conditions and was UV-resistant. This opened up the possibility of creating highly functional composite materials for packaging and smart quality control systems. To improve the barrier properties of PVA nanocomposite films, S.V. Nguyen & B.-K. Lee (2023) used cellulose nanocrystals in combination with titanium dioxide. In particular, this resulted in improved resistance to water vapour permeation, enhanced UV protection, and an effective extension of shelf life due to the high antioxidant and antimicrobial properties of the resulting nanocomposite.

Encapsulating fresh products in film packaging made from active packaging materials has become a cost-effective way to prevent the impact of external conditions and to maintain high food quality. As noted by S. Yildirim *et al.* (2017), the primary objective of active packaging is to ensure microbiological and chemical safety, extend the shelf life of food products, and, in some cases, preserve or improve their sensory characteristics, such as taste, aroma or appearance. Interest in PVA stems from a combination of its properties that are important for food packaging: high flexibility, excellent film-forming ability, pronounced biodegradability, chemical stability, significant hydrophilicity and biocompatibility. An additional advantage was that PVA was considered an edible material, which expanded its potential applications in the food industry. Assessing the impact of various additives on the physicochemical and functional properties of PVA films became crucial, as this enabled the development of optimal materials suitable for use as active food packaging. R. Dermondes Souza *et al.* (2024) noted the use of PVA-based films containing sodium nitrite as active packaging for meat products. It was established that the properties of such films contributed to more effective preservation of chilled meat, in particular by inhibiting microbiological processes and reducing oxidative changes due to the high gas barrier properties of PVA. This modification of the material provided the potential to extend the shelf life of pork by reducing microbiological spoilage of the product. Furthermore, in the work by A. Jayakumar *et al.* (2023), a smart composite film based on polyvinyl alcohol was developed for the safe packaging of food products. In this system, chitosan combined with zinc oxide nanoparticles acted as antimicrobial agents, whilst sweet purple potato extract was used as a sensitive indicator of changes in product quality.

X. Dang *et al.* (2025) identified encapsulation as the ideal method for storing fresh fruit and vegetables, where products can slow down the loss of quality and nutrients, thereby maximising shelf life. The developed eco-friendly, multifunctional food packaging for food products based on PVA exhibited good water vapour barrier properties, resistance to ultraviolet radiation, and antimicrobial activity. The data obtained by the author regarding the film demonstrated thermal stability and antioxidant activity. Encapsulation in the films obtained prevented product spoilage, extended shelf life, and significantly expanded the possibilities for their use in safe packaging, such as edible coatings, as investigated by B.R. Moreira *et al.* (2020). The combination of PVA with biopolymers such as starch and chitosan improved the materials' biodegradability and enabled waste disposal via industrial composting (anaerobic) or decomposition in soil (aerobic process). Combining polyvinyl alcohol with natural polymers, particularly polysaccharides, has not only improved the performance properties of film materials but also significantly enhanced their biodegradability.

Film materials containing polyvinyl alcohol in combination with maize starch are capable of degradation under the action of enzymatic processes as well as under natural soil and compost conditions. The results of the analysis of biodegradation studies of composite materials based on polyvinyl alcohol and starch indicated that, under the influence of microorganisms present in biohumus, there was intensive and relatively rapid destruction of the biopolymer matrix. Biodegradable polymers from renewable sources have become a promising solution not only as effective packaging but also as an environmentally friendly solution to the waste problem. The widespread adoption of biodegradable packaging is associated with various challenges, such as cost-effectiveness, technological limitations, labelling and waste management. The aim of this study was to investigate the performance properties of film materials based on polyvinyl alcohol, water-soluble maize starch and glycerine at various concentrations of sodium tetraborate, and the potential for their use as eco-friendly packaging.

Materials and Methods

Polyviol G 04/140 (Germany) polyvinyl alcohol was used as the polymeric base for the production of film materials. Water-soluble corn starch (DSTU 3976-2000, 2001) was added to the pre-prepared aqueous PVA solution as a biodegradable component. The gelation process was carried out by heating the composition to a temperature of 363 K whilst stirring until a homogeneous gel-like system was formed. After the mixture had cooled partially, glycerine of the FS 42-2202-84 grade (Ukraine) was introduced into its composition, which was used as a plasticising additive. The addition of glycerine improved the flexibility and elasticity of the films. Furthermore, glycerine facilitated a more uniform distribution of polymer chains within the composite structure. To impart antimicrobial properties to the films, sodium tetraborate ($Na_2B_4O_7$) was incorporated into the composition. Thanks to this composition, the resulting film materials could be effectively used in the packaging of food products, hygiene items and medicines. The films were formed by casting the solution onto a glass substrate, after which the samples were dried at a temperature of 293 K on a flat surface to ensure uniform film thickness. This process corresponded to the solution casting method. After the drying process was completed, the films were subjected to heat treatment at temperatures of 393 K and 423 K for 30 minutes to stabilise their structure. Three samples of each film composition were produced. The film thickness was measured using an IZV-2 (USSR) thickness gauge at five different points on each sample, and the average value was calculated. Tests of tensile strength and relative elongation at break were carried out on a universal tensile testing machine manufactured by VEB Werkstoff-Prufmaschinen (Germany). The film samples measured 100×15 mm, with a distance of 50 mm between the grips. Measurements of tensile strength and relative elongation at break were carried out in accordance with DSTU EN ISO 8067:2018 (2020). The tensile stress was defined as the tensile force per unit area of the film's cross-section at the moment of its failure. The tensile stress σ (MPa) was calculated using the formula:

$$\sigma = \frac{P}{S}, \tag{1}$$

where P – the applied tensile force, S – the cross-sectional area of the film specimen.

The relative elongation at break was calculated in accordance with DSTU EN ISO 8067:2018 (2020) using the formula:

$$\varepsilon = \frac{\Delta l}{l_o} \cdot 100\%, \tag{2}$$

where l_0 – initial film length, l film length at the moment of rupture, $\Delta l = l - l_0$.

The film spectra were obtained using a PerkinElmer Spectrum Two Fourier-transform infrared (FTIR) spectrometer from PerkinElmer (UK), equipped with a single-element UATR attachment with a diamond crystal. The infrared (IR) analysis of the films was carried out in the range of 4,000-400 cm^{-1}.

Results and Discussion

Polyvinyl alcohol, as a non-toxic, water-soluble polymer, formed the basis for the film materials developed. As the semi-crystalline structure of PVA contains a significant number of hydroxyl groups capable of forming intermolecular hydrogen bonds, this has enabled the effective combination of synthetic polyvinyl alcohol with a biopolymer – maize starch. In this process, glycerol, acting as a plasticiser, facilitated the formation of a uniform polymer matrix. One of the key performance properties of PVA-based films was gas impermeability under conditions of low relative humidity. At the same time, its high hygroscopicity proved to be a significant drawback, as it led to increased water permeability. To overcome this drawback, a cross-linking method was employed. Sodium tetraborate hydrolysed in water to form orthoboric acid, which proved to be an effective cross-linking agent. Film samples containing 5% and 10% borax (relative to the content of other components) were produced using the solution casting method. The composition of the formulations is given in Table 1.

Heat treatment of the films at temperatures of 393 K (samples 2, 5, 8) and 423 K (samples 3, 6, 9) contributed to the strengthening and stabilisation of the structure. It is worth noting that raising the heating temperature above 433 K led to yellowing of the films. This effect was particularly evident when the composition contained a higher proportion of thermally unstable maize starch. The film samples were produced with thicknesses ranging from 0.0552 to 0.0734 mm (samples 1-6) and from 0.1953 to 0.2240 mm (samples 7-9). The measured average film thicknesses are given in Table 1. The film samples combining polyvinyl alcohol with starch, glycerine and borax had a uniform thickness, were practically transparent, colourless and homogeneous. The films were soft to the touch and stretchable. During storage under room conditions, good resistance to moisture absorption from the air was observed. For testing the strength of the films under load, strips measuring 100 mm in length and 15 mm in width were prepared (Fig. 1).

Table 1. *Composition and average thickness of films*

Sample No	Stabilisation temperature, K	Composition of film samples, wt.%				Film thickness, mm
		PVA	Starch	Glycerol	Sodium tetraborate	
1	293	45	10	40	5	0.0635
2	393	45	10	40	5	0.0616
3	423	45	10	40	5	0.0552
4	293	40	10	40	10	0.0734
5	393	40	10	40	10	0.0657
6	423	40	10	40	10	0.0612
7	293	40	10	40	10	0.2240
8	393	40	10	40	10	0.2150
9	423	40	10	40	10	0.1953

Source: *compiled by the authors*

Figure 1. *Film samples for determining physico-mechanical properties*
Source: *compiled by the authors*

Uniform strips 15 mm wide were cut from the film materials. Three samples of each film composition were prepared for the study. The tensile strength and elongation at break were determined using a universal testing machine (dynamometer). The measurements were carried out with a crosshead speed of 0.5 mm/s. Figure 2 shows the average values of the experimentally determined tensile strength of bioplastic films based on polyvinyl alcohol, corn starch, glycerine and sodium tetraborate. The results of the tensile strength measurements showed that the tensile strength of the films increased with increasing sodium tetraborate concentration. Heat treatment of the films also increased their strength. The highest tensile strength values – 18.79 N, 28.1 N and 66.2 N – were obtained for samples stabilised at 423 K.

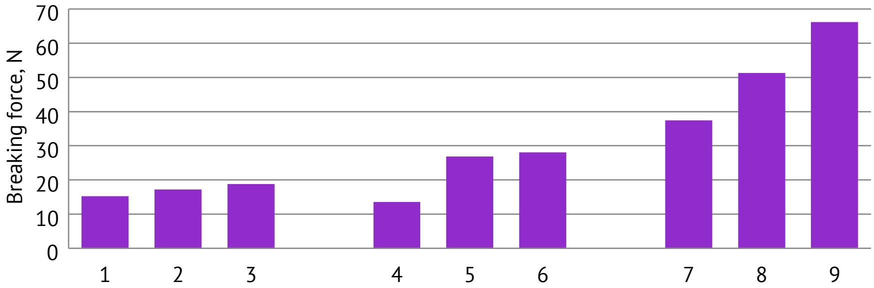

Figure 2. *Tensile strength of bioplastic films based on polyvinyl alcohol, maize starch, glycerine and sodium tetraborate*
Note: *the numbers 1 to 9 are sample numbers*
Source: *developed by the authors*

As the thickness of the samples increased, the tensile strength also increased: the tensile strength of films with a thickness of 0.1953-0.2240 mm was 2-3.5 times greater than the corresponding values for samples with a thickness of 0.0552-0.0734 mm. The main strength characteristic of the film materials was the tensile stress at break, as this parameter took into account the dimensions of the sample, in particular its thickness. Tensile stress is defined as the tensile load per unit cross-sectional area of the film material at the moment of failure. The calculation of tensile stress, or tensile strength, as one of the key performance characteristics, was performed using formula (1). The highest tensile strength values – 22.7 MPa, 30.5 MPa and 22.6 MPa – were obtained for samples stabilised at 423 K (Fig. 3).

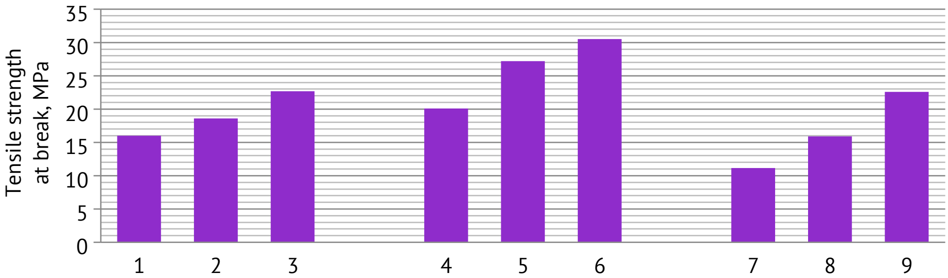

Figure 3. *Tensile strength at break of films based on polyvinyl alcohol, maize starch, glycerine and sodium tetraborate*
Note: *the numbers 1 to 9 are sample numbers*
Source: *developed by the authors*

PVA/starch films exhibited tensile strength under load. The relative elongation at break for the films under investigation was calculated using formula (2). Figure 4 shows the variation in relative elongation at break for the films under investigation with different compositions. The best tensile strength was demonstrated by film samples containing 10% sodium tetraborate. It is worth noting that, compared to tensile strength, the change in relative elongation at break showed a slightly different trend. It was found that at higher concentrations of borax, the relative elongation at break was greater. At the same time, a higher stabilisation temperature of the samples led to a decrease in elongation at break. This could be attributed to a reduction in the water content of the film material and the cross-linking and strengthening of the polymer matrix, which led to a decrease in elasticity.

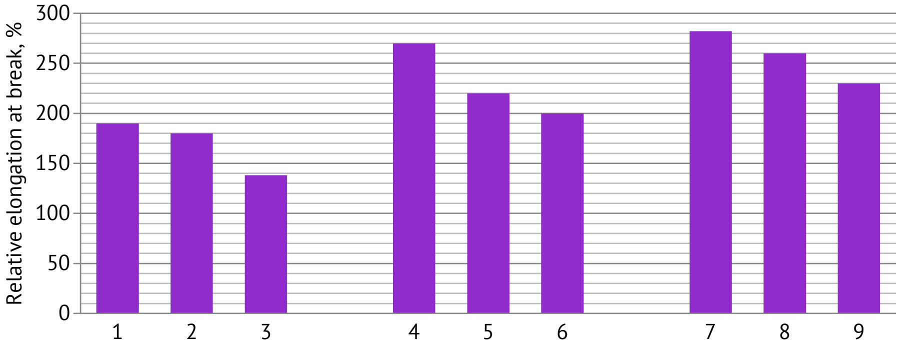

Figure 4. *Change in relative elongation at break for films based on polyvinyl alcohol, maize starch, glycerine and sodium tetraborate*
Note: *the numbers 1 to 9 are sample numbers*
Source: *developed by the authors*

Studies of tensile strength and elongation, as well as calculated values of tensile stress at break for the resulting film materials containing polyvinyl alcohol, maize starch, glycerine and borax, demonstrated their potential for use as packaging materials, particularly for food products and for encapsulating fresh vegetables and fruit. To produce films with improved strength, a 10% sodium tetraborate content proved promising, as this composition resulted in an increase in the tensile strength of the films. In terms of the "material strength – film thickness" ratio, film materials with a thickness of 0.0612-0.0734 mm exhibited the best performance characteristics. The results of the study of film materials using infrared spectroscopy indicated that the main characteristic bands in samples 4, 5 and 6 predominantly corresponded to the spectrum of polyvinyl alcohol. At the same time, no significant changes in the position or shape of these bands were detected in the samples that had undergone heat treatment (samples 5 and 6). In the spectra of films stabilised at 393 K and 423 K (samples 5 and 6, respectively), a noticeable decrease in the intensity of absorption bands associated with the hydroxyl groups of water was observed, particularly in the regions around 2,300 cm^{-1} and 1,670-1,630 cm^{-1}. In addition, for sample 6, the appearance of a shoulder at 1,701 cm^{-1} was recorded, which corresponded to the valence vibrations of the ester-type carbonyl group (C = O), indicating the possible formation of new chemical bonds in the material's structure as a result of heat treatment. In the spectrum of the untreated sample 4, characteristic bands at 1,148 and 1,078 cm^{-1} were clearly evident. After annealing, these bands disappeared, indicating structural transformations in the polymer matrix. At the same time, for sample 6, an increase in the intensity of the absorption band associated with C-O group vibrations was observed in the 1,120-1,080 cm^{-1} range. Furthermore, the shift of the most intense C-O group absorption peak from 1,023 to 1,034 cm^{-1} indicated a decrease in the degree of crystallinity of the starch amylose under the influence of elevated temperature (Fig. 5).

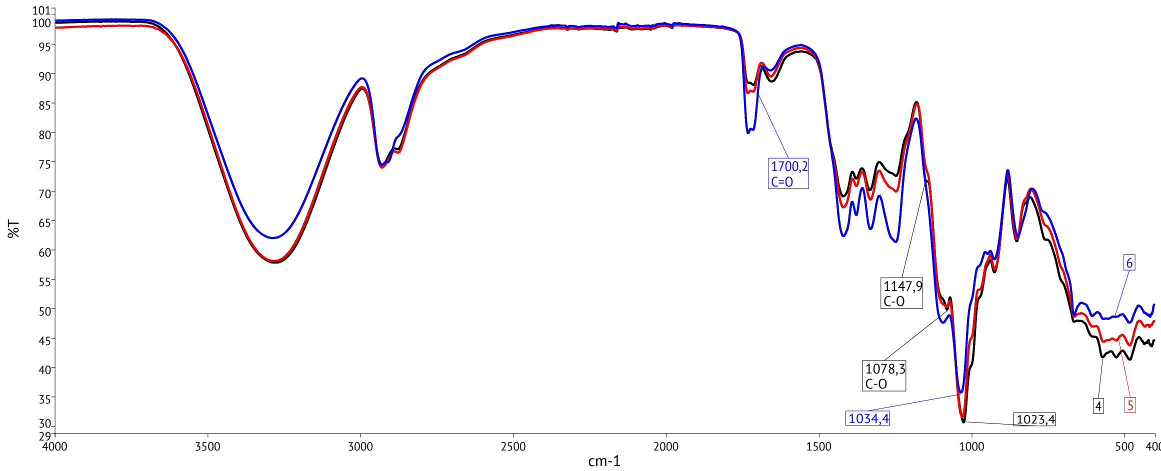

Figure 5. *Spectra of films based on polyvinyl alcohol and starch (4,000-400 cm^{-1} range)*
Source: *developed by the authors*

Thus, sodium tetraborate emerged as one of the key components ensuring the formation of a stable and robust structure in the film materials under investigation; it was incorporated into the composition to impart antimicrobial properties to the potential packaging materials. In an aqueous environment, sodium tetraborate underwent hydrolysis to form orthoboric acid, which initiated cross-linking processes between the polyvinyl alcohol macromolecules. The implementation of this mechanism contributed to the strengthening of intermolecular interactions between the system's components, particularly between the polyvinyl alcohol and starch chains, which had a positive effect on the structural integrity and performance characteristics of the films. The presence of cross-linking processes was confirmed by the appearance in the spectrum of sample 6 of a characteristic band corresponding to ester groups at 1,701 cm^{-1}, as well as an increase in the intensity of the absorption band in the 1,120-1,080 cm^{-1} range. These spectral changes indicated the formation of new chemical bonds in the structure of the composite film materials. As a result, a film material was formed that was characterised by increased mechanical strength and greater structural stability.

The results obtained correlated with the work of S. Zhang *et al.* (2023), where the task of increasing the mechanical strength of polyvinyl alcohol-based films was solved by chemical cross-linking with boric acid, which made it possible to significantly improve the mechanical properties of the material without compromising its optical transparency. Furthermore, in the work by A.K. Sonker & V. Verma (2017), it was determined that the addition of an organic acid to the polyvinyl alcohol polymer matrix led to the strengthening of the films and a reduction in water absorption. The introduction of sodium tetraborate into the polymer matrix could be considered more promising, as it not only improved the strength of the film materials but also imparted antimicrobial properties. The stabilisation of the film materials at temperatures of 393 K and 423 K contributed to the strengthening of the material – a functional characteristic such as tensile strength increased. The results of this study were consistent with those of L. Li *et al.* (2024), who reported that the presence of water in polyvinyl alcohol films reduced the material's mechanical properties, particularly tensile strength, but increased its ductility. The thermal method of film strengthening became more expensive compared to cross-linking as the boric acid content increased. Similar results are reported in the study by V. Sytar *et al.* (2020). The authors found that the maximum resistance of the film composition to dissolution in water is achieved both by heating to 443 K for 30 minutes and by adding boric acid (30% relative to the dry weight of PVA). Thus, the introduction of sodium tetraborate into the composition of polyvinyl alcohol, maize starch and glycerine proved to be an effective solution, contributing to an increase in the material's chemical stability and an improvement in its performance properties, in particular an increase in strength and the assurance of material stability during prolonged use. The films under investigation may also find application in agriculture, particularly for the bio-packaging of plant protection products. J. Song *et al.* (2024) developed a new strategy combining mechanical activation with esterification and blending with polyvinyl alcohol (PVA), to produce biodegradable and cold-water-soluble starch (St)/PVA films with excellent mechanical properties, solubility and oxygen barrier properties. The resulting films effectively improve the emulsification and dispersibility of fat-soluble pesticides, thereby enhancing their efficacy when packaged in St/PVS films.

Since disposal has become a crucial stage in the "life cycle" of packaging, the inclusion of biopolymers in the polymer composition enables the biodegradation of the materials under investigation and significantly accelerates the biodegradation processes of the films, as established by N.N. Nasir & S.A. Othman (2021) due to the presence of starch. Furthermore, the authors noted that optimising the concentrations of starch and glycerol allows the properties of the films to be maximised for various applications, ensuring a balance of strength, flexibility and hydrophilicity. M.C. Alvarado (2024) investigated the use of composite films based on polyvinyl alcohol and nanocellulose for packaging materials, demonstrating that the addition of nanocellulose improves the mechanical properties and barrier characteristics of the films. In the work by A.A. Oun *et al.* (2022), the combination of PVA with various biopolymers and functional materials was analysed, highlighting the potential for using such composites as packaging materials. Research by O. Fedoryshyn *et al.* (2024) on experimental and industrial film materials containing maize and potato starch demonstrated increased microbial activity on their surfaces in soil and biodegradability. Research by V. Lebedev *et al.* (2022) investigated the hybrid modification of environmentally friendly polylactic acid polymers with humic substances and identified an intermolecular bond between polylactic acid and humic substances. Furthermore, the researchers noted that the modification mechanism promoted increased crystallisation and the formation of complex bonds, which improved the mechanical properties of the materials. In the work by O. Krykhovets & V. Slobodianyk (2023), the wetting of polyvinyl alcohol-based film surfaces by test liquids was investigated. Thanks to their good printability, polyvinyl alcohol-based films can be printed to a high standard for applying the information required for packaging. The authors S. Sheikh *et al.* (2021) demonstrated the economic viability of using biodegradable compositions containing polyvinyl alcohol as active packaging. The combination of enhanced mechanical properties, high transparency, biodegradability and antimicrobial activity has made the studied film materials promising for the production of environmentally safe packaging.

Conclusions

Film materials combining polyvinyl alcohol, maize starch, glycerol and sodium tetraborate were found to be transparent, of uniform thickness, soft and elastic. It was established that the physical and mechanical properties of the biopolymer films varied depending on the composition of polyvinyl alcohol, corn starch, glycerine and sodium tetraborate, and the temperature at which they were stabilised. The tensile strength of films containing 10% sodium tetraborate increased by 125% compared to those containing 5% sodium tetraborate at a temperature of 293 K and by 151% after heat treatment. The introduction of 10% sodium tetraborate enabled the effective production of films with increased strength. The highest tensile strengths – 18.79 N, 28.1 N and 66.2 N – were recorded for samples stabilised at 423 K. Heat treatment of the film materials at temperatures of 393 K and 423 K contributed to the strengthening of the material, in particular improving functional characteristics such as tensile strength. Furthermore, the results of IR spectroscopy of the films indicated structural transformations in the polymer matrix. The formation of new chemical bonds in the material structure as a result of heat treatment was evidenced by the appearance of a band corresponding to the valence vibrations of the ester-type carbonyl group. With film thicknesses ranging from 0.0552 to 0.2240 mm, which met the requirements for packaging films, the biofilms obtained exhibited high performance properties. The ability of the studied materials to undergo relative elongation within the range of 130%–280%, combined with the high gas barrier properties of polyvinyl alcohol, made it possible to predict the potential use of transparent PVA/starch films for encapsulating food products, particularly vegetables and fruit. The presence of a biopolymer in the film composition will allow packaging waste to be disposed of by composting or burial in soil, thereby helping to improve its composition. The study of the conditions and rates of biodegradation of polyvinyl alcohol-starch films is the subject of further research.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Alvarado, M.C. (2024). Recent progress in polyvinyl alcohol (PVA)/nanocellulose composite films for packaging applications: A comprehensive review of the impact on physico-mechanical properties. *Food Bioengineering*, 3(2), 189-209. doi: 10.1002/fbe2.12086.

[2] Dang, X., Han, S., Du, Y., Fei, Y., Guo, B., & Wang, X. (2025). Engineered environment-friendly multifunctional food packaging with superior nonleachability, polymer miscibility and antimicrobial activity. *Food Chemistry*, 466, article number 142192. doi: 10.1016/j.foodchem.2024.142192.

[3] Dermondes Souza, R., Ribeiro Lopes, E., Mendes Ramos, E., Veloso de Oliveira, T., & de Patrícia Oliveira, C. (2024). Active packaging: Development and characterization of polyvinyl alcohol (PVA) and nitrite film for pork preservation. *Food Chemistry*, 437, article number 137811. doi: 10.1016/j.foodchem.2023.137811.

[4] DSTU 3976-2000. (2001). *Maize starch, dry. Technical specifications. With amendment No. 1 (IPS No. 12-2013) and correction (IPS No. 11-2000)*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=70422.

[5] DSTU EN ISO 8067:2018. (2020). *Polymeric porous elastic materials. Method for determining tear strength*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=79406.

[6] Fedoryshyn, O., Chervetsova, V., Yaremkevych, O., Skril, Yu., Khomyak, S., & Kohut, A. (2024). Physico-chemical and microbiological characterization of starch-based biodegradable films. *Chemistry & Chemical Technology*, 18(3), 417-425. doi: 10.23939/chcht18.03.417.

[7] Hussain, R., Batool, S.A., Aizaz, A., Abbas, M., & Ur Rehman, M.A. (2023). Biodegradable packaging based on poly(vinyl alcohol) and carboxymethyl cellulose films incorporated with ascorbic acid for food packaging applications. *ACS Omega*, 8(45), 42301-42310. doi: 10.1021/acsomega.3c04397.

[8] Jayakumar, A., Radoor, S., Shin, G.H., Siengchin, S., & Kim, J.T. (2023). Active and intelligent packaging films based on PVA/Chitosan/Zinc oxide nanoparticles/Sweet purple potato extract as pH sensing and antibacterial wraps. *Food Bioscience*, 56, article number 103432. doi: 10.1016/j.fbio.2023.103432.

[9] Krasinskyi, V., Dulebova, L., Gajdoš, I., & Ivanukh, O. (2021). Research of nanocomposite based on polyvinyl alcohol by differential scanning calorimetry. *Chemistry, Technology and Application of Substances*, 4(2), 188-194. doi: 10.23939/ctas2021.02.188.

[10] Krykhovets, O., & Slobodianyk, V. (2023). Research of polyvinyl alcohol-based films as environmentally friendly flexible packaging. *Visnyk of Vinnytsia Politechnical Institute*, 2, 15-20. doi: 10.31649/1997-9266-2023-167-2-15-20.

[11] Kumar, S., Mukherjee, A., & Dutta, J. (Eds.). (2022). *Biopolymer-based food packaging: Innovations and technology applications*. Hoboken: John Wiley & Sons, Inc. doi: 10.1002/9781119702313.

[12] Lebedev, V., Miroshnichenko, D., Bilets, D., & Mysiak, V. (2022). Investigation of hybrid modification of eco-friendly polymers by humic substances. *Solid State Phenomena*, 334, 154-161. doi: 10.4028/p-gv30w7.

[13] Li, L., Xu, H., Liu, L., Sun, P., Cao, Q., Xu, Z., Fan, Z., & Wang, H. (2021). Water governs the mechanical properties of poly(vinyl alcohol). *Polymer*, 213, article number 123330. doi: 10.1016/j.polymer.2020.123330.

[14] Li, X., Fan, Y., Guo, J., Li, R., Liu, Z., Hou, Y., Qu, Z., & Liu, Q. (2024). Polyvinyl alcohol/kappa-carrageenan-based package film with simultaneous incorporation of ferric ion and polyphenols from *Capsicum annuum* leaves for fruit shelf-life extension. *International Journal of Biological Macromolecules*, 266, article number 131002. doi: 10.1016/j.ijbiomac.2024.131002.

[15] Moreira, B.R., Pereira-Junior, M.A., Fernandes, K.F., & Batista, K.A. (2020). An ecofriendly edible coating using cashew gum polysaccharide and polyvinyl alcohol. *Food Bioscience*, 37, article number 100722. doi: 10.1016/j.fbio.2020.100722.

[16] Nasir, N.N., & Othman, S.A. (2021). The physical and mechanical properties of corn-based bioplastic films with different starch and glycerol content. *Journal of Physical Science*, 32(3), 89-101. doi: 10.21315/jps2021.32.3.7.

[17] Nguyen, S.V., & Lee, B.-K. (2023). Multifunctional nanocomposite based on polyvinyl alcohol, cellulose nanocrystals, titanium dioxide, and apple peel extract for food packaging. *International Journal of Biological Macromolecules*, 227, 551-563. doi: 10.1016/j.ijbiomac.2022.12.073.

[18] Oun, A.A., Shin, G.H., Rim, J.-W., & Kim, J.T. (2022). Recent advances in polyvinyl alcohol-based composite films and their applications in food packaging. *Food Packaging and Shelf Life*, 34, article number 100991. doi: 10.1016/j.fpsl.2022.100991.

[19] Sheikh, S., Yaqoob, M., & Aggarwal, P. (2021). An overview of biodegradable packaging in food industry. *Current Research in Food Science*, 4, 503-520. doi: 10.1016/j.crfs.2021.07.005.

[20] Song, J., Lin, X., Wu, H., Huang, Z., Gan, T., Hu, H., Qin, Y., & Zhang, Y. (2024). Fabrication of biodegradable and cold-water-soluble starch/polyvinyl alcohol films as inner packaging materials of pesticides: Enhanced emulsification, dispersibility, and efficacy. *Carbohydrate Polymers*, 328, article number 121713. doi: 10.1016/j.carbpol.2023.121713.

[21] Sonker, A.K., & Verma, V. (2017). Influence of crosslinking methods toward poly(vinyl alcohol) properties: Microwave irradiation and conventional heating. *Journal of Applied Polymer Science*, 135(14), article number 46125. doi: 10.1002/app.46125.
[22] Sytar, V., Sukhyy, K., Mitina, N., Garmash, S., & Lisichenko, B. (2020). The preparation of biodegradable composite materials based on polyvinyl alcohol. *Issues of Chemistry and Chemical Technology*, 1, 86-91. doi: 10.32434/0321-4095-2020-128-1-86-91.
[23] Wang, C., Shu, H., Sun, D., Yan, L., Song, K., Zhang, H., Chen, D., Ma, Y., & Yang, W. (2024). Synthesis of poly(maleic anhydride-co-vinyl chloride) crosslinked microspheres and its superior enhancement in mechanical strength and antibacterial activity for poly(vinyl alcohol) composite films. *Polymer*, 298, article number 126918. doi: 10.1016/j.polymer.2024.126918.
[24] Xie, Y., Cai, P., Cao, X., Chen, B., & Pan, Y. (2024). Water-resistant poly(vinyl alcohol)/ZnO nanopillar composite films for antibacterial packaging. *ACS Omega*, 9(51), 50403-50413. doi: 10.1021/acsomega.4c07173.
[25] Yildirim, S., Röcker, B., Pettersen, M.K., Nilsen-Nygaard, J., Ayhan, Z., Rutkaite, R., Radusin, T., Suminska, P., Marcos, B., & Coma, V. (2017). Active packaging applications for food. *Comprehensive Reviews in Food Science and Food Safety*, 17(1), 165-199. doi: 10.1111/1541-4337.12322.
[26] Zhang, S., Wei, D., Xu, X., & Guan, Y. (2023). Transparent, high-strength, and antimicrobial polyvinyl alcohol/boric acid/poly hexamethylene guanidine hydrochloride films. *Coatings*, 13(6), article number 1115. doi: 10.3390/coatings13061115.

Експлуатаційні властивості плівкових матеріалів для біопакування

Олександра Криховець
Кандидат хімічних наук, доцент
Національний університет «Львівська політехніка»
79013, вул. С. Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0002-2603-0991
В'ячеслав Репета
Доктор технічних наук, професор
Національний університет «Львівська політехніка»
79013, вул. С. Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0003-3204-1512
Ольга Гулай
Доктор педагогічних наук, професор
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-1120-6165

Анотація. Розробка екологічно безпечних матеріалів для пакування стало однією з ключових вимог 2026 року. У різних сегментах сучасного ринку чітко спостерігалося стабільне зростання інтересу до біополімерних матеріалів, що виготовлялися з відновлюваних джерел сировини і були потенційно здатні до біорозкладу. Метою роботи стало дослідження експлуатаційних характеристик плівок на основі полівінілового спирту, кукурудзяного крохмалю, гліцерину і натрій тетраборату, а також оцінка можливості їх застосування як екологічно безпечного пакувального матеріалу. У процесі проведення дослідження плівки отримували методом лиття з розчину на скляну основу з термічною обробкою за температурах 393 К та 423 К. Було виготовлено зразки різної товщини: у діапазоні 0,0552-0,0616 мм, а також плівки більшої товщини – від 0,1953 до 0,2240 мм. Фізико-механічні характеристики матеріалів було визначено за допомогою універсальної розривної машини. Було з'ясовано, що експериментальні значення розривного зусилля для одержаних плівкових матеріалів зростали із збільшенням вмісту натрій тетраборату – від 18,79 Н до 66,2 Н. Напруження при розриві досягало 30,5 МПа при вмісті натрій тетраборату 10 % і температурі стабілізації плівок 423 К. Відносне видовження при розриві поступово знижувалося при вищій температурі стабілізації зразків. Зростання межі міцності при розтязі для плівок із вмістом 10 % натрій тетраборату зробили цей склад ефективним для одержання плівок покращеної міцності. Плівкові матеріали товщиною 0,0612-0,0734 мм показали найкращі експлуатаційні характеристики за співвідношенням «міцність матеріалу – товщина плівки». Результати дослідження експлуатаційних характеристик плівкових матеріалів, сформованих на основі полівінілового спирту, водорозчинного кукурудзяного крохмалю та гліцерину за різного вмісту натрій тетраборату дозволили розглядати можливість їх використання для пакування продуктів харчування, капсулювання свіжих овочів і фруктів

Ключові слова: біорозкладні матеріали; фізико-механічні властивості; біополімери; полівініловий спирт; межа міцності

COMMODITY BULLETIN
Journal homepage: https://c-bulletin.com.ua/en
DOI: 10.62763/cb/2.2025.30

Article's History: Received: 15.08.2025 Revised: 01.12.2025 Accepted: 26.12.2025 Published: 02.01.2026

ISSN 2310-5283; e-ISSN 3041-1432 Vol. 18, No. 2, 2025, 30-42

UDC 663.86

Plant-based milk powders: A critical review of processing techniques, functional properties, and food applications

Igor Dudarev*
Doctor of Technical Sciences, Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-2016-5342

Vasylyna Shemet
PhD in Chemical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0001-8952-5097

Oleksandr Karakulko
PhD Student на Postgraduate Student
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0009-0001-9983-8967

Abstract. The growing demand for sustainable and functional food ingredients has intensified interest in plant-based milk powders as alternatives to conventional dairy products. The aim of this study was to evaluate plant-based milk powders by comparing their physicochemical, nutritional, and functional properties and processing technologies. The study was based on a structured analysis of scientific literature, including systematic database searches. It was established plant-based milk powders are emerging as versatile and promising food ingredients due to their distinctive physicochemical, nutritional, and functional properties. These powders can be obtained from a variety of plant-based milks. It was found that plant-based milk powders exhibit significant variability in macronutrient composition depending on the raw material. Almond milk powder is characterised by a high fat content, soy milk powder is rich in protein, whereas oat and rice milk powders are predominantly carbohydrate-based. These powders exhibit a wide range of physicochemical properties, which significantly affect their reconstitution. Solubility varied markedly among different types, ranging from low values in almond and soy milk powders to very high values in oat milk powder, reaching up to 98.5%. Bulk density ranges from 0.25 to 0.61 g/mL, moisture contented from 2.1 to 7.9%, and pH from 5.6 to 6.9, reflecting variations in raw materials and processing conditions. The production of plant-based milk powders involved several critical stages. It was established that drying plays a pivotal role, as it directly influences powder properties. The combination of nutritional composition and physicochemical properties makes plant-based milk powders suitable for bakery products, confectionery, frozen desserts, chocolate, sauces, pâtés and sausages, fermented foods, and dairy alternatives, thereby supporting the development of sustainable, functional, and nutritionally balanced food systems

Keywords: plant-based alternatives; functional food; lactose-free food; nutritional value; plant-based beverages

Suggested Citation:
Dudarev, I., Shemet, V., & Karakulko, O. (2025). Plant-based milk powders: A critical review of processing techniques, functional properties, and food applications. *Commodity Bulletin*, 18(2), 30-42. doi: 10.62763/cb/2.2025.30.

**Corresponding author*

Introduction

The development of sustainable and functionally efficient food ingredients has become a key priority in modern food systems. Increasing emphasis is placed on ingredients capable of maintaining consistent quality and functionality under varying processing and storage conditions. In this context, plant-based milk powders are gaining importance due to the growing need for shelf-stable and versatile alternatives to traditional dairy ingredients. Over the 2010s, the demand for non-alcoholic beverages such as plant-based milk has been steadily increasing (Popova *et al.*, 2023). C.B. Penha *et al.* (2021) noted that this trend is driven by changing dietary preferences, including a growing interest in plane-based foods, as well as by lactose intolerance and allergies to animal-derived milk products. N. Sharma *et al.* (2024) highlighted that approaches such as nutrient enrichment and the modification of sensory attributes, including taste, colour, and texture, can be employed to meet diverse consumer preferences, thereby enhancing the appeal of plant-based beverages. J. Rachtan-Janicka *et al.* (2025) noted that ethical and environmental concerns also influence consumer choices, including considerations related to animal welfare and the environmental impact of production, such as greenhouse gas emissions, water consumption, and land use. These factors contribute to the expansion of the plant-based beverage market, particularly given the growing popularity of beverages that mimic cow's milk in terms of sensory properties, consistency, and shelf life.

As noted by M.A. Nawaz *et al.* (2023), the food industry is developing a variety of plant-based milk alternatives that are nutritious, sustainable, and appealing to consumers. K. Marafon *et al.* (2025) emphasised that plant-based beverages offer unique benefits due to the presence of bioactive compounds, which may contribute to improve the health of their consumers. W.J. Craig & U. Fresán (2021) indicate that consumers should be informed of the nutritional composition and potential health benefits of plant-based beverages as the nutritional content can vary greatly among different types of products.

Plant-based milk is often processed into powder to extend shelf life and simplify transportation and storage. As pointed out by T. Dippong *et al.* (2025), plant-based milk powders contain plant proteins, fats, and carbohydrates, as well as bioactive compounds, particularly unsaturated fatty acids and dietary fibre. The nutritional composition of plant-based milk powders depends on the type of raw materials used and the production method. According to I. Fructuoso *et al.* (2021), common raw materials include soybeans, oats, almonds, rice, coconut kernel, and other types of cereals, nuts and seeds of vegetables and fruits. Their use is due to their high nutritional value and the presence of various bioactive compounds. They also contain oil that is free of trans-fat and low in saturated fat.

The nutritional and physicochemical properties of plant-based milk powders contribute to the widespread use in the production of various food products as full or partial substitutes for cow's milk powder, as well as functional additives for product enrichment. These plant-based milk powders are not only nutritionally versatile but also economically accessible, providing an affordable option for lower-income populations in developing countries and regions with limited access to animal milk and dairy products. A key advantage of plant-based milk powders is their long shelf life, which is especially valuable in areas facing challenges with refrigeration and cold-chain infrastructure. Plant-based milk powders have the potential to enhance dietary diversity and nutritional intake while offering a sustainable and cost-effective alternative to conventional dairy products.

The aim of this study was to conduct a meta-analysis of plant-based milk powders by evaluating their physicochemical, nutritional, and functional properties, as well as processing technologies, in order to identify key trends and factors influencing their potential applications in food systems.

The methodology of this study was based on a structured meta-analysis of scientific literature on plant-based raw materials, plant-based milks, and milk powders. Original research articles, systematic reviews, and meta-analyses were also analysed to examine the global perspective on the use of plant-based milk powders in food products. Manufacturer-reported data on the nutritional composition of dairy alternatives were also included. Studies were selected according to predefined criteria, including the availability of quantitative data on the physicochemical, nutritional, and functional properties of plant-based raw materials, plant-based milks, and milk powders. Data collection was conducted through systematic searches in scientific database, including Web of Science, Scopus, and Google Scholar, using targeted keywords and was supplemented with publicly available data from food manufacturers. The extracted data were analysed to identify trends and the underlying causes of differences in properties.

Comparative analysis of plant-based raw materials and derived milk alternatives

The mean nutritional composition of five plant-based raw material commonly used in the manufacture of plant-based milk alternatives – soybean, oat, almond, rice, and coconut kernel – is presented in Table 1. The results reveal pronounced differences in macronutrient distribution, which are critical for determining the nutritional value, technological functionality, and sensory characteristics of the final beverages.

Table 1. *Nutritional composition of raw materials for plant-based milk (mean)*

Compound	Soybeans	Oats	Almonds	Rice	Coconut kernel
Protein (%)	36.5[1]	13.5[3]	15.6[4]	7.1[5]	4.5[6]
Fat (%)	19.9[1]	8.8[3]	37.5[4]	1.2[5]	36.7[6]
Carbohydrates (%)	30.2[1]	38.7[3]	19.7[4]	78.9[5]	9.3[6]
Moisture content (%)	8.5[1]	14.5	5.3[4]	12.0[5]	46.0[6]
Dietary fibre (%)	27.0*[2]	21.9[3]	11.8[4]	1.5[5]	2.9[6]

Note: **– % DM (percentage of dry matter); [1] – K. Chen et al. (2012); [2] – J. Medic et. al. (2014); [3] – V. Sterna et al. (2016); [4] – C.-Y. Chen et al. (2006); [5] – M. Carcea (2021); [6] – G. Adoyo et al. (2021)*
Source: *prepared by the authors based on data reported in the scientific literature*

Soybeans are a valuable source of protein (36.5%) in the human diet, and are rich in isoflavones, dietary fibre, and vitamins A, B_6, B_{12}, and C (Chen *et al.*, 2012; Medic *et al.*, 2014). The protein content of soybeans substantially exceeds that of almonds (15.6%) (Chen *et al.*, 2006) and oats (13.5%) (Sterna *et al.*, 2016). It is also higher than that of rice (7.1%) (Carcea, 2021) and coconut kernel (4.5%) (Adoyo *et al.*, 2021). This finding confirms the suitability of soybeans as a primary protein source in plant-based milk formulations. However, it should be noted that soy protein may cause allergic reactions in sensitive individuals and is recognised as one of the eight major food allergens. The high protein content contributes not only to enhanced nutritional value but also to improved functional properties, including emulsification, foaming capacity, and colloidal stability. In contrast, rice and coconut kernel contain relatively low levels of protein, which limits their potential to provide significant protein enrichment without additional fortification.

Oats are recognised as a healthy food containing soluble dietary fibre, β-glucans, vitamin E, and polyunsaturated fatty acids (Sterna *et al.*, 2016). According to C.-Y. Chen *et al.* (2006), almonds are a source of monounsaturated fatty acids, dietary fibre, vitamin E, riboflavin, copper, magnesium, manganese, and phosphorus. Rice is an energy-rich food, as approximately 80% of the grain dry matter consist of carbohydrates and starch (Carcea, 2021). As pointed out by G. Adoyo *et al.* (2021), coconut kernel is also a good source of dietary fibre. The highest fat contents are observed in almonds (37.5%) (Chen *et al.*, 2006) and coconut kernel (36.7%) (Adoyo *et al.*, 2021), followed by soybeans (19.9%) (Chen *et al.*, 2012), oats (8.8%) (Sterna *et al.*, 2016), and rice (1.2%) (Carcea, 2021). The substantial lipid fraction in almonds and coconut kernel contributes to enhanced creaminess and improved mouthfeel of the resulting beverages. Coconut is traditionally classified as a source of saturated fat and is therefore often recommended for limited consumption due to its potential association with adverse health effects. S. Hewlings (2020) emphasised that different types of saturated fatty acids, including medium-chain or ling-chain fatty acids, may affect human health in different ways. Rice, due to its minimal fat content, is more suitable for low-fat beverage formulations.

Rice is characterised by a markedly high carbohydrate content (78.9%) (Carcea, 2021), primarily in the form of starch, making it a carbohydrate-rich raw material. Oats (38.7%) (Sterna *et al.*, 2016) and soybeans (30.2%) (Chen *et al.*, 2012) contain moderate levels of carbohydrates, whereas almonds (19.7%) (Chen *et al.*, 2006) and coconut kernel (9.3%) (Adoyo *et al.*, 2021) contain comparatively lower amounts. In oat- and rice-based systems, carbohydrates contribute to viscosity development and natural sweetness, particularly following enzymatic hydrolysis during processing.

Coconut kernel exhibits the highest moisture content (46.0%) (Adoyo *et al.*, 2021), considerably exceeding that of the other raw materials. Oats (14.5%) and rice (12.0%) (Carcea, 2021) demonstrate intermediate values, whereas soybeans (8.5%) (Chen *et al.*, 2012) and almonds (5.3%) (Chen *et al.*, 2006) contain comparatively lower moisture levels. Variations in moisture content may affect storage stability, shelf life, and processing efficiency, including grinding and drying operations.

Soybeans (27.0% DM) (Medic *et al.*, 2014) and oats (21.9%) (Sterna *et al.*, 2016) contain the highest levels of dietary fibre, followed by almonds (11.8%) (Chen *et al.*, 2006). In contrast, rice (1.5%) (Carcea, 2021) and coconut kernel (2.9%) (Adoyo *et al.*, 2021) provide minimal amounts of fibre. Elevated fibre levels may enhance the functional and potential health-promoting properties of plant-based beverages. Oats contain 4.5-5.4% β-glucans, whereas rice contains only 0.4-0.9% (Mykhalevych *et al.*, 2022). These polysaccharides exhibit pronounced technological functionality in food systems, including gel formation, high water-binding capacity, texture development, and contribution to specific sensory characteristics (Mykhalevych *et al.*, 2022). Plant-based beverages should provide functional benefits that take into account the lifestyle and needs of consumers, including health maintenance (Sethi *et al.*, 2016). However, in practice, each beverage exhibits unique chemical and sensory properties, which are determined by the type of raw materials used and the specific processing techniques (McClements, 2020). The nutritional composition of plant-based milk alternatives is presented in Table 2.

Table 2. *Nutritional composition of plant-based milk (mean)*

Compound	Soy milk	Oat milk	Almond milk	Rice milk	Coconut milk
Protein (g/100 g)	3.2[1]	1.6[4]	1.4[1]	0.5*[7]	1.7*[6]
Fat (g/100 g)	1.8[1]	0.4[4]	3.0[5]	1.4*[7]	1.0*[6]
Carbohydrates (g/100 g)	1.6[2]	3.8[5]	0.8*[6]	11.7*[7]	10.0*[6]
Ash content (%)	0.64[1]	0.20[1]	0.40[1]	0.12[1]	0.83[9]
Dietary fibre (g/100 g)	1.3[3]	0.8*[6]	0.4*[6]	0.3[8]	-

Note: **– g/100 mL; [1] – S. Jeske et al. (2016); [2] – S. Moore et al. (2023); [3] – S. Giri and S. Mangaraj (2012); [4] – N. Babolanimogadam et al. (2023); [5] – B. Walther et al. (2022); [6] – F. Reyes-Jurado et al. (2021); [7] – I. Vitoria (2017); [8] – R. Giugliano et al. (2023); [9] – S. Tulashie et al. (2022)*

Source: *prepared by the authors based on data reported in the scientific literature*

Soy milk exhibits the highest protein content (3.2 g/100 g) (Jeske *et al.*, 2016), reflecting the naturally high protein concentration of soybeans, whereas rice milk contains the lowest protein level (0.5 g/100 mL) (Vitoria, 2017), consistent with the inherently low protein content of rice. Fat content varies depending on the lipid profile of the source material and the production process. Almond milk has the highest fat content (3.0 g/100 g) (Walther *et al.*, 2022) due to the high oil content of almonds, whereas oat milk (0.4 g/100 g) (Babolanimogadam *et al.*, 2023) and coconut milk (1.0 g/100 mL) (Reyes-Jurado *et al.*, 2021) contain comparatively lower amounts of fat. The relatively low fat content of coconut milk is primarily a result of the production process, during which a substantial portion of the coconut oil is removed. Carbohydrate content is highest in rice milk (11.7 g/100 mL) (Vitoria, 2017), reflecting the starch-rich nature of rice. Soy (1.6 g/100 g) (Moore *et al.*, 2023) and oat (3.8 g/100 g) (Walther *et al.*, 2022) milks exhibit lower carbohydrate levels, whereas almond milk contains the lowest content (0.8 g/100 mL) (Reyes-Jurado *et al.*, 2021). Ash content, which reflects the mineral composition, is relatively high in coconut milk (0.83%) (Tulashie *et al.*, 2022) and low in rice milk (0.12%) (Jeske *et al.*, 2016). Dietary fibre content is highest in soy milk (1.3 g/100 g) (Giri & Mangaraj, 2012), moderate in oat (0.8 g/100 mL) and almond (0.4 g/100 mL) milks (Reyes-Jurado *et al.*, 2021), and lowest in rice milk (0.3 g/100 g) (Giugliano *et al.*, 2023). In comparison with cow's milk, which contains 3.7 g/100 g of protein, 3.3 g/100 g of fat, 4.9 g/100 g of carbohydrates, and 0.62% ash (Jeske *et al.*, 2016), plant-based milks exhibit considerable variability in macronutrient composition depending on the type of raw material.

The omega-6 to omega-3 fatty acid ratio varies considerably among plant-based milk alternatives and differs from that of cow's milk. Cow's milk exhibits a relatively balanced ratio of 2–3:1, whereas most plant-based beverages display much higher ratios. Almond milk shows the highest imbalance, ranging from 127 to 235:1, followed by rice (92-175:1) and oat beverages (84-105:1). In contrast, soy and coconut beverages present a more favourable profile, with ration of 7-8:1 and 11-18:1, respectively (Walther *et al.*, 2022). These differences indicate that, although plant-based milks can provide beneficial unsaturated fatty acids, many varieties – particularly almond, oat, and rice – contain an excessive amount of omega-6 relative to omega-3.

The comparative analysis of plant-based raw materials demonstrates pronounced variability in macronutrient composition, which directly determines their nutritional potential in beverage formulation. Protein-rich raw materials such as soybeans provide enhanced functional properties, whereas carbohydrate-dominant materials such as rice primarily contribute to energy value. High-fat raw materials, including almonds and coconut kernel, are mainly responsible for improved sensory attributes such as creaminess and mouthfeel, although their lipid profiles may raise nutritional considerations. At the same time, variations in dietary fibre and moisture content significantly influence processing behaviour, storage stability, and final product quality. Overall, the analysis findings confirm that raw material selection critically determines the nutritional balance and functional performance of plant-based milk alternatives. It should also be noted that the nutritional composition of plant-based milks is not fixed and can vary depending on processing techniques, including filtration, homogenisation, fortification, and the incorporation of functional components. In particular, filtration removes insoluble particles, which can affect the final protein and fat content, as well as the functional and sensory properties of the beverage.

Processing of plant-based milk powders

The production of plant-based milk powders involves several key stages: pre-treatment of the plant raw material, soaking, wet grinding, and aqueous extraction to obtain the plant-based milk, followed by filtration and homogenisation to stabilise the dispersion, fortification and incorporation of functional ingredients, and finally drying to produce a reconstitutable powdered product (Fig. 1). In some methods, maltodextrin or gum arabic is added to enhance powder flowability and solubility, as well as to reduce hygroscopicity, thereby improving the technological performance and storage stability of the powders.

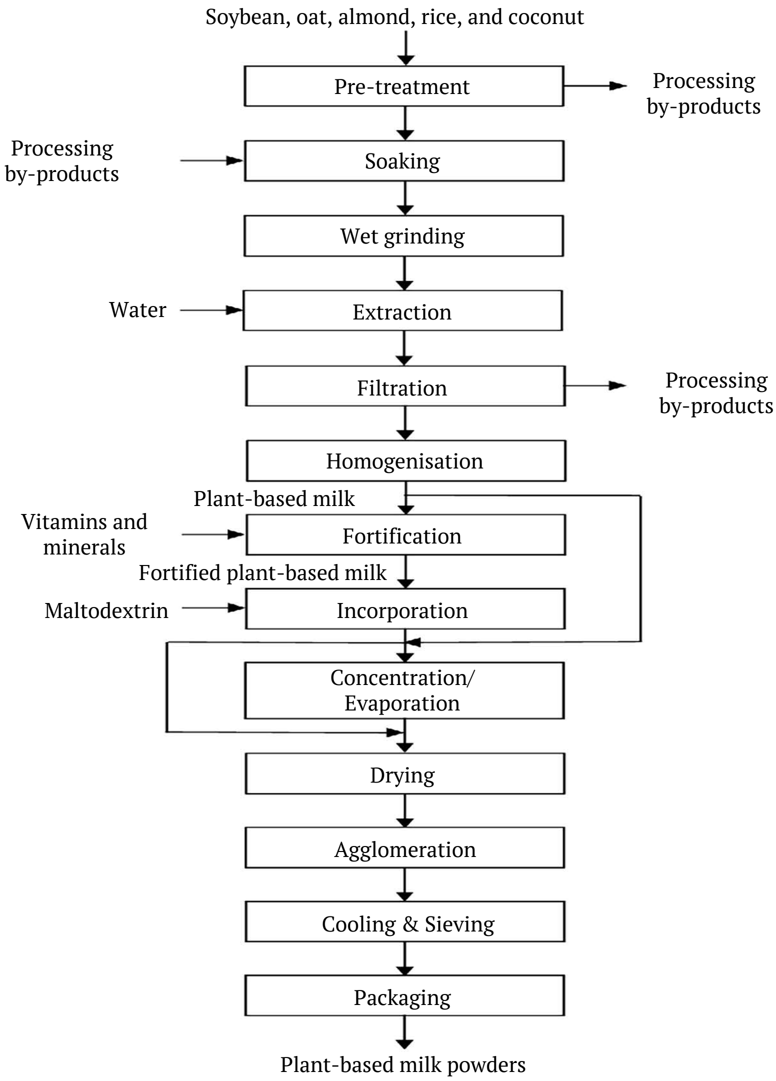

Figure 1. *Flowchart of plant-based milk powder production*
Source: *developed by the authors*

Pre-treatment of plant raw materials is one of the initial and critical stages in the production of plant-based milk powders, aimed at enhancing the sensory and nutritional properties of the final product while reducing undesirable components. This stage involves cleaning and sorting the cereal or nut materials to remove mechanical impurities and damaged particles, thereby ensuring consistent quality of the intermediate product and the safety of the final powder (Jeske *et al.*, 2016). The materials are further processed by removing husks or shells. Blanching is applied to remove the skin, inactivate enzymatic systems, reduce undesirable flavours, and enhance the microbiological stability of the raw materials (Jeske *et al.*, 2016). Roasting certain types of raw materials enhances the aromatic and flavour characteristics of the final products (Reyes-Jurado *et al.*, 2021). Coconuts are grated prior to extraction, whereas rice may undergo pre-cooking before soaking. Defatting and fermentation of the raw materials (soybeans, almonds, rice, and oats) improve the bioavailability of nutrients and reduce the content of antinutritional factors.

Soaking is performed to hydrate and soften the plant raw materials, facilitate subsequent grinding, and enhance the efficiency of nutrient extraction. This process also contributes to the reduction of antinutrients, such as phytic acid, and improves the sensory properties of the final product. Soaking can be carried out in water for 3-18 hours or in alkaline sodium bicarbonate ($NaHCO_3$) solutions at concentrations of 0.2-2.0% using a raw material-to-solution ratio of 1:2-1:12 (Reyes-Jurado *et al.*, 2021). Such treatment further softens the materials and helps eliminate characteristic beany or nutty flavours.

After pre-treatment and soaking (if necessary), the plant raw materials are ground to a specified particle size, which ensures better contact between the solid phase and water in subsequent stages, facilitates the formation of a homogeneous suspension, and stabilises the rheological properties prior to drying. The degree of grinding significantly affects the yield of dry matter and the quality of the plant-based milk, and, consequently, the properties of the resulting plant-based milk powder. Aqueous extraction is a key stage in the production of plant-based milk, involving the contact of ground plant materials with water under controlled temperature and time conditions. During extraction, soluble and dispersed components – including proteins, carbohydrates, lipids, and bioactive compounds – are transferred into the aqueous phase, thereby shaping the nutritional profile of the plant-based milk. The efficiency of extraction determines the nutritional value, sensory properties, and stability of the resulting product and largely depends on the raw material-to-water ratio and the degree of prior processing of the plant matrix.

Filtration is an essential stage in the production of plant-based milk following aqueous extraction and is aimed at removing insoluble cell wall fragments, fibre residues, and coarse particles. The use of filtration materials with varying porosity allows for the formation of a homogeneous liquid phase with improved sensory properties and reduced sedimentation. The quality of filtration directly affects the stability of the suspension, the efficiency of the subsequent homogenisation, and the sensory characteristics of the plant-based milk. Homogenisation is applied to stabilise plant-based milk by reducing the size of fat globules and dispersed solid particles, ensuring uniform distribution of components throughout the system. As a result, homogenisation decreases creaming and sedimentation rates, improves the rheological and sensory properties of the product, and enhances its physical stability during storage and subsequent processing. High-speed mixers, colloid mills, high-pressure homogenisers, and microfluidizers are commonly used for this process (Reyes-Jurado *et al.*, 2021). The efficiency of homogenisation is critical for forming a homogeneous suspension prior to drying and for the subsequent reconstitution of the powder with water.

If specified by the formulation, plant-based milk can be fortified with bioactive compounds, vitamins, and minerals to enhance its nutritional value. In addition, technological additives, such as maltodextrin, may be incorporated to improve functional properties, including solubility, flowability, and stability during processing and storage. The combined use of fortification and additives contributes to the production of powders with consistent quality, prolonged shelf life, and enhanced performance in functional and fortified food applications.

Prior to drying, plant-based milk is typically subjected to membrane concentration or evaporation. This reduces energy consumption during drying and increases the efficiency of the technological process. Membrane concentration (ultrafiltration) of the liquid phase is performed to achieve a dry matter content of 22-24% (Giri & Mangaraj, 2012). This non-thermal method preserves the nutritional value and bioactive compounds of the product by minimising thermal impact on proteins. Evaporation, in contrast, is a thermal process in which water is removed through heating under vacuum conditions.

Drying is the final stage in the production of plant-based milk powders. Its primary purpose is to reduce moisture content, thereby enhancing product stability and extending shelf life. Spray drying is the most widely used technique in the industrial production of plant-based milk powders. Alternatively, freeze-drying can be employed, which maximally preserves thermolabile bioactive compounds and the structural integrity of the product, although it is more energy-intensive and costly. Some processes utilise roller or convective drying, which are technologically simpler but may result in changes to colour, flavour, and functional properties of the plant components. The choice of drying method depends on the type of plant raw material, the desired powder quality, and economic feasibility. The optimal inlet temperature for spray drying plant-based milk is 170-180°C. Foam drying is also employed, in which sodium caseinate (4.0%) acts as a foaming agent and maltodextrin (17.5%) ensures a free-flowing powder consistency (Shameena Beegum *et al.*, 2022).

After drying, the powder undergoes agglomeration and final drying in a fluidised bed. During agglomeration, fine powder particles are combined into larger granules using binding and moistening agents. This process take place in fluidised-bed dryers, where the powder is suspended and treated with hot air, ensuring uniform drying, formation of stable granules, and the desired product quality. Following final drying, the plant-based milk powder is cooled, sieved, and packaged in airtight containers to protect it from ambient moisture. The moisture content of plant-based milk powders typically ranges from 2 to 4%.

The analysis of plant-based milk powder production reveals a multistage and highly integrated system in which each technological step critically influences final product quality. Pre-treatment, soaking, grinding, and aqueous extraction determine the efficiency of nutrient release and the initial composition of plant-based milk, whereas filtration and homogenisation ensure system stability, uniformity, and improved sensory properties. Subsequent stages, including fortification and the incorporation of functional additives, enable targeted modification of nutritional and technological characteristics, thereby enhancing the functional value of the product. Concentration and drying operations represent key stages that determine powder stability, shelf life, and reconstitution properties. The quality of plant-based milk powders is governed by the combined effects of raw material properties and precise control of processing parameters across all stages of production.

Properties of plant-based milk powders

Over the past decade, plant-based milk powders derived from various plant sources have attracted considerable attention from both scientific researchers and food industry manufacturers. This interest is driven by their nutritional value, functional properties, and potential to serve as alternatives to cow's milk powder in a wide range of food applications. As shown in Table 3, the nutritional composition of plant-based milk powders varies widely depending on the source. Protein levels vary considerably among plant-based milk powders and across different literature sources. Almond milk powder exhibits the highest protein content among the analysed plant-based samples (28.4 g/100 g); however, other reported values (18.4 g/100 g (Lipan *et al.*, 2020) and 4.43% DM (Bueno *et al.*, 2022)) indicate substantial variability depending on product formulation and processing conditions. Soy milk powder contains 12.0 g/100 g protein in the commercial sample, whereas literature sources report values as high as 44.43 g/100 g (Taşoyan & Yolacaner, 2023), reflecting differences in composition. Coconut milk powder contains 7.0 g/100 g protein in the commercial sample, while values reported in the literature range from 6.29 to 8.89 g/100 g (Muthia *et al.*, 2021), indicating relatively minor variation compared with other plant-based powder. Oat and rice milk powders contain relatively low protein levels in commercial products (2.9 and 1.7 g/100 g, respectively), although powders from certain oat formulations and rice varieties may exhibit higher protein content. In contrast, dairy milk powder consistently demonstrates higher and more stable protein concentrations: whole cow's milk powder contains 31.5 g/100 g protein (Magan *et al.*, 2019), while skimmed cow's milk powder contains 32.0 g/100 g. Therefore, even the most protein-rich plant-based samples do not surpass the protein content of dairy powders under typical conditions, whereas most plant-based powders provide substantially lower protein levels.

Fat content also shows pronounced variability. In commercial samples, soy milk powder contains 64.0 g/100 g fat, although literature reports lower values of 18.14 g/100 g (Taşoyan & Yolacaner, 2023). Almond milk powder contains 56.3 g/100 g fat in the commercial sample, while literature sources report lower values ranging from 42.8 g/100 g (Lipan *et al.*, 2020) to 2.27% DM (Bueno *et al.*, 2022), indicating that fat content can vary considerably depending on product formulation and processing methods. Coconut milk powder contains 25.0 g/100 g fat in commercial products, with literature values ranging from 4.85 to 15.11 g/100 g (Muthia *et al.*, 2021). Oat and rice milk powders contain moderate fat levels (22.0 and 21.0 g/100 g, respectively), although rice milk powders from certain varieties may exhibit much lower fat contents (0.45–2.05%) (Silva *et al.*, 2018).

Table 3. *Nutritional composition of plant-based milk powders*

Plant-based milk powder	Protein (g/100 g)	Fat (g/100 g)	Carbohydrates (g/100 g)	Source / Manufacturers
Soy milk powder	12.0 44.43	64.0 18.14	24.0 27.96	Bifood, Czech Republic[1]
Oat milk powder	2.9[i1] 9.74	22.0[i1] 4.23	63.0[i1] 82.26	Manteca, Ukraine[2]
Almond milk powder	28.4 18.4 4.43**	56.3 42.8 2.27**	11.1 36.4 86.47**	TSUKUBA, Japan[3], [4]
Rice milk powder White rice Red rice Black rice	1.7[i2] 7.56 12.39 10.75	21.0[i2] 0.45 2.05 1.81	62.0[i2] 87.43 76.73 84.12	Manteca, Ukraine[5]
Coconut milk powder	7.0[i3] 6.29-8.89	25.0[i3] 4.85-15.11	31.0[i3] 65.01-75.24	Manteca, Ukraine[6]
Whole cow's milk powder	31.5	25.5	35.6*	J.B. Magan *et al.*[7]
Skimmed cow's milk powder	32.0	1.5	50.0	Profiprot, Ukraine

Note: ** – lactose; ** – % DM (percentage of dry matter); [i1] – ingredient list: oats, coconut, dried glucose syrup, E472e (emulsifier), potassium phosphate, silicon dioxide (anti-caking agent), salt, dextrose (1%), plant-derived maltodextrin (2%), and inulin; [i2] – ingredient list: rice, dried glucose syrup (2%), dextrose, inulin, coconut, E472e (emulsifier), and potassium phosphate (1%); [i3] – ingredient list: coconut dry milk (100% coconut flesh ground into powder), maltodextrin 2%; [1] – IC. Taşoyan & E.T. Yolacaner (2023); [2] – P. Angel Sharon & P. Gurumoorthi (2024); [3] – L. Lipan et al. (2020); [4] – F. Bueno et al. (2022); [5] – L.R.D. Silva et al. (2018); [6] – A.J. Muthia et al. (2021); [7] – J.B. Magan et al. (2019)*

Source: *prepared by the authors based on data reported in the scientific literature and manufacturers' product information*

Whole cow's milk powder provides 25.5 g/100 g fat (Magan *et al.*, 2019), which is comparable to coconut powder and similar to oat and rice powders in certain formulations. Skimmed cow's milk powder contains only

1.5 g/100 g fat, representing the lowest value among all analysed products. Therefore, plant-based powders can contain significantly more fat (soy, almond), similar amounts (coconut, oat, rice), or, in some cases, less fat than whole milk powder, whereas skimmed milk powder consistently remains very low in fat. Carbohydrates predominate in oat and rice milk powders. Commercial oat milk powder contains 63.0 g/100 g carbohydrates, with literature data reporting values up to 82.26% (Angel Sharon & Gurumoorthi, 2024). Rice milk powder contains 62.0 g/100 g carbohydrates, while powders from certain rice varieties can reach even higher levels (up to 87.43 g/100 g) (Silva *et al.*, 2018), reflecting the starch-rich composition of rice and, in some cases, the addition of carbohydrate-based ingredients such as glucose syrup or maltodextrin. Coconut milk powder contains 31.0 g/100 g carbohydrates in commercial samples, with reported values ranging from 65.01 to 75.24% in other formulations (Muthia *et al.*, 2021). Soy milk powder contains 24.0 g/100 g carbohydrates, with some sources reporting slightly higher values of 27.96% (Taşoyan & Yolacaner, 2023). Almond milk powder has the lowest carbohydrate content among commercial plant-based powders, at 11.1 g/100 g, although much higher values – 36.4 g/100 g (Lipan *et al.*, 2020) and 86.47% DM (Bueno *et al.*, 2022) – have been reported in the literature.

In dairy powders, carbohydrate content ranges from 35.6 g/100 g (Magan *et al.*, 2019) in whole milk powder to 50.0 g/100 g in skimmed milk powder and is primarily represented by lactose. The higher carbohydrate content in skimmed milk powder is associated with fat removal and the relative increase in the proportion of lactose. Plant-based milk powders generally exhibit higher and more variable carbohydrate content – particularly in oat and rice milk powders – compared with cow's milk powder, where carbohydrates are more consistent. Overall, the comparison demonstrates that dairy powders provide consistently high and stable protein levels, whereas plant-based powders exhibit considerable variability in protein, fat, and carbohydrate composition, depending on the raw material, processing technology, and the presence of technological additives. This variability should be carefully considered when evaluating plant-based milk powders as nutritional and functional alternatives to dairy milk powders.

Solubility is a critical technological parameter that determines the ability of milk powders to reconstitute in water and form a homogeneous beverage without sedimentation. Bulk density is another important characteristic, influencing packaging, transportation efficiency, and powder handling during processing. Among dairy powders, skimmed cow's milk powder demonstrates relatively high solubility (77.9%) and a bulk density of 0.415 g/mL (Taşoyan & Yolacaner, 2023). Whole cow's milk powder exhibits slightly lower solubility (70%) and a lower bulk density (0.326 g/mL) (Taşoyan & Yolacaner, 2023). In contrast, plant-based milk powders show considerable variability in technological properties depending on the raw material type and processing conditions (Table 4). Soy milk powder exhibits relatively low solubility (40.0%) and low bulk density (0.256 g/mL) (Taşoyan & Yolacaner, 2023), which may negatively affect its reconstitution efficiency and dispersion in aqueous systems. Its solubility is markedly lower than that of whole cow's milk powder and skimmed cow's milk powder. Soy milk powder has a moisture content of 3.4%, an ash content of 6.06%, and a near-neutral pH of 6.9 (Taşoyan & Yolacaner, 2023).

Table 4. *Physicochemical properties of plant-based milk powders*

Plant-based milk powder	Moisture content (%)	Ash content (%)	Bulk density (g/ml)	Solubility (%)	pH
Soy milk powder	3.4[1]	6.06[1]	0.256[1]	40.0[1]	6.9[1]
Oat milk powder	2.17-4.85[2]	1.81[2]	0.313-0.420[2]	84.2-98.49[2]	n.d.
Almond milk powder	2.83-3.26[3]	6.84*[4]	0.30-0.32[3]	11.1-13.1[3] mL	6.42-6.66[3]
Rice milk powder White rice Red rice Black rice	 4.11[5] 7.85[5] 2.13[5]	 0.45[5] 0.99[5] 0.19[5]	0.25-0.61[6]	72.8[6]	 5.93[5] 6.11[5] 6.20[5]
Coconut milk powder	2.22-4.11**[7]	7.33-9.43[8]	0.43-0.49**[7]	39.57**[7]	5.63-6.37[8]

Note: *n.d. – no data; * – % DM (percentage of dry matter); ** – skimmed coconut milk powder; [1] – İ. Taşoyan and E. Yolacaner (2023); [2] – P. Angel Sharon & P. Gurumoorthi (2024); [3] – L. Lipan et al. (2020); [4] – F. Bueno et al. (2022); [5] – L. Silva et al. (2018); [6] – M. Padma et al. (2022); [7] – J. Duangchuen et al. (2021); [8] – A.J. Muthia et al. (2021)*

Source: *prepared by the authors based on data reported in the scientific literature*

Oat milk powder demonstrates the highest solubility among the analysed plant-based powders (84.2–98.49%) (Angel Sharon & Gurumoorthi, 2024), exceeding that of whole cow's milk powder (70%) and, in some cases, even that of skimmed cow's milk powder (77.9%). Its bulk density ranges from 0.313 to 0.420 g/mL, which is comparable to that of skimmed cow's milk powder (0.415 g/mL). The moisture content of oat milk powder varies between 2.17 and 4.85%, while its ash content is 1.81% (Angel Sharon & Gurumoorthi, 2024), indicating a relatively low mineral fraction compared with some other plant-based powders. Almond milk powder exhibits its low solubility (11.1-13.1 mL) (Lipan *et al.*, 2020). Its bulk density ranges from 0.30 to 0.32 g/mL (Lipan *et al.*, 2020), which is slightly lower than that of whole cow's milk powder and skimmed cow's milk powder. The moisture content varies between 2.83 and 3.26% (Lipan *et al.*, 2020), while the ash content reaches 6.84% DM (Bueno *et al.*, 2022), reflecting a relatively high mineral fraction. The limited solubility may be associated with specific particle characteristics formed during the drying process.

Rice milk powder demonstrates moderate solubility (72.8%) (Padma *et al.*, 2022), which is comparable to that of whole cow's milk powder (70%) but slightly lower than that of skimmed cow's milk powder (77.9%). Its bulk density varies considerably (0.25-0.61 g/mL) (Padma *et al.*, 2022), depending on the rice variety and processing conditions. The moisture content differs among white (4.11%), red (7.85%), and black (2.13%) rice powders, while ash content ranges from 0.19 to 0.99%, indicating a relatively low mineral fraction compared with almond or soy milk powders (Silva *et al.*, 2018). The pH values (5.93-6.20) suggest slightly acidic to near-neutral conditions (Silva *et al.*, 2018). These variations confirm that the physicochemical and technological properties of rice milk powder are strongly influenced by the type of raw material and processing parameters.

Coconut milk powder demonstrates relatively low solubility (39.57%), similar to soy milk powder, and a comparatively high bulk density (0.43-0.49 g/mL) (Duangchuen *et al.*, 2021). Its higher ash content (7.33-9.43%) and slightly acidic pH (5.63-6.37) may influence dispersion behaviour (Muthia *et al.*, 2021). Overall, dairy powders, particularly skimmed cow's milk powder, exhibit superior and more stable solubility characteristics compared with most plant-based milk powders. Among plant-based alternatives, oat and rice milk powders show the most favourable reconstitution properties, whereas almond, soy, and coconut milk powders demonstrate limited solubility.

Application of plant-based milk powders

Plant-based milk powders are increasingly utilised in the food industry, the restaurant sector, and home cooking for the preparation of a wide range of food products (Fig. 2). They can be reconstituted in water to produce plant-based milk, which can then be combined with juices to create functional beverages (Rodríguez-Roque *et al.*, 2014) or with beer to produce beer-based mixes. This enriches beverages with plant proteins and dietary fibre, improves sensory characteristics, texture, and other physicochemical properties, and results in lactose-free products. By blending plant-based milk powders or reconstituted beverages with fresh fruits, berries, and vegetables, and other ingredients, healthy smoothies can be prepared at home to support a nutritious diet (Neelissen *et al.*, 2023) Smoothies can also be made using cow's milk supplemented with plant-based milk powders, which increases protein content, enhances viscosity and sensory properties, and diversifies the range of available beverages.

An important application of plant-based milk powders is in the production of bakery, confectionery and snack products (Nilufer-Erdil *et al.*, 2012; Arii & Nishizawa, 2024). The powders can be used in their dry form during dough preparation as a nutritional enrichment additive, partially or completely replacing flour. Alternatively, they can be incorporated into product formulations after reconstitution in water or milk-based beverages. The inclusion of plant-based milk powders enhances the fibre and protein content of the products, improves their structure and volume, slows staling, and positively affects both sensory attributes and nutritional composition.

Plant-based milks are widely used in the production of frozen desserts and ice cream (Dudarev *et al.*, 2025), and plant-based milk powders are also suitable for these applications. In such products, traditional ingredients, such as milk or milk powder, can be partially or completely replaced by plant-based milk or by combination of different plant-based milks. This substitution can influence the texture, overrun, and melting rate of the product. It also enables the creation of diverse flavours and makes the product suitable for consumers with milk protein allergies or lactose intolerance, as well as for vegans and vegetarians.

The production of sauces, particularly mayonnaise, using plant-based milk, especially when reconstituted from powder, is also a promising approach (Dudarev *et al.*, 2024). Such sauces exhibit a smooth texture, appealing appearance, and a delicate flavour profile with subtle notes of the plant-based raw materials. Incorporating plant-based milk into sauce formulations further enables enrichment with bioactive compounds while reducing the caloric content of the final product.

The potential use of plant-based milk, or plant-based milk reconstituted from powder, in the production of fermented beverages and foods – such as yogurt, kefir, and cottage cheese – has been investigated (Yilmaz-Ersan & Topcuoglu, 2022) In these applications, animal milk is typically partially replaced by a plant-based alternative. This substitution promotes fermentation, enhances the sensory properties of the final products, and affects their texture and nutritional composition. Plant-based milk powders are also utilised in the production of various types of chocolate (Obatoye *et al.*, 2014; Taşoyan & Yolacaner, 2023). They are incorporated into formulations to increase the protein and fibre content, improve the texture and flavour of chocolate, enhance its melting properties, and reduce production costs.

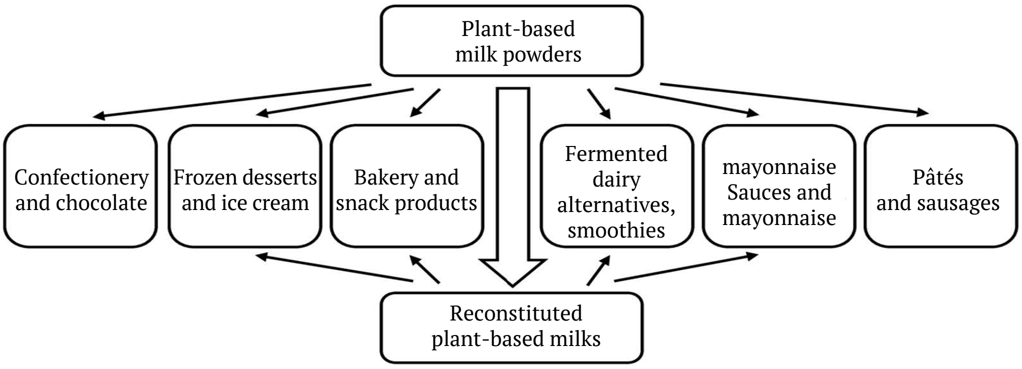

Figure 2. *Application of plant-based milk powders*

Source: *developed by the authors*

Plant-based milk powder can be incorporated into recipes for combined pâtés and sausages made from both meat and plant raw materials to enrich them with nutrients and improve rheological properties. Consequently, plant-based milk powders have a wide range of culinary applications. Further development of manufacturing technologies, optimisation of powder composition, and investigation of the potential for forming mixtures with various powders and other bulk components, such as functional and technological additives, represent a highly promising direction for future research.

Conclusions

Plant-based milk powders are a valuable ingredient in modern food formulations, offering nutritional versatility and functional benefits. The analysis enabled the identification of key factors influencing potential applications of plant-based milk powders in food systems. It was found that their macronutrient profile strongly depends on both the plant source and processing technology. Almond milk powder is particularly rich in fat (up to 56.3 g/100 g), soy milk powder is protein-dense (up to 44.43 g/100 g), whereas rice, oat, and coconut milk powders are characterised by high carbohydrate contents (up to 87.43, 82.26, and 75.24 g/100 g, respectively). In addition to macronutrients, plant-based milk powders contain bioactive compounds such as unsaturated fatty acids and dietary fibre, which may contribute to their potential health-promoting properties.

The physicochemical properties of plant-based milk powders vary significantly depending on the source material and processing techniques, influencing solubility, bulk density, and reconstitution performance in beverages and other food products. These powders offer several advantages, including extended shelf life, convenient storage and transportation, and potential for fortification. Their nutritional diversity and functional characteristics make them versatile ingredients for a wide range of applications, such as bakery and snack products, confectionery, ice cream and frozen desserts, chocolate, sauces, pâtés and sausages, fermented foods, and dairy alternatives, thereby contributing to the development of sustainable and health-oriented food systems.

Despite the growing body of literature on plant-based milk powders, several important research gaps remain. Current studies are often fragmented and focus on individual raw materials or specific processing stages, limiting a comprehensive understanding of the relationships between composition, processing conditions, and final product functionality. Limited attention has been given to the interaction effects of formulation variables and processing technologies on the sensory properties of reconstituted beverages. Moreover, the majority of studies are product-specific, which restricts the generalisation of findings across different plant-based systems.

Future research should focus on the development of harmonised methodological approaches for the characterisation of plant-based milk powders, enabling more reliable cross-study comparisons. In addition, systematic investigations into combined raw materials systems and hybrid formulations are needed to better understand synergistic effects on nutritional and functional performance of plant-based milk powders. Greater emphasis should also be placed on consumer-oriented studies addressing sensory acceptance, nutritional perception, and market adaptability. Such efforts will contribute to the development of high-quality plant-based milk powders and support their broader application in food systems. Furthermore, in-depth research is required to evaluate the applicability of plant-based milk powders in a wide range of food products, as well as their effects on the nutritional, physicochemical, rheological, and sensory properties of these systems.

Acknowledgements

None.

Funding

The study was not funded.

Conflict of Interest

None.

References

[1] Adoyo, G.O., Sila, D.N., & Onyango, A.N. (2021). Physico-chemical properties of kernel from coconut (*Cocos nucifera* L.) varieties grown at the Kenyan Coast. *African Journal of Food Science*, 15(8), 313-321. doi: 10.5897/AJFS2021.2116.

[2] Angel Sharon, P., & Gurumoorthi, P. (2024). Optimization of spray drying process parameters for the production of cranberry flavoured oat milk powder using response surface methodology. *Food Science and Technology*, 12(1), 48-61. doi: 10.13189/fst.2024.120104.

[3] Arii, Y., & Nishizawa, K. (2024). Influence of ingredients on the physical properties and taste of a new plant-based sweet confection being developed for individuals with food restrictions. *International Journal of Gastronomy and Food Science*, 35, article number 100859. doi: 10.1016/j.ijgfs.2023.100859.

[4] Babolanimogadam, N., Gandomi, H., Akhondzadeh Basti, A., & Taherzadeh, M.J. (2023). Nutritional, functional, and sensorial properties of oat milk produced by single and combined acid, alkaline, α-amylase, and sprouting treatments. *Food Science & Nutrition*, 11, 2288-2297. doi: 10.1002/fsn3.3171.

[5] Bueno, F., Chouljenko, A., Reyes, V., & Sathivel, S. (2022). Spray-dried almond milk powder containing microencapsulated flaxseed oil. *Drying Technology*, 40(16), 3496-3508. doi: 10.1080/07373937.2022.2061507.

[6] Carcea, M. (2021). Value of wholegrain rice in a healthy human nutrition. *Agriculture*, 11(8), article number 720. doi: 10.3390/agriculture11080720.

[7] Chen, C.-Y., Lapsley, K., & Blumberg, J. (2006). A nutrition and health perspective on almonds. *Journal of the Science of Food and Agriculture*, 86(14), 2245-2250. doi: 10.1002/jsfa.2659.

[8] Chen, K.I., Erh, M.H., Su, N.W., Liu, W.-H., Chou, C.C., & Cheng, K.-C. (2012). Soyfoods and soybean products: From traditional use to modern applications. *Applied Microbiology and Biotechnology*, 96, 9-22. doi: 10.1007/s00253-012-4330-7.

[9] Craig, W.J., & Fresán, U. (2021). International analysis of the nutritional content and a review of health benefits of non-dairy plant-based beverages. *Nutrients*, 13(3), article number 842. doi: 10.3390/nu13030842.

[10] Dippong, T., Muresan, L.E., & Senila, L. (2025). Comparison of the thermal behavior and chemical composition of milk powders of animal and plant origin. *Foods*, 14(3), article number 389. doi: 10.3390/foods14030389.

[11] Duangchuen, J., Pathaveerat, S., Noypitak, S., & Jermwongruttanachai, P. (2021). Effect of spray drying air temperature to the changes of properties of skimmed coconut milk powder. *Applied Science and Engineering Progress*, 14(2), 187-195. doi: 10.14416/j.asep.2020.04.009.

[12] Dudarev, I., Kuzmin, O., Stukalska, N., Antonenko, A., Brovenko, T., Kovalenko, N., & Lebedenko, T. (2024). Using oat milk to reduce the caloric value of a functional mayonnaise sauce. *Acta Scientiarum Polonorum Technologia Alimentaria*, 23(1), 29-38. doi: 10.17306/J.AFS.001184.

[13] Dudarev, I., Shemet, V., Sydoruk, T., Andrushchenko, M., Semenov, A., Borusiewicz, A., & Hutsol, T. (2025). Physicochemical and sensory properties of frozen dessert containing soy milk. *Applied Sciences*, 15(21), article number 11455. doi: 10.3390/app152111455.

[14] Fructuoso, I., Romão, B., Han, H., Raposo, A., Ariza-Montes, A., Araya-Castillo, L., & Zandonadi, R. P. (2021). An overview on nutritional aspects of plant-based beverages used as substitutes for cow's milk. *Nutrients*, 13(8), article number 2650. doi: 10.3390/nu13082650.

[15] Giri, S., & Mangaraj, S. (2012). Processing influences on composition and quality attributes of soymilk and its powder. *Food Engineering Reviews*, 4(3), 149-164. doi: 10.1007/s12393-012-9053-0.

[16] Giugliano, R., Musolino, N., Ciccotelli, V., Ferraris, C., Savio, V., Vivaldi, B., Ercolini, C., Bianchi, D.M., & Decastelli, L. (2023). Soy, rice and oat drinks: Investigating chemical and biological safety in plant-based milk alternatives. *Nutrients*, 15(10), article number 2258. doi: 10.3390/nu15102258.

[17] Hewlings, S. (2020). Coconuts and health: Different chain lengths of saturated fats require different consideration. *Journal of Cardiovascular Development and Disease*, 7(4), article number 59. doi: 10.3390/jcdd7040059.

[18] Jeske, S., Zannini, E., & Arendt, E.K. (2016). Evaluation of physicochemical and glycaemic properties of commercial plant-based milk substitutes. *Plant Foods for Human Nutrition*, 72(1), 26-33. doi: 10.1007/s11130-016-0583-0.

[19] Lipan, L., Rusu, B., Sendra, E., Hernández, F., Vázquez-Araújo, L., Vodnar, D.C., & Carbonell-Barrachina, Á.A. (2020), Spray drying and storage of probiotic-enriched almond milk: Probiotic survival and physicochemical properties. *Journal of the Science of Food and Agriculture*, 100(9), 3697-3708. doi: 10.1002/jsfa.10409.

[20] Magan, J.B., Tobin, J.T., O'Callaghan, T.F., Kelly, A.L., Fenelon, M.A., Hennessy, D., & McCarthy, N.A. (2019). Physicochemical properties of whole milk powder derived from cows fed pasture or total mixed ration diets. *Journal of Dairy Science*, 102(11), 9611-9621. doi: 10.3168/jds.2019-16415.

[21] Marafon, K., Prestes, A.A., Carvalho, A.C., de Souza, C.K., & Prudencio, E.S. (2025). Bioactive compounds' importance in plant-based beverages: A review. *Current Opinion in Food Science*, 63, article number 101304. doi: 10.1016/j.cofs.2025.101304.

[22] McClements, D.J. (2020). Development of next-generation nutritionally fortified plant-based milk substitutes: Structural design principles. *Foods*, 9(4), article number 421. doi: 10.3390/foods9040421.
[23] Medic, J., Atkinson, C., & Hurburgh, C.R. (2014). Current knowledge in soybean composition. *Journal of the American Oil Chemists' Society*, 91, 363-384. doi: 10.1007/s11746-013-2407-9.
[24] Moore, S. S., Costa, A., Pozza, M., Vamerali, T., Niero, G., Censi, S., & De Marchi, M. (2023). How animal milk and plant-based alternatives diverge in terms of fatty acid, amino acid, and mineral composition. *npj Science of Food*, 7, article number 50. doi: 10.1038/s41538-023-00227-w.
[25] Muthia, A. J., Budi, S., Zuraidah, N., & Ahmad, S. (2021). Effects of variety and maturity stage of coconut on physicochemical and sensory characteristics of powdered coconut drink. *Foods and Raw Materials*, 9(1). doi: 43-51. 10.21603/2308-4057-2021-1-43-51.
[26] Mykhalevych, A., Polishchuk, G., Nassar, K., Osmak, T., & Buniowska-Olejnik, M. (2022). β-Glucan as a techno-functional ingredient in dairy and milk-based products – a review. *Molecules*, 27(19), article number 6313. doi: 10.3390/molecules27196313.
[27] Nawaz, M.A., Buckow, R., Katopo, L., & Stockmann, R. (2023). Plant-based beverages. In S. Prakash, B.R. Bhandari & C. Gaiani (Eds.), *Engineering plant-based food systems* (pp. 99-129). London: Academic Press. doi: 10.1016/B978-0-323-89842-3.00015-4.
[28] Neelissen, J., Leanderson, P., Jonasson, L., & Chung, R.W.S. (2023). The effects of dairy and plant-based liquid components on lutein liberation in spinach smoothies. *Nutrients*, 15(3), article number 779. doi: 10.3390/nu15030779.
[29] Nilufer-Erdil, D., Serventi, L., Boyacioglu, D., & Vodovotz, Y. (2012). Effect of soy milk powder addition on staling of soy bread. *Food Chemistry*, 131(4), 1132-1139. doi: 10.1016/j.foodchem.2011.09.078.
[30] Obatoye, A., Ogunwolu, S., & Idowu, M. (2014). Quality evaluation of chocolate produced using soy-cow milk. *Nutrition & Food Science*, 44(1), 57-63. doi: 10.1108/NFS-07-2013-0078.
[31] Padma, M., Jagannadha Rao, P.V.K., Edukondalu, L., Aparna, K., & Ravi Babu, G. (2022). Determining the effects of spray drying conditions on water absorption index, water solubility index, solubility and water activity (a_w) of rice milk powder. *Current Advances in Geography, Environment and Earth Sciences*, 9, 16-36. doi: 10.9734/bpi/cagees/v9/17314D.
[32] Penha, C.B., Santos, V.D.P., Speranza, P., & Kurozawa, L.E. (2021). Plant-based beverages: Ecofriendly technologies in the production process. *Innovative Food Science & Emerging Technologies*, 72, article number 102760. doi: 10.1016/j.ifset.2021.102760.
[33] Popova, A., Mihaylova, D., & Lante, A. (2023). Insights and perspectives on plant-based beverages. *Plants*, 12(19), article number 3345. doi: 10.3390/plants12193345.
[34] Rachtan-Janicka, J., Gajewska, D., Szajewska, H., Włodarek, D., Weker, H., Wolnicka, K., Wiśniewska, K., Socha, P., & Hamulka, J. (2025). The role of plant-based beverages in nutrition: An expert opinion. *Nutrients*, 17(9), article number 1562. doi: 10.3390/nu17091562.
[35] Reyes-Jurado, F., Soto-Reyes, N., Dávila-Rodríguez, M., Lorenzo-Leal, A.C., Jiménez-Munguía, M.T., Mani-López, E., & López-Malo, A. (2021). Plant-based milk alternatives: Types, processes, benefits, and characteristics. *Food Reviews International*, 39(4), 2320-2351. doi: 10.1080/87559129.2021.1952421.
[36] Rodríguez-Roque, M.J., Rojas-Graü, M.A., Elez-Martínez, P., & Martín-Belloso, O. (2014). *In vitro* bioaccessibility of health-related compounds from a blended fruit juice-soymilk beverage: Influence of the food matrix. *Journal of Functional Foods*, 7, 161-169. doi: 10.1016/j.jff.2014.01.023.
[37] Sethi, S., Tyagi, S.K., & Anurag, R.K. (2016). Plant-based milk alternatives an emerging segment of functional beverages: A review. *Journal of Food Science and Technology*, 53, 3408-3423. doi: 10.1007/s13197-016-2328-3.
[38] Shameena Beegum, P.P., Manikantan, M.R., Anju, K.B., Vinija, V., Pandiselvam, R., Jayashekhar, S., & Hebbar, K.B. (2022). Foam mat drying technique in coconut milk: Effect of additives on foaming and powder properties and its economic analysis. *Journal of Food Processing and Preservation*, 46, article number e17122. doi: 10.1111/jfpp.17122.
[39] Sharma, N., Yeasmen, N., Dube, L., & Orsat, V. (2024). Rise of plant-based beverages: A consumer-driven perspective. *Food Reviews International*, 40(10), 3315-3341. doi: 10.1080/87559129.2024.2351920.
[40] Silva, A.R.A., Silva, M.M.N., & Ribeiro, B.D. (2022). Plant-based milk products. In R. Bhat (Ed.), *Future Foods* (pp. 233-249). London: Academic Press. doi: 10.1016/B978-0-323-91001-9.00025-6.
[41] Silva, L.R.D., Almeida Bachega Casari, A.C., Velasco, J.I., & Matta Fakhouri, F. (2018). Nutritional potential of dehydrated residues from rice milk production. In *IDS'2018: 21st International drying symposium* (pp. 951-956). València: Universitat Politècnica de València. doi: 10.4995/ids2018.2018.7650.
[42] Sterna, V., Zute, S., & Brunava, L. (2016). Oat grain composition and its nutrition benefice. *Agriculture and Agricultural Science Procedia*, 8, 252-256. doi: 10.1016/j.aaspro.2016.02.100.
[43] Taşoyan, İ.C., & Yolacaner, E.T. (2023). Physical properties of some soy powders and functional and sensory properties of milk chocolates prepared with these powders. *Turkish Journal of Agriculture-Food Science and Technology*, 11(2), 246-257. doi: 10.24925/turjaf.v11i2.246-257.5444.

[44] Tulashie, S.K., Amenakpor, J., Atisey, S., Odai, R., & Akpari, E.E.A. (2022). Production of coconut milk: A sustainable alternative plant-based milk. *Case Studies in Chemical and Environmental Engineering*, 6, article number 100206. doi: 10.1016/j.cscee.2022.100206.
[45] Vitoria, I. (2017). The nutritional limitations of plant-based beverages in infancy and childhood. *Nutrición Hospitalaria*, 34, 1205-1214. doi: 10.20960/nh.931.
[46] Walther, B., Guggisberg, D., Badertscher, R., Egger, L., Portmann, R., Dubois, S., Haldimann, M., Kopf-Bolanz, K., Rhyn, P., Zoller, O., Veraguth, R., & Rezzi, S. (2022). Comparison of nutritional composition between plant-based drinks and cow's milk. *Frontiers in Nutrition*, 9, article number 988707. doi: 10.3389/fnut.2022.988707.
[47] Yilmaz-Ersan, L., & Topcuoglu, E. (2022). Evaluation of instrumental and sensory measurements using multivariate analysis in probiotic yogurt enriched with almond milk. *Journal of Food Science and Technology*, 59, 133-143. doi: 10.1007/s13197-021-04994-w.

Сухе рослинне молоко: критичний огляд способів виробництва, функціональних властивостей та використання у харчових продуктах

Ігор Дударєв
Доктор технічних наук, професор
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-2016-5342
Василина Шемет
Кандидат хімічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0001-8952-5097
Олександр Каракулько
Аспірант
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0009-0001-9983-8967

Анотація. Зростаючий попит на стійкі та функціональні харчові інгредієнти посилив інтерес до сухого «рослинного молока» як альтернативи традиційним молочним продуктам. Метою цього дослідження було оцінити сухе «рослинне молоко» шляхом порівняльного аналізу його фізико-хімічних, харчових та функціональних властивостей, а також технологій виробництва. Дослідження базувалося на структурованому аналізі наукової літератури, зокрема на систематичному пошуку інформації у наукових базах даних. Встановлено, що сухе «рослинне молоко» є універсальним та перспективним харчовим інгредієнтом завдяки своїм відмінним фізико-хімічним, харчовим та функціональним властивостям. Цей продукт можна отримати з різних видів «рослинного молока». Виявлено, що сухе «рослинне молоко» демонструє значну мінливість макронутрієнтного складу залежно від сировини. Зокрема, сухе «мигдалеве молоко» характеризується високим вмістом жиру, «соєве молоко» багате на білок, тоді як вівсяне та рисове «молоко» переважно містять вуглеводи. Ці продукти демонструють широкий спектр фізико-хімічних властивостей, які суттєво впливають на їхню відновлюваність. Розчинність значно варіюється між продуктами з різної сировини, починаючи від низьких значень у сухому мигдальному та соєвому «молоці» до дуже високих значень у сухому «вівсяному молоці», сягаючи 98,5 %. Насипна густина продуктів коливається від 0,25 г/мл до 0,61 г/мл, вологість від 2,1 % до 7,9 %, а pH від 5,6 до 6,9, внаслідок різних видів сировини та умов виробництва. Встановлено, що технологія виробництва, зокрема стадія сушіння, відіграє визначальну роль у формуванні властивостей сухого «рослинного молока». Поєднання складу поживних речовин та фізико-хімічних властивостей робить сухе «рослинне молоко» перспективним інгредієнтом для використання у хлібобулочних та кондитерських виробах, заморожених десертах, шоколаді, соусах, паштетах та ковбасах, ферментованих продуктах та альтернативних молочних продуктах, сприяючи розвитку стійких, функціональних та збалансованих за поживністю харчових систем

Ключові слова: рослинні замінники; функціональні продукти харчування; безлактозні продукти; харчова цінність; рослинні напої

COMMODITY BULLETIN
Journal homepage: https://c-bulletin.com.ua/en
DOI: 10.62763/cb/2.2025.43

Article's History: Received: 11.08.2026 Revised: 21.11.2025 Accepted: 26.12.2025 Published: 02.01.2026

ISSN 2310-5283; e-ISSN 3041-1432 Vol. 18, No. 2, 2025, 43-52

UDC 339.543:658.56

Improving methods of commodity examination at the stage of customs control

Olena Pakholiuk*
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-3484-0468

Andrii Dziubynskyi
PhD in Economic Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0001-5156-9852

Galina Golodyuk
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-9740-5498

Oksana Peredriy
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0002-5464-2020

Tetiana Yaroshevych
PhD in Technical Sciences, Associate Professor
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
https://orcid.org/0000-0001-8003-0514

Abstract. In the context of growing international trade flows, the intensification of customs procedures, and increasing risks of smuggling and goods falsification, improving methods of commodity examination at the stage of customs control is becoming particularly important. The aim of the article was to provide a scientific rationale and to develop proposals for improving methods of commodity examination at the stage of customs control through the integration of modern instrumental, digital, and analytical technologies. This process involved increasing the accuracy, speed, and objectivity of expert procedures, harmonising national methodologies with international standards, and creating the preconditions for more effective functioning of the customs control system in Ukraine. The efficiency and accuracy of expert procedures determined the level of the state's economic security, ensure transparency of foreign economic operations, and contribute to the protection of the domestic market. However, existing examination methods did not always meet the requirements of efficiency, reliability, and adaptability to new challenges, which highlights the need for the implementation of innovative approaches. The study substantiated the possibilities of improving commodity examination at the stage of customs control through the use of instrumental and digital technologies capable of significantly increasing the effectiveness of expert

Suggested Citation:
Pakholiuk, O., Dziubynskyi, A., Golodyuk, G., Peredriy, O., & Yaroshevych, T. (2025). Improving methods of commodity examination at the stage of customs control. *Commodity Bulletin*, 18(2), 43-52. doi: 10.62763/cb/2.2025.43.

**Corresponding author*

procedures. A systematisation of modern expert analysis methods has been carried out and their compliance with the tasks of customs control has been assessed, and the prospects for the application of digital solutions and artificial intelligence in analytical processes have been identified. A set of practical recommendations has been developed to align national approaches with international standards. The creation of a unified electronic database of product samples, the use of mobile laboratories, and the development of standards adapted to global requirements were proposed, which will contribute to improving the efficiency of customs control and expanding Ukraine's integration opportunities in global trade. The practical significance of the study lies in the possibility of applying its results to modernise the customs control system, optimise the operation of customs laboratories, improve electronic databases, and implement internationally harmonised methods of examination, thereby strengthening the state's economic security and stimulating the development of foreign trade

Keywords: standard; customs duty; commodity assessment; regulation; digitalisation

Introduction

The issue of improving customs control and developing commodity examination is widely addressed in contemporary academic research. M. Ghidotti *et al.* (2021) highlighted the growing role of instrumental analytical methods (FTIR spectroscopy, X-ray fluorescence analysis, chromatography) in ensuring the accuracy of goods identification. The authors demonstrated that energy-dispersive X-ray fluorescence (ED-XRF) is a versatile and rapid instrumental method that requires virtually no sample preparation and enables multi-element analysis of various materials for the needs of customs laboratories. Researchers P. Bergey *et al.* (2024) emphasised the importance of digital technologies and blockchain solutions for verifying product origin and ensuring supply chain transparency. The authors noted that the integration of blockchain can not only optimise operational activities and strengthen consumer confidence in the authenticity of goods, but also promote more ethical, sustainable and responsible practices within the global supply chain. O. Amel *et al.* (2023) proposed a new multimodal approach for automatically predicting HS codes in customs declarations based on a combination of textual and visual features using deep neural networks. Experimental results showed that their model, using the proposed MultConcat fusion method, achieved high classification accuracy compared to existing approaches, highlighting the effectiveness of using multimodal data for this task. O. Punda & D. Arziantseva (2019) and Makedon *et al.* (2024) noted the importance of modernising customs laboratories, expanding technical equipment and harmonising examination methods with international standards, emphasising the need to improve procedures for appointing and conducting customs examinations to reduce organisational and methodological errors. The researchers emphasised that without systematic upgrading of laboratory infrastructure and staff training, the introduction of modern technologies would not deliver the expected results.

In the study by S. Petrukha *et al.* (2022), the post-war potential and regulatory capabilities of rural local authorities in forming cluster-based and integrated agri-food value chains were analysed. The authors emphasised the importance of integrating local economies and improving customs regulation to enhance the competitiveness of the agricultural sector. A. Grainger (2024) highlighted that modern systems of tariff classification of goods in customs practice were increasingly utilising auxiliary digital technologies to improve the accuracy and consistency of decision-making. In the author's view, the introduction of automated decision-support tools will help reduce the human factor, harmonise interpretations of HS codes and speed up customs clearance procedures. A similar position was held by O. Ozturk (2024), who examined the potential of artificial intelligence in the field of international trade. The author noted that the application of artificial intelligence systems, in particular predictive analytics, automated document verification and intelligent risk assessment, will improve the efficiency, transparency and controllability of cross-border operations.

The study by I.M. de Artiñano *et al.* (2023) was empirical in nature and demonstrated the potential of using machine learning algorithms and large language models (LLMs) for the automatic classification of goods in international trade. The results showed that such models can correctly identify HS codes with an accuracy of over 90%, significantly reducing the time and labour costs of customs experts. B. Dangsawang & S. Nuchitprasitcha (2024) expanded on previous work, focusing on the problem of detecting customs fraud. In their study, the authors applied unstructured data analysis and machine learning algorithms to create a risk management system capable of rapidly identifying suspicious trade declarations. The researchers concluded that intelligent analytics could become an effective preventive tool in the fight against smuggling and customs duty evasion. S. Vijayakumar (2025) examined the integration of artificial intelligence technologies from the perspective of supply chain management and trade security. The researcher demonstrated that combining real-time risk analysis systems with digital data-sharing platforms between customs authorities and logistics operators formed a "smart border ecosystem", which simultaneously facilitated trade and enhanced national security. This approach was consistent with the principles of the

WCO SAFE Framework of Standards (Mikuriya, 2021) and reflected a shift towards a new model of proactive customs administration. The analysed sources indicated a steady trend towards the digital transformation of customs examination worldwide. Researchers emphasised that artificial intelligence, machine learning and analytical tools had become integral elements of modern customs control, ensuring greater transparency, efficiency and the compatibility of national systems with international standards. The aim of the study was to identify conceptual approaches and practical directions for improving commodity examination in the customs sector, taking into account global trends in digitalisation, the development of instrumental methods and the standardisation of customs control procedures.

Materials and Methods

The study was based on an analysis of current practices regarding commodity examination during customs control in Ukraine and European Union countries – specifically Poland, Germany, Lithuania and the Czech Republic. These countries were selected due to the presence of effectively functioning customs laboratories and the implementation of innovative technologies in accordance with the recommendations of the WCO (World Customs Organization) and ISO standards. The study took into account the provisions of the Customs Code of Ukraine No. 4495-VI (2012) and Regulation (EU) No. 952/2013 (2013). Furthermore, data from the standards DSTU ISO 9001:2015 (2016), ISO/IEC 17025:2017 (2017) and the guidance documents of the World Customs Organization (2022; 2023), which define the procedures for the identification, classification and valuation of goods, were examined. A set of complementary methods was applied during the research, ensuring a comprehensive examination of the issue. A comparative legal analysis made it possible to investigate the differences between the Ukrainian and European regulatory frameworks in the field of customs regulation, identify gaps in the organisation of expert procedures, and propose directions for harmonising the Ukrainian system with international standards. Instrumental methods – FTIR spectroscopy and X-ray fluorescence analysis (XRF) – were used to determine the qualitative characteristics and origin of goods. As part of the experimental section, 12 product samples were examined that were most frequently subject to customs examination: food products (olive oil, coffee, chocolate), textiles (cotton fabric, denim, polyester), electronic goods (smartphones, power banks, headphones) and chemicals (varnishes, solvents, cosmetics). The samples came from various countries – Ukraine, Poland, Italy, Turkey and China – ensuring the representativeness of the sample and the ability to assess the effectiveness of the methods for products from different markets. FTIR spectroscopy was used to identify organic compounds and polymeric materials present in food, cosmetic and textile products. The method enabled the chemical composition to be determined and the authenticity of the products to be confirmed by comparing spectra with reference databases (Open Spec Database, EU Customs Laboratory Network). XRF was used to determine the elemental composition of metal components, dyes and impurities in the samples, which made it possible to identify non-compliance with international safety requirements (the presence of lead, cadmium and nickel). The application of the proposed methodology ensured the comprehensiveness of the study, the reproducibility of the results obtained, and the possibility of practical application of the developed recommendations in the activities of customs authorities. It also created a basis for further harmonisation of Ukrainian methods of commodity examination with international requirements and for improving the efficiency of customs control in the context of the digital transformation of trade.

Results and Discussion

Commodity examination at customs plays a key role in ensuring the state's economic security, protecting the domestic market from counterfeit goods, unsafe products, and evasion of customs payments. Modern practice in Ukraine has relied both on organoleptic methods (visual inspection, labelling, packaging) and on certain instrumental approaches (analysis of samples in customs laboratories). However, in the context of increasing volumes of international trade and the emergence of new groups of goods, traditional methods have been losing their effectiveness. Table 1 outlines the problems of modern commodity examination that arose at the stage of customs control.

Table 1. *Main problems of modern commodity examination at the stage of customs control*

Problem	Characteristics	Consequences
Slowness of procedures	Lengthy laboratory analysis of samples	Delays, queues, and reduced efficiency of foreign economic activity
Limited equipment	Presence of outdated instruments, lack of modern methods	Uneven quality of examination across regions
Insufficient digitalisation	Absence of unified databases and integration	Classification errors, duplication of work
Lack of analytics	ML and AI are not used in goods classification	High risk of subjectivity and inaccuracies
Low harmonisation with international standards	Non-compliance with ISO and WCO recommendations	Risk of non-recognition of examination results by international partners

Note: *ML – machine learning, AI – artificial intelligence*

Source: *Regulation (EU) No. 952/2013 (2013)*

Thus, one of the main problems was the slowness of expert procedures. The examination of qualitative characteristics of goods in laboratories took a considerable amount of time, which led to delays in customs clearance and created conditions for the accumulation of queues at the border, reducing the competitiveness of enterprises and complicating international trade. Another issue was the limited technical equipment of customs laboratories. In most cases, the equipment did not meet modern international standards, such as Regulation (EU) No. 952/2013 (2013), DSTU ISO 9001:2015 (2016), and ISO/IEC 17025:2017 (2017), while the use of instrumental methods such as FTIR spectroscopy or XRF was restricted to large customs centres only, creating uneven quality of examination depending on the region. An important challenge was the insufficient digitalisation of processes. Databases of reference samples, classifiers, and reference materials were, in most cases, not integrated into a unified information system, which complicated rapid access to information for experts. The absence of a centralised digital database led to duplication of procedures, reduced accuracy, and increased risk of incorrect classification of goods (World Customs Organization, 2022). Another significant issue was the insufficient use of analytical technologies – decision-support systems, machine learning algorithms, and artificial intelligence. While EU countries, the USA, and China actively used automated systems for classifying goods according to HS codes, in Ukraine these technologies were still only at the stage of testing. There was also the problem of insufficient harmonisation of national procedures with international standards. Although Ukraine has integrated into the global trading system and cooperates with the WCO, the level of implementation of international recommendations in customs examination practice remained insufficient, creating risks of non-recognition of examination results in international courts or in bilateral trade disputes.

The analysis of data on the organisation of customs control, the structure of customs laboratories, technical equipment, level of digitalisation, and methodological approaches to commodity examination in European Union countries – Poland, Germany, Lithuania, and the Czech Republic – was important for understanding international experience in customs control practice. The functioning of customs laboratories in these countries demonstrated a high level of technological modernisation and the implementation of innovative solutions. In particular, Germany and Poland actively applied FTIR spectroscopy, XRF, chromatographic methods, and mass spectrometry, ensuring the accuracy of goods identification at the level of 95–99%. In Lithuania and the Czech Republic, mobile laboratory complexes were widely used, allowing rapid analysis directly at customs posts (European Commission, 2025; European Commission, n.d.a; n.d.b). In all four countries, a unified electronic network for the exchange of laboratory data was in operation, integrated with EU systems (EU Customs Laboratory Network, TRACES, ICS2). As a result of the analysis of the characteristics of customs examination of goods, the main organoleptic properties and compliance with the technical characteristics of products most frequently subject to customs examination were identified (Table 2).

Table 2. *Analysis of various product samples subject to customs examination*

Category of goods	Product name	Country of origin	Main organoleptic properties	Presence of foreign impurities	Safety analysis	Compliance with technical characteristics
Food products	Olive oil	Italy, Turkey	Characteristic colour, smell, and viscosity meet the standards	No impurities detected (FTIR)	Acidity and peroxide value indicators are within the norm	Complies with declared data
	Coffee	Poland, Italy	Uniform colour, aroma without signs of spoilage	No cereal impurities detected (HPLC)	Safe, no toxic substances detected	Caffeine content corresponds to labelling
	Chocolate	Ukraine, Turkey	Homogeneous texture, cocoa smell	Vegetable fats detected in Turkish samples	Complies with safety standards	Turkish samples – partial non-compliance with composition
Textiles	Cotton fabric	Turkey, China	Even weaving, no foreign odour	Up to 15% polyester in the Chinese sample	Safe colourants	Chinese sample does not correspond to declared 100% cotton
	Denim	Turkey	Density and strength within the norm	Not detected	Meets standards	Full compliance with labelling
	Polyester	China	Uniform structure	No impurities detected	No hazardous colourants (REACH)	Complies with declared data
Electronics	Smartphones	China	n/a (organoleptic assessment not applicable)	No hazardous metal impurities detected (XRF)	Pb, Cd, Hg – within RoHS limits	20% of samples – non-compliance with technical parameters

Table 2. Continued

Category of goods	Product name	Country of origin	Main organoleptic properties	Presence of foreign impurities	Safety analysis	Compliance with technical characteristics
	Power banks	China, Poland	n/a	n/a	Safe, no overheating detected	Chinese samples: capacity lower by 25–30%
	Headphones	Ukraine, China	Sound without distortion	n/a	No hazardous materials detected	Full compliance with labelling
Chemicals	Nail varnish	Poland, Ukraine	Uniformity, characteristic colour	No impurities detected	VOC – within EU limits	Complies with technical documentation
	Solvents	China, Turkey	Transparency, characteristic smell	In Chinese samples – up to 3% methanol	Exceedance of permissible limits in Chinese samples	Partial non-compliance with declared composition
	Cosmetics	Ukraine, Italy	Consistency and smell within the norm	Not detected	pH meets standards, no toxic substances detected	Complies with labelling

Note: *VOC – Volatile Organic Compounds*
Source: *DSTU ISO 9001:2015 (2016), ISO/IEC 17025:2017 (2017), World Customs Organization (2022; 2023)*

The analysis showed that EU countries have achieved a high level of digitalisation in their expert procedures. The use of electronic registers of reference samples, automated product classification, blockchain technologies for verifying product origin, and machine learning systems for analysing declarations has significantly reduced the risk of errors, accelerated data processing, and stood in stark contrast to the current situation in Ukraine, where such digital and technical integration was only at the stage of gradual implementation. The comparative analysis also revealed that Poland, Italy and Turkey had already fully harmonised their methodologies with the international standards DSTU ISO 9001:2015 (2016), ISO/IEC 17025:2017 (2017), as well as the World Customs Organization's guidance documents (2022; 2023), which ensured mutual recognition of examination results within the EU and reduced the number of trade disputes. In Ukraine, the level of such harmonisation has been partial, confirming the need for standardisation of laboratory procedures and updating of the regulatory framework.

Modern customs analysis has gradually shifted from traditional organoleptic methods to the use of high-precision instrumental technologies. One of the most promising areas has been the introduction of spectroscopic analysis methods (FTIR spectroscopy, UV-visible spectroscopy, XRF). These have enabled the rapid and reliable determination of the chemical composition of materials, which is crucial when inspecting products that may be counterfeit or hazardous to health. For example, using FTIR spectroscopy, EU customs laboratories successfully determined the authenticity of polymers in plastic products, specifically identifying low-density polyethylene (LDPE) and polyvinyl chloride (PVC) in batches of packaging imported from South-East Asian countries. This enabled the rapid detection of material substitution with cheaper alternatives not specified in the documentation. XRF has been widely used to monitor the safety of metal goods; for example, when testing children's toys from China, XRF made it possible to detect lead levels exceeding the permissible limit in the paints used for coating, thereby preventing the import of hazardous products. The use of portable XRF analysers has made it possible to carry out such checks directly at customs posts (Intertek, n.d.).

Another promising area has been gas and liquid chromatography, which has enabled the accurate detection of impurities, additives or prohibited substances in foodstuffs, medicinal products or chemical materials. In particular, in the practice of German customs laboratories, gas chromatography coupled with mass spectrometry (GC-MS) was used to detect illegal flavourings and synthetic preservatives in consignments of coffee and chocolate imported into the EU (German Federal Institute for Risk Assessment, n.d.). Similarly, liquid chromatography was used to detect counterfeits in perfumery products: it enabled the detection of cheap alcohol mixtures in place of the declared essential components (Intertek, n.d.). The digitisation of expert processes has also become an important aspect. The use of centralised databases containing digital reference standards (spectral characteristics, photographs, descriptions of quality indicators) has enabled the rapid identification of goods and helped to avoid classification errors. The implementation of such databases, integrated into international systems (e.g., the WCO Data Model), will facilitate the harmonisation of national methodologies with international standards and simplify data exchange with the customs administrations of other countries. The application of AI and ML in the process of commodity examination has become a promising development. ML algorithms can automatically analyse large volumes of data (images, spectra, technical descriptions) and classify goods according to HS codes with a high degree of accuracy, which will reduce the subjective element in the expert's work and shorten decision-making times. By 2025, text and image recognition systems were being successfully used worldwide for the automated verification of product labelling (Magai & Ilomo, 2024). Another area of focus is the implementation of blockchain technologies to track the supply chain of goods. Thanks to decentralised data storage, customs authorities have been able to verify the authenticity of certificates of origin and quality guarantees without the risk of forgery, which has significantly reduced the risks of fraud, smuggling and the falsification of documents accompanying the goods.

An important component of the digital transformation has been the creation of mobile laboratories and rapid testing stations. These have made it possible to conduct preliminary examinations directly at the customs post, using portable devices and rapid test systems. This approach reduced the workload on central laboratories, cut waiting times for businesses and ensured rapid decision-making during customs inspections. The application of AI and ML algorithms in customs practice has opened up new possibilities for the automated classification and identification of goods. Traditional methods, based on manual document checks and organoleptic assessment, could not keep pace with the growth in international trade volumes and the diversity of goods flows (Makedon *et al.,* 2025). In this context, AI is capable of significantly improving the efficiency, accuracy and speed of expert decision-making (Table 3).

Table 3. *Potential for the use of AI/ML in customs examination*

Area of application	Example of technology	Expected effect
Automatic classification	ML models for coding goods according to HS codes.	Reduction in the number of errors, acceleration of processing
Goods identification	Computer vision, image recognition	Detection of counterfeits, rapid product recognition
Documentation analysis	NLP for customs declarations and certificates	Identification of inconsistencies and falsifications
Risk management	Predictive analytics algorithms	Automatic identification of "high-risk" consignments
Integration with instrumental methods	AI-based analysis of spectral data	Improved accuracy of goods composition examination

Note: *NLP – Natural Language Processing*
Source: *ISO/IEC 17025:2017 (2017)*

Thus, one of the promising areas has become the automated recognition and classification of goods according to HS codes. ML models, trained on large datasets of customs declarations, product samples and their characteristics, can automatically assign goods to the appropriate category, which has reduced the frequency of errors caused by human error and accelerated the cargo clearance process. The use of computer vision was of significant importance. Thanks to image analysis, the system was able to automatically identify goods by their external characteristics: shape, colour, labelling and packaging structure. Combined with spectral characteristics (for example, from FTIR analysis or X-ray fluorescence), ML algorithms are capable of generating a comprehensive product profile for rapid authenticity verification. The application of natural language processing (NLP) to analyse accompanying documentation has also become important. AI was able to automatically verify customs declarations, certificates of origin and certificates of conformity, identify discrepancies between the declared and actual characteristics of goods, and predict the risks of document forgery. Furthermore, AI technologies held potential in the field of risk management.

By predicting the likelihood of violations in specific consignments (based on historical data, country of origin, product category and behavioural factors of foreign trade participants), the system was able to automatically determine which consignments required more detailed inspection, and which could be cleared under a simplified procedure, thereby reducing the workload on customs authorities and optimising resources. The use of artificial intelligence and ML in the automated classification and identification of goods created the conditions for improving the efficiency of customs control, reducing the level of smuggling and counterfeiting, and integrating Ukraine into the global system of "smart" customs. Thus, improving commodity examination methods at the customs control stage required a comprehensive approach combining technical modernisation, process digitalisation, staff training and integration into the international standards system.

The issue of harmonising examination methods with international standards became crucial. The Ukrainian customs system must be guided by the requirements of ISO/IEC 17025:2017 (2017), which regulate the competence and impartiality of laboratories; and by the recommendations of the World Customs Organization (Mikuriya, 2021) regarding security and trade facilitation. Attention should also be paid to EU regulations set out in Regulation (EU) No. 952/2013 (2013) and to the provisions of the Agreement on Trade Facilitation, which established the principles of transparency and simplification of customs procedures (Protocol Amending the Marrakesh Agreement..., 2014). Their consistent implementation into national legislation and the working practices of customs laboratories has laid the groundwork for the mutual recognition of examination results, a reduction in the number of trade disputes, and the deepening of Ukraine's integration into the global trading system. It has become advisable to introduce a system of regular audits to ensure that examination methods comply with international requirements. It is worth noting the training of personnel and the development of experts' professional competence. Training in modern instrumental and digital methods, internships at international customs organisations, and participation in joint scientific and practical programmes with the EU will contribute to professional development and the creation of a unified professional environment. The first step should be to upgrade the technical infrastructure of customs laboratories: the introduction of FTIR spectroscopy, X-ray fluorescence analysis, gas chromatography and other high-precision methods that have already been successfully used in EU countries, which will enable faster and more accurate determination of the quality characteristics of goods. The implementation of these measures will enhance the transparency and effectiveness of customs control, reduce the level of smuggling and contribute to Ukraine's integration into the global foreign trade system.

The works of contemporary researchers reveal a clear trend towards the digitalisation and automation of customs control processes, which has influenced the development of commodity examination. Scholar E. Oluwagbade (2025) emphasised the need to integrate algorithmic classification into global trade compliance systems, which enabled the automation of the goods identification process and reduced the number of human errors. V. Marinova (2024) emphasised that artificial intelligence is not merely an innovative tool but also a practical component of customs authorities' operations, enhancing the speed of decision-making and the accuracy of controls. Research by Y. Liu *et al.* (2025) drew attention to the development of a network of lower-tier customs laboratories, their technical equipment, and the need to standardise examination procedures in accordance with the requirements of ISO/IEC 17025:2017 (2017), which laid the foundation for harmonising approaches to goods identification. An important area identified in the study by A. Dziubynskyi *et al.* (2025) was the digital transformation of customs laboratories, based on the experience of the Republic of Korea and the EU. The authors demonstrated that the modernisation of the technical infrastructure and the digital integration of laboratories contributed to the standardisation of examination procedures and enhanced confidence in their results within the international community. S. Vijayakumar (2025) focused on deep neural networks for classifying goods in the e-commerce sector, where the high volume of data required automated solutions based on machine learning. Researchers K. Houssini *et al.* (2025) and Y. Zhao *et al.* (2025) highlighted the importance of creating intelligent decision support systems in international supply chains, enabling customs authorities to assess risks promptly, ensure compliance with standards and reduce transaction costs. Thus, the research demonstrated an interdisciplinary approach to the development of customs examination – ranging from technical improvements to laboratories and the implementation of IoT technologies to the creation of digital risk management ecosystems and automated goods classification. Thus, an analysis of scientific sources has confirmed that the global scientific community is moving towards the creation of "smart" customs control systems based on the use of artificial intelligence, big data and standardised protocols. For Ukraine, this means the need to adapt international practices, develop the digital infrastructure of customs laboratories and train highly qualified specialists capable of working with intelligent technologies in their expert activities.

Conclusions

The modern system of commodity examination at the customs control stage has faced a number of challenges, including slow procedures, insufficient technical equipment in customs laboratories, limited digitalisation, and a lack of full harmonisation with international standards. This has led to delays in customs clearance, increased the risk of incorrect classification of goods, and created favourable conditions for the spread of counterfeit products. food products, textile materials, electronic products, and chemical substances) confirmed the presence of significant challenges in the practical work of customs laboratories. The findings confirmed that the introduction of modern instrumental and digital technologies (spectroscopy, chromatography, X-ray fluorescence analysis, electronic databases, blockchain solutions) can improve the accuracy and speed of expert procedures, create the conditions for more effective control, reduce the risks of counterfeiting, and ensure integration with international information systems. The use of artificial intelligence and machine learning algorithms has become a promising development, enabling the automation of goods classification, analysis of accompanying documentation, identification of products based on visual, spectral and structural characteristics, as well as the prediction of smuggling risks. This laid the groundwork for a transition to a flexible, intelligence-led model of customs control that aligned with global trends. The practical recommendations emphasised a comprehensive approach to modernisation: upgrading the technical infrastructure of customs laboratories, the widespread introduction of digital technologies, the application of artificial intelligence, the harmonisation of methodologies with international standards, and the development of systematic training and professional development for staff. The implementation of these measures will contribute to increasing the efficiency and transparency of customs control, reducing the level of smuggling and counterfeiting, and strengthening Ukraine's economic security. Prospects for further research lie in the creation of an integrated "smart customs examination" platform, which will combine artificial intelligence algorithms, automatic image analysis modules, spectral databases and risk management systems, thereby ensuring the creation of a unified digital environment for customs control, compatible with the international systems of the EU and the WCO.

Acknowledgements
None.

Funding
None.

Conflict of Interest
None.

References
[1] Amel, O., Stassin, S., Mahmoudi, S.A., & Siebert, X. (2023). Multimodal approach for harmonized system code prediction. In *ESANN 2023 proceedings, European symposium on artificial neural networks, computational intelligence and machine learning*. Bruges, Belgium.
[2] Bergey, P., Vazquez Melendez, E.I., & Smith, B. (2024). Blockchain technology for supply chain provenance: Increasing supply chain efficiency and consumer trust. *Supply Chain Management*, 29(4), 706-730. doi: 10.1108/SCM-08-2023-0383.
[3] Dangsawang, B., & Nuchitprasitchai, S. (2024). A machine learning approach for detecting customs fraud using unstructured data analysis in media. *Decision Analytics Journal*, 10, article number 100408. doi: 10.1016/j.dajour.2024.100408.
[4] de Artiñano, I.M., Depetris, F.R., & Martincus, C.V. (2023). Automatic product classification in international trade: Machine learning and large language models. *IDB Working Paper Series No. IDB- WP-01494*. Retrieved from https://publications.iadb.org/publications/english/document/Automatic-Product-Classification-in-International-Trade-Machine-Learning-and-Large-Language-Models.pdf.
[5] DSTU ISO 9001:2015. (2016). *Quality management systems. Requirements (ISO 9001:2015, IDT)*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=64013.
[6] Dziubynskyi, A., Pakholiuk, O., Dziubynska, O., Shehynskyi, O., & Shehynskyi, V. (2025). Customs policy as a tool to stimulate exports under martial law. *Economic Forum*, 15(1), 83-92. doi: 10.62763/ef/1.2025.83.
[7] European Commission. (2025). *EU Customs Laboratories Scientific laboratories that support EU customs and tax authorities*. Retrieved from https://taxation-customs.ec.europa.eu/customs/customs-controls/eu-customs-laboratories_en.
[8] European Commission. (n.d.a). *Traces*. Retrieved from https://food.ec.europa.eu/horizontal-topics/traces_en.
[9] European Commission. (n.d.b). *Import Control System 2 (ICS2)*. Retrieved from https://taxation-customs.ec.europa.eu/customs/customs-security/import-control-system-2_en.
[10] German Federal Institute for Risk Assessment. (n.d.). *National reference laboratory for food additives and flavourings*. Retrieved from https://www.bfr.bund.de/en/about-us/institutions-at-the-bfr/reference-laboratories/nrl-food-additives-and-flavourings.
[11] Ghidotti, M., Papoci, S., Dumitrascu, C., Zdiniakova, T., Fiamegos, Y., & de la Calle Gutiñas, M.B. (2021). ED-XRF as screening tool to help customs laboratories in their fight against fraud. State-of-the-art. *Talanta Open*, 3, article number 100040. doi: 10.1016/j.talo.2021.100040.
[12] Grainger, A. (2024). Customs tariff classification and the use of assistive technologies. *World Customs Journal*, 18(1), 3-32. doi: 10.55596/001c.116525.
[13] Houssini, K., Li, J., & Tan, Q. (2025). Complexities of the global plastics supply chain revealed in a trade-linked material flow analysis. *Communications Earth & Environment*, 6, article number 257. doi: 10.1038/s43247-025-02169-5.
[14] Intertek. (n.d.). *Fourier transform infrared spectroscopy analysis of polymers and plastics*. Retrieved from https://www.intertek.com/polymers-plastics/analysis-ftir/.
[15] ISO/IEC 17025:2017. (2017). *General requirements for the competence of testing and calibration laboratories*. Retrieved from https://www.iso.org/standard/66912.html.
[16] Liu, Y., Zuo, P., & Yuan, X. (2025). Research on the current situation and development of grassroots customs laboratories. *Engineering Advances*, 5(4), 152-154. doi: 10.26855/ea.2025.10.004.
[17] Magai, P.S., & Ilomo, M. (2024). Revisiting the effect of the EAC customs union on intra-regional trade performance: Does it only matter for exports? *Cogent Economics & Finance*, 12(1), article number 2363458. doi: 10.1080/23322039.2024.2363458.
[18] Makedon, V., Myachin, V., Aloshyna, T., Cherniavska, I., & Karavan, N. (2025). Improving the readiness of enterprises to develop sustainable innovation strategies through fuzzy logic models. *Economic Studies*, 34(5), 165-179.
[19] Makedon, V., Trachova, D., Myronchuk, V., Opalchuk, R., & Davydenko, O. (2024). The development and characteristics of sustainable finance. In A. Hamdan (Ed.), *Achieving sustainable business through AI, technology education and computer science* (Vol. 163, pp. 373-382). Cham: Springer. doi: 10.1007/978-3-031-73632-2_31.

[20] Marinova, V. (2024). Artificial intelligence in customs. *Izvestia Journal of the Union of Scientists – Varna. Economic Sciences Series*, 13(1), 253-263. doi: 10.56065/IJUSV-ESS/2024.13.1.253.
[21] Mikuriya, K. (2021). *SAFE Framework of Standards 2021*. Brussels: World Customs Organization.
[22] Oluwagbade, E. (2025). Customs and code: Integrating algorithmic classification into global trade compliance systems. *Research Gate*. Retrieved from https://www.researchgate.net/publication/392402797_Customs_and_Code.
[23] Ozturk, O. (2024). The impact of AI on international trade: Opportunities and challenges. *Economies*, 12(11), article number 298. doi: 10.3390/economies12110298.
[24] Petrukha, S., Petrukha, N., Alekseienko, N., Mazur, A., & Maltsev, M. (2022). The post-war potential and regulatory capacity of rural territorial communities in the clustering and integrating agri-food chains of local added value creation. In *Modern foundations of economics, management and tourism* (pp. 96-126). Boston: International Science Group; Primedia eLaunch. doi: 10.46299/ISG.2022.MONO.ECON.4.3.1.
[25] Protocol Amending the Marrakesh Agreement Establishing the World Trade Organization. Agreement on Trade Facilitation. (2014, November). Retrieved from https://www.wto.org/english/docs_e/legal_e/downloads_e/TFA_en.pdf.
[26] Punda, O., & Arziantseva, D. (2019). Development of the system of customs examinations in Ukraine in the context of compliance with the requirements of the European Union. *University Scientific Notes*, 4, 106-117. doi: 10.37491/UNZ.72.11.
[27] Regulation (EU) No. 952/2013 of the European Parliament and of the Council laying down the Union Customs Code. (2013, October). Retrieved from https://eur-lex.europa.eu/eli/reg/2013/952/oj/eng.
[28] The Customs Code of Ukraine No. 4495-VI. (2012, March). Retrieved from https://zakon.rada.gov.ua/laws/show/4495-17?lang=en#Text.
[29] Vijayakumar, S. (2025). Technology-centric and data-driven customs risk management for supply chain security. *World Customs Journal*, 19(1), 38-63. doi: 10.55596/001c.131745.
[30] World Customs Organization. (2022). *Customs laboratory guide*. Retrieved from https://www.wcoomd.org/en/media/newsroom/2022/january/the-hs-2022-version-of-the-customs-laboratory-guide-is-now-available.aspx.
[31] World Customs Organization. (2023). *Research & policy note on Generative Artificial Intelligence for customs*. Retrieved from https://www.wcoomd.org/-/media/wco/public/global/pdf/topics/research/papers/researchpolicynote_genai_en_06122023.pdf.
[32] Zhao, Y., Kim, T.Y., & Hwang, B.-S. (2025). Improving customs clearance bottleneck in the Chinese B2C import cross-border e-commerce: Extending sampling methods by two stages. *Humanities and Social Sciences Communications*, 12, article number 1001. doi: 10.1057/s41599-025-05261-5.

Удосконалення методів товарознавчої експертизи на етапі митного контролю

Олена Пахолюк
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-3484-0468
Андрій Дзюбинський
Кандидат економічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0001-5156-9852
Галина Голодюк
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-9740-5498
Оксана Передрій
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-5464-2020
Тетяна Ярошевич
Кандидат технічних наук, доцент
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0001-8003-0514

Анотація. В умовах зростання міжнародних торговельних потоків, інтенсифікації митних процедур та посилення ризиків контрабанди й фальсифікації товарів, особливого значення набуває удосконалення методів товарознавчої експертизи на етапі митного контролю. Метою статті стало наукове обґрунтування та розробка пропозицій щодо удосконалення методів товарознавчої експертизи на етапі митного контролю шляхом інтеграції сучасних інструментальних, цифрових і аналітичних технологій. Цей процес передбачав підвищення точності, швидкості та об'єктивності експертних процедур, гармонізацію національних методик з міжнародними стандартами та створення передумов для ефективнішого функціонування системи митного контролю в Україні. Ефективність і точність експертних процедур визначили рівень економічної безпеки держави, забезпечили прозорість зовнішньоекономічних операцій та сприяли захисту внутрішнього ринку. Проте, наявні методи експертизи не завжди відповідали вимогам оперативності, достовірності та адаптивності до нових викликів, що актуалізувало потребу у впровадженні інноваційних підходів. У дослідженні обґрунтовано можливості вдосконалення товарознавчої експертизи на етапі митного контролю шляхом використання інструментальних і цифрових технологій, здатних суттєво підвищити результативність експертних процедур. Проведено систематизацію сучасних методів експертного аналізу та оцінено їх відповідність завданням митного контролю, а також визначено перспективи застосування цифрових рішень і штучного інтелекту в аналітичних процесах. Сформовано комплекс практичних рекомендацій щодо узгодження національних підходів із міжнародними стандартами. Запропоновано створення єдиної електронної бази даних зразків товарів, використання мобільних лабораторій та розроблення стандартів, адаптованих до глобальних вимог, що сприятиме підвищенню ефективності митного контролю та розширенню інтеграційних можливостей України у світовій торгівлі. Практичне значення дослідження полягає у можливості застосування його результатів для модернізації системи митного контролю, оптимізації роботи митних лабораторій, удосконалення електронних баз даних і впровадження міжнародно узгоджених методів експертизи, що підсилить економічну безпеку держави та стимулюватиме розвиток зовнішньої торгівлі

Ключові слова: стандарт; мито; товарознавча оцінка; регулювання; цифровізація

COMMODITY BULLETIN
Journal homepage: https://c-bulletin.com.ua/en
DOI: 10.62763/cb/2.2025.53

Article's History: Received: 04.08.2025 Revised: 17.11.2025 Accepted: 26.12.2025 Published: 02.01.2026

ISSN 2310-5283; e-ISSN 3041-1432 Vol. 18, No. 2, 2025, 53-67

UDC 664.6:664.8.03:676

Moisture loss of bread in different packaging materials and the potential of flax-based materials

Svitlana Yaheliuk*

Doctor of Technical Sciences, Professor
Lutsk National Technical University
43018, Lvivska Str., 75, Lutsk, Ukraine
https://orcid.org/0000-0002-7428-0848

Vladyslav Chasnikov

Postgraduate Student
Lutsk National Technical University
43018, Lvivska Str., 75, Lutsk, Ukraine
https://orcid.org/0009-0004-4008-9502

Abstract. The accumulation of plastic waste, particularly from single-use food packaging, poses a significant environmental challenge, making it essential to explore alternative, sustainable packaging materials to reduce ecological impact and preserve product quality. The aim of the study was to comparatively evaluate the effectiveness of paper, biopolymer, polypropylene and experimental non-woven flax packaging in preserving the freshness of wheat and rye bread using weight loss as an indicator of moisture exchange. The paper analysed the environmental burden in Ukraine caused by the use of polymer materials in the baking industry, where packaging consumption reaches about 9 billion units annually. It has been experimentally established that polypropylene film provides the highest barrier properties, maintaining stable weight and high organoleptic indicators for 7 days. Traditional paper packaging proved to be the least effective due to high vapour permeability, leading to a loss of up to 21% of moisture and rapid staling of products. Biopolymer bags demonstrated the ability to retain moisture only for a short period (up to 3 days), after which their protective properties decrease significantly. As an environmentally safer and functional alternative, paper made from oil flax cellulose can be considered promising. Due to the dense structure of long fibres and the presence of natural antiseptic compounds (lignans), such packaging may help extend bread freshness while aligning with the principles of the circular economy. The practical value of the study lies in the scientific justification of the selection of biodegradable packaging materials based on flax cellulose for bakery products, which can be applied in the food industry to reduce plastic waste while maintaining product quality

Keywords: bakery products; staling kinetics; shelf life; biodegradable materials; flax cellulose; organoleptic quality; barrier properties

Introduction

The global community faces one of the major environmental challenges – the accumulation of persistent plastic waste, which has a long-term and often irreversible impact on the environment and human health. S. Perreard *et al.* (2025) indicated continued growth in global plastic waste (from 205 million tons in 2021 to 225 million tons by 2025), highlighting the urgent need for circular economy strategies. According to a press re-

Suggested Citation:
Yaheliuk, Ya., & Chasnikov, V. (2025). Moisture loss of bread in different packaging materials and the potential of flax-based materials . *Commodity Bulletin*, 18(2), 53-67. doi: 10.62763/cb/2.2025.53.

*Corresponding author

lease by the UN Environment Programme (UNEP, 2023), plastic pollution could be reduced by 80% by 2040 if countries and companies implement deep policy and market changes using existing technologies. Supporting this transition, N.M. Samoilenko & Yu.S. Hadayeva (2025) explored current aspects of the development and use of biopolymer materials for single-use packaging, which represents a critical technological shift towards more sustainable and environmentally friendly alternatives. The authors concluded that despite the high potential of polylactic acid (PLA) and its composites, their immediate large-scale implementation is hindered by underdeveloped infrastructure for collection and composting, higher production costs compared to traditional plastics, and certain performance limitations, which necessitates the development of advanced materials using agricultural waste and nanotechnology.

Polymer materials used for bread packaging predominantly enter municipal solid waste streams after short service life, creating an environmental burden. According to the "Consumer basket", the average annual consumption of bakery products in Ukraine is 98.4 kg per person. Data from the State Statistics Service of Ukraine (2022) indicated that with a population of approximately 41.17 million people, the total annual volume of bakery product consumption exceeded 4 million tons. Assuming that the average mass of one bread unit is approximately 0.45 kg, this volume corresponds to the need to package about 9 billion packaged units per year. Such a mass scale causes a consistently high demand for single-use packaging materials, which, in the event of plastic dominance, leads to the generation of thousands of tons of non-degradable polymer waste and necessitates the urgent search for alternative eco-friendly materials.

Bakery products are an important focus of food packaging research due to their high consumption and sensitivity to environmental conditions. M. Aravindan *et al.* (2022) summarised key trends in regulating moisture exchange to inhibit microbiological spoilage, confirming that freshness loss in bread begins in the first hours after baking and is largely determined by the barrier properties of the packaging material. The process of bread staling is a multifaceted phenomenon primarily driven by starch retrogradation and the continuous redistribution of moisture, which significantly impacts the shelf life and structural integrity of the final product. Y. Zhang *et al.* (2024) further elucidated these mechanisms by evaluating the effects of wheat oligopeptides on the baking and retrogradation properties of bread rolls. Their research specifically focused on the evaluation of crumb hardness, moisture content, and starch crystallisation, demonstrating that maintaining a stable moisture balance is crucial for suppressing the formation of starch crystals during storage. T. Mohammadi-Moghaddam *et al.* (2024) provide a comprehensive review of bread staling, emphasising that moisture migration and redistribution are pivotal factors in the deterioration of bread texture and quality during storage.

Traditional polymer materials provide high barrier properties but create a significant environmental burden. V. Kumar *et al.* (2022) experimentally confirmed that polypropylene film demonstrated superior moisture barrier performance and mechanical structural integrity compared to other polymer films used in food packaging, establishing it as the most functionally effective conventional option. Conversely, paper packaging, while eco-friendly, faces limitations due to its capillary-porous structure. N.M. Samoilenko & Yu.S. Hadayeva (2025) explored biopolymer materials, noting their potential for single-use packaging despite current limitations in food quality impact studies. The rational use of plant residues as raw materials is becoming a critical technological shift. S. Yaheliuk *et al.* (2022) conducted comprehensive research on the identification and classification of crop residues for industrial use. Agricultural crops, specifically oil flax stalks, are valuable sources of cellulose for biodegradable materials.

Modern literature indicates that mechanisms of bread staling and packaging barrier properties are often studied separately. Experimental comparative studies evaluating the influence of different packaging types on bread mass loss and sensory quality under identical storage conditions remain limited. This gap justifies the relevance of the present research. The aim of this study was to experimentally evaluate bread mass loss and organoleptic changes during storage in different packaging materials as indicators of moisture exchange, and to outline the prospects of plant-based packaging concepts derived from flax processing residues.

Materials and Methods

The research objects were industrially produced bakery products of the Kyivkhlib brand. Two types of bread were selected for the study: rye bread "Domashnii Zhitnii"; wheat bread "Baton Molochnyi". The product characteristics, physical and chemical indicators (moisture, acidity, porosity), nutritional value, composition, storage conditions, and organoleptic indicators of the products studied are presented in Table 1.

Four types of packaging materials were used in the study: paper packaging sealed with starch paste; polypropylene film; and a biodegradable biopolymer bag, experimental non-woven oil flax material. Paper packaging was a capillary-porous material characterised by high air and water vapour permeability. For this study, sealing was performed using starch paste. Polypropylene film was a non-porous polymer material with low water vapour permeability. The biodegradable biopolymer bag was a polymer material with moderate barrier properties. Experimental non-woven oil flax material was a fibrous substrate produced from oil flax processing residues. This material was characterised by a porous structure and a specific surface density, which facilitates moisture and gas exchange. The material contained natural phenolic compounds, including lignans, inherent to the fibre source. An alphanumeric coding system was utilised for sample identification. The initial letter or combination signified the packaging material: P – paper, B – biopolymer, PL – polypropylene, and NF – experimental non-woven flax fibre. The subsequent letter indicates the bread variety: R – rye and W – wheat.

Table 1. *Main characteristics of "Molochnyi" loaf and "Domashnii Zhytnii" rye bread*

Type of bread	Milk loaf, sliced	Homemade rye bread
Photo		
Shelf life	3 days	5 days
DSTU standard	DSTU 4587:2023	DSTU 4583:2023
Physicochemical parameters according to DSTU	Crumb moisture content, %, not more than 34.0-45.5 Crumb acidity, degrees, not more than 3.5 Crumb porosity, %, not less than 68.0	Crumb moisture content, %, not more than 41.0-53.0 Crumb acidity, degrees, not more than 5.0–12.0 Crumb porosity, %, not less than 46.0
Manufacturer	TM "Kyivkhlib"	TM "Kyivkhlib"
Ingredients	Premium-grade wheat flour, drinking water, sugar, baker's yeast, table salt, skimmed milk powder 0.9%, dry milk whey 0.9%, table margarine, flour improver (contains wheat flour), acidity regulator: lactic acid	Wholemeal rye flour 41.6%, drinking water, first-grade wheat flour, dry fermented rye malt 3.4%, sugar, sifted rye flour 2.4%, table salt, compressed yeast
Nutritional value	Energy value per 100 g: 1146 kJ / 270 kcal Fats: 1.5 g – of which saturated 0.3 g Carbohydrates: 55 g – of which sugars 5.2 g Dietary fibre: 2.6 g Proteins: 8.1 g Salt: 1.1 g	Energy value per 100 g: 990 kJ / 234 kcal Fats: 1.2 g – of which saturated 0.1 g Carbohydrates: 45 g – of which sugars 4.3 g Dietary fibre: 7.3 g Proteins: 7.2 g Salt: 1.2 g
Storage conditions	>+6°C <+28°C	>+6°C <+28°C
Organoleptic characteristics	Shape: elongated, regular Surface: smooth, without burnt areas Crust colour: light golden Crumb: soft, tender, fine-porous, white Taste and aroma: slightly sweet, with a pronounced milky flavour, without off-odours	Shape: elongated, regular Surface: even, without cracks Crust colour: dark brown Crumb: elastic, evenly porous, dark Taste and aroma: characteristic of rye bread, with a slight sourness, without foreign tastes or odours

Source: *compiled by the authors based on data from Kyivkhlib (n.d.a; n.d.b) and DSTU 4583:2023 (2023), DSTU 4587:2023 (2023)*

Three separate bread samples were prepared for each bread–packaging combination and assigned to different storage periods (1, 3, and 7 days). Separate samples were therefore used for each storage period and each type of packaging. All experiments were conducted in triplicate, and the values presented in the tables represent average values of three independent measurements. The samples were coded according to the type of bread, packaging material, and storage time. Rye bread samples in paper packaging were labelled as PR1, PR3, and PR7; in biopolymer packaging as BR1, BR3, and BR7; in polypropylene packaging as PLR1, PLR3, and PLR7; and in experimental non-woven flax packaging as NFR1, NFR3, and NFR7. Similar labelling was used for wheat bread: PW1, PW3, and PW7 – paper packaging; BW1, BW3, and BW7 – biopolymer packaging; PLW1, PLW3, and PLW7 – polypropylene packaging; and NFW1, NFW3, and NFW7 – non-woven flax packaging. The number in the sample code indicates the storage duration in days. Each sample was weighed and evaluated once after the corresponding storage period.

All samples were stored at a constant temperature of 12°C in a room without direct sunlight. The storage conditions complied with the manufacturer's recommendations. All samples were packaged under identical conditions immediately after purchase. The condition of the bread was assessed after 1 day; after 3 days; after 7 days of storage, which allowed the dynamics of weight loss and organoleptic changes to be tracked. Changes in bread moisture content were assessed indirectly by periodically weighing samples on electronic scales. Since weight loss during storage occurs mainly due to water evaporation, the shrinkage index was taken as an indicator of moisture loss. For paper packaging, additional weight loss associated with the drying of starch paste was taken into account. For the organoleptic evaluation of bread samples, a 5-point scale was used for each indicator. Each quality indicator has five levels, expressed in points as follows: 5 – excellent quality; 4 – good quality; 3 – satisfactory quality; 2 – unsatisfactory quality; 1 – poor quality (DSTU 9188:2022, 2022).

Evaluated indicators:

- mass loss: weight change (in grams and percent) as the main indicator of moisture loss. For paper packaging, the following measurements were made relative to the weight recorded after the paste dried on day 1;
- organoleptic indicators: softness/hardness, aroma, presence of mould.

Statistical analysis was applied to the experimental data to evaluate differences in bread quality parameters across packaging types and storage periods. To quantitatively assess changes in the moisture content of rye bread during storage in different types of packaging, statistical processing of experimental data was performed. The mean weight loss and standard deviation of the samples were determined. The arithmetic method was calculated as the sum of the weight loss values divided by the number of samples in the respective series. The standard deviation was determined using the formula:

$$s = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}, \quad (1)$$

where x_i – the individual value of mass loss, $\bar{x}$ – the average value, n – the number of samples. This evaluation approach made it possible to compare the effectiveness of the tested packaging materials in preserving bread quality during storage.

Results

The results of the experiment were analysed with regard to packaging type, bread type, and storage duration. Changes in the weight of bread slices during storage were measured directly. Since the main reason for weight reduction in bakery products is water evaporation, weight change was considered an indirect indicator of moisture loss. The visual appearance and weighing results of the rye bread control samples after 1 day of storage in different types of packaging are presented in Figure 1.

BR1 Packaging type: Biopolymer bag Type of bread: **Rye**	**PLR1** Packaging type: Polypropylene film Type of bread: **Rye**	**PR1** Packaging type: Paper bag Type of bread: **Rye**	**NFR1** Packaging type: Experimental non-woven flax packaging Type of bread: **Rye**

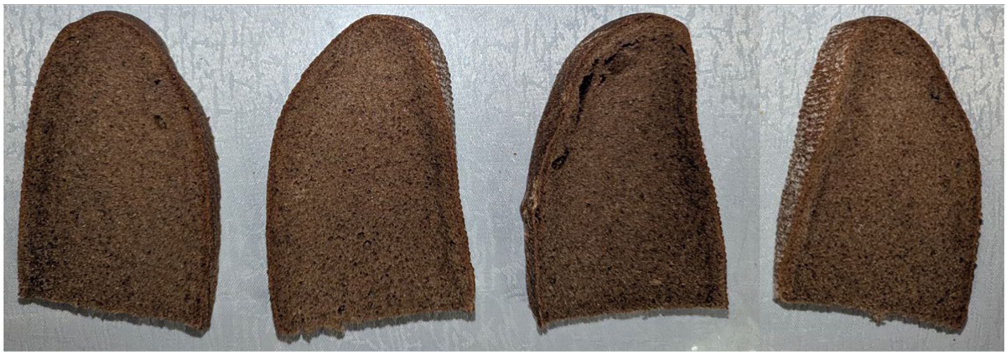

Figure 1. *Samples of rye bread after 1 day of packaging*

Source: *compiled by the authors*

Paper packaging (PR1) showed an 11.3% mass loss (5 g) due to the porosity of the material and the drying out of the gelatinised starch. Intense moisture evaporation led to lower ratings for aroma (4 points) and crumb condition (4 points), which corresponds to good quality with initial signs of loss of softness. Biopolymer packaging (BR1) showed zero weight loss (0%), ensuring complete moisture retention inside. High airtightness allowed the product to retain its excellent quality: the aroma and crumb condition were rated at 5 points, with no signs of staling. Polypropylene packaging (PLR1) also eliminated moisture loss (0%), ensuring the stability of physical and chemical properties. The sample received the highest scores for aroma (5 points) and crumb (5 points), noting maximum elasticity and the most pronounced aroma of fresh bread. Experimental flax packaging (NFR1) showed moderate moisture loss – 5.2% (2 g), which was lower than in paper packaging but higher than in hermetic polymer materials. The breathable structure of the non-woven flax material allowed partial moisture exchange with the environment, preventing excessive condensation inside the package. Despite some dehydration, the sample retained good sensory quality: the aroma was rated at 4 points and the crumb condition at 5 points, indicating excellent crumb elasticity and acceptable freshness at this stage of storage. The visual appearance and weighing results of the rye bread control samples after 3 days of storage in different types of packaging are presented in Figure 2.

The paper packaging (PR3) showed a 12.5% loss in weight (4 g) compared to the weight after 24 hours, when the paste dried, which led to significant staling due to intense dehydration, although the sample remained less hard than the wheat counterpart. There was no mould, but due to drying, the aroma became faint (3 points – satisfactory quality), and the crumb lost its elasticity and became hard (2 points – unsatisfactory quality). The biopolymer bag (BR3) ensured moderate softness despite a 10% loss in weight (4 g). The sample did not show critical staling and showed no signs of mould, although its elasticity was slightly inferior to that of the fresh product: the aroma was rated at 4 points, and the condition of the crumb at 4 points, which corresponds to good quality. The polypropylene film (PLR3) demonstrated absolute weight stability (0% loss), which allowed the moisture inside to be completely preserved. The bread retained maximum softness, no mould, and the most pronounced aroma, receiving the highest scores – 5 points (excellent quality) for both indicators. The experimental flax packaging (NFR3) demonstrated moderate moisture loss – 10% (4 g) after 3 days of storage. The breathable structure of the non-woven flax material provided limited resistance to moisture migration over time, resulting in gradual dehydration of the bread. Nevertheless, the material prevented excessive moisture accumulation and condensation inside the package. The aroma and crumb condition were rated at 3 points (satisfactory quality), indicating noticeable staling and loss of softness, although the bread remained acceptable for consumption and did not show signs of mould development. The visual appearance and weighing results of the rye bread control samples after 7 days of storage in different types of packaging are presented in Figure 3.

PLR3 Packaging type: Polypropylene film Type of bread: **Rye**	**BR3** Packaging type: Biopolymer bag Type of bread: **Rye**	**PR3** Packaging type: Paper bag Type of bread: **Rye**	**NFR3** Packaging type: Experimental non-woven flax packaging Type of bread: **Rye**

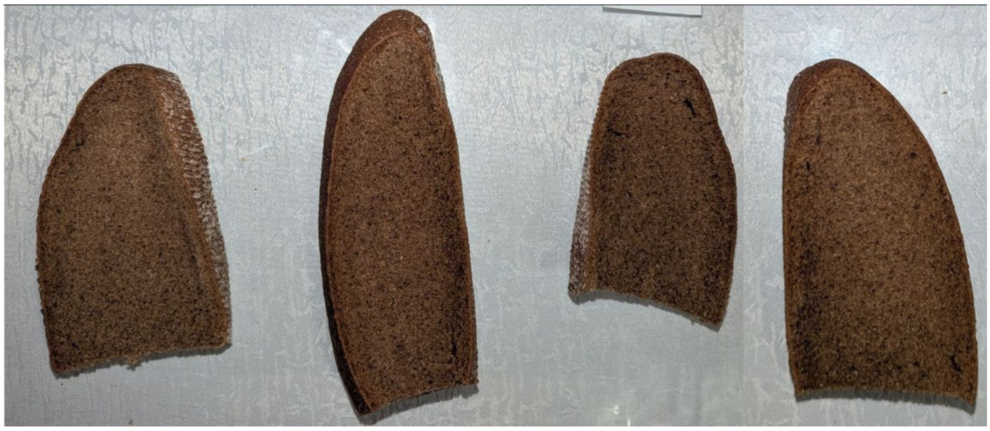

Figure 2. *Samples of rye bread after 3 days of packaging*

Source: *compiled by the authors*

PR7 Packaging type: Paper bag Type of bread: **Rye**	**BR7** Packaging type: Biopolymer bag Type of bread: **Rye**	**PLR7** Packaging type: Polypropylene film Type of bread: **Rye**	**NFR7** Packaging type: Experimental non-woven flax packaging Type of bread: **Rye**

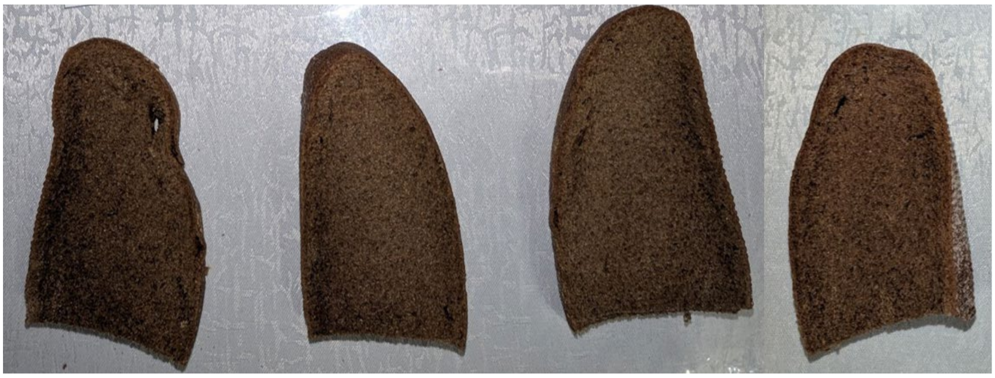

Figure 3. *Samples of rye bread after 7 days of packaging*

Source: *compiled by the authors*

In paper packaging (PR7), the sample almost completely lost its consumer properties due to critical dehydration: its weight decreased by 21% (8 g). The sample became very hard and resembled a cracker-like structure, which corresponds to a crumb condition rating of 1 point (poor quality). The aroma became barely noticeable, although there were no foreign impurities (1 point – poor quality), and there was no mould. In a biopolymer bag (BR7), the sample showed a significant loss of mass – 20% (7 g), which led to the product becoming stale. However, compared to paper packaging, the bread did not become as hard, and its aroma was preserved somewhat better (3 points for aroma – satisfactory quality). The condition of the crumb due to significant moisture loss and starch retrogradation was rated at 2 points (unsatisfactory quality), no signs of mould were found. Polypropylene film (PLR7) proved to be the most effective, recording a minimal weight loss of only 2.7% (1 g). Due to its high moisture content, the bread remained acceptable for consumption, retaining relative softness and the most pronounced aroma among all samples. The organoleptic indicators of aroma and crumb condition remain at 4 points (good quality), no signs of microbiological spoilage were recorded. Experimental non-woven flax packaging (NFR7) demonstrated intermediate performance after 7 days of storage. The sample showed weight loss of 16.3% (7 g), indicating gradual dehydration due to the breathable structure of the material. Compared to paper packaging, the bread did not reach a critically dry, cracker-like structure, but significant staling occurred. The aroma and crumb condition were rated at 2 points (unsatisfactory quality), indicating noticeable loss of sensory and structural properties. The bread had partially lost its characteristic smell and had become noticeably hard, although no mould development was observed. These results indicate that flax packaging provides moderate moisture retention but does not prevent staling during prolonged storage.

The quantitative data regarding mass loss (as an indicator of moisture dynamics) and the organoleptic evaluation of rye bread samples over the seven-day storage period across different packaging types are summarised in Table 2.

Table 2. *Dynamics of weight change (as an indicator of moisture loss) and organoleptic indicators of rye bread over 1, 3 and 7 days depending on packaging*

Indicator	PR1	PR3	PR7	BR1	BR3	BR7	PLR1	PLR3	PLR7	NFR1	NFR3	NFR7
Initial weight, g	44/39*	37/32*	43/38*	37	40	35	39	36	37	38	40	43
Weight after storage, g	39	28	30	37	36	28	39	36	36	36	36	36
Moisture loss (weight loss), g	5	4	8	0	4	7	0	0	1	2	4	7
Aroma, points	4	3	1	5	4	3	5	5	4	4	3	2
Crumb texture, points	4	2	1	5	4	2	5	5	4	5	3	2

Note: **weight loss in paper packaging after 1 day is due to the drying of the paste. Abbreviations: PR1, PR3, PR7 – rye bread stored in paper packaging for 1, 3 and 7 days, respectively; BR1, BR3, BR7 – rye bread stored in biopolymer packaging for 1, 3 and 7 days, respectively; PLR1, PLR3, PLR7 – rye bread stored in polypropylene packaging for 1, 3 and 7 days, respectively; NFR1, NFR3, NFR7 – rye bread stored in experimental non-woven flax packaging for 1, 3 and 7 days, respectively. Separate samples were used for each storage period*

Source: *compiled by the authors based on experimental data*

The statistical analysis of moisture dynamics for rye bread was conducted based on the experimental data presented in Table 2. At the initial stage of storage (after 1 day), the average values obtained from three independent measurements were analysed. In these cases, the average weight loss was 0 g for biopolymer and polypropylene packaging and moderate for flax packaging with a standard deviation of $s = 0$ g. A zero standard deviation indicates a complete absence of variability within the sample at this stage: both materials demonstrated high airtightness and completely eliminated moisture loss during the first 24 hours. Paper packaging was not included in the statistical analysis after 1 day due to additional mass loss associated with paste drying rather than only moisture migration. Therefore, the statistical comparison was performed starting from the 3-day storage period.

The comparative analysis confirmed a significant gradient in dehydration intensity depending on the barrier properties of the material. Paper packaging exhibited the highest intensity of moisture loss, with an average weight reduction of 4.5 g, which is attributed to its high vapour permeability and capillary-porous structure. Biopolymer packaging demonstrated intermediate performance with an average loss of 3.5 g, while polypropylene film remained the most effective barrier, limiting the average moisture loss to only 0.5 g. Experimental flax packaging demonstrated intermediate behaviour between paper and biopolymer materials due to its porous but thicker fibre structure, which provided controlled moisture exchange with the environment. The calculated standard deviation (s) is identical for all considered packaging types at this stage. This uniform level of dispersion indicates a consistent and predictable rate of moisture migration within the rye bread crumb across the different samples. The transition from a zero deviation on the first day to $s \approx 0.71$ g on the third day suggests the onset of active moisture redistribution processes, although the variations remain minimal. Ultimately, these results underscore that while the absolute moisture retention capacity differs drastically by material, the internal dynamics of staling in rye bread follow a stable structural pattern during the middle storage period. The visual appearance and weighing results of the wheat bread control samples after 1 day of storage in different types of packaging are presented in Figure 4.

Figure 4. *Samples of wheat bread after 1 day of packaging*
Source: *compiled by the authors*

Paper packaging (PW1) showed a 14.3% mass loss (4 g) after 1 day due to the porosity of the material and the drying out of the gelatinised starch. Intense moisture evaporation led to lower ratings for aroma (3 points) and crumb condition (3 points), which corresponds to satisfactory quality with noticeable loss of softness and a perceptible reduction in freshness at this early stage of storage. Despite this, the aroma was rated at 3 points (satisfactory quality) and the crumb condition also at 3 points (satisfactory quality), suggesting that wheat bread proved more susceptible to detectable quality change than rye bread under the same packaging conditions at this early stage.

The biopolymer bag (BW1) ensured complete preservation of the initial weight (0% loss), which prevented staling at the initial stage. The condition of the crumb and the aroma received 4 points (good quality), as the product retained its softness and pleasant aroma, which was noticeably more intense than in paper packaging. Polypropylene film (PLW1) showed the best results: there was no change in weight (0%), thanks to which the bread retained a condition as close as possible to freshly baked. The aroma and softness indicators received the highest rating – 5 points (excellent quality), the product was characterised by a pronounced aroma and the highest elasticity of the crumb among all the samples studied. Experimental flax packaging (NFW1) demonstrated moderate moisture loss after 1 day of wheat bread storage. The sample lost 4.0% of its initial weight (1 g), which was significantly lower than that of paper packaging and comparable to the results obtained for biopolymer packaging. The breathable structure of the non-woven flax material allowed limited moisture exchange with the environment, preventing both excessive drying and moisture accumulation inside the package. The aroma and crumb condition were rated at 4 points (good quality), indicating that the packaging provided sufficient protection and preserved the sensory and structural properties of the wheat bread at this stage of storage. The visual appearance and weighing results of the wheat bread control samples after 3 days of storage in different types of packaging are presented in Figure 5.

In paper packaging (PW3), the weight decreased by 4.5% (1 g) relative to the indicators after the paste dried. Despite the relatively small loss of mass compared to rye bread, which is explained by the lower initial moisture content of the loaf, the product became very dry and brittle. The aroma completely disappeared (2 points – unsatisfactory quality), and the crumb became hard and brittle (2 points – unsatisfactory quality), with no mould. The biopolymer bag (BW3) showed a significant loss of mass – 12.5% (3 g), which led to a noticeable deterioration in texture. The product became stale at the edges, although the central part of the crumb still retains its ability to deform (3 points – satisfactory quality). The bread aroma was only partially preserved (2 points – unsatisfactory quality), no signs of microbiological spoilage were found. Polypropylene film (PLW3) provided the best quality preservation, despite a slight weight loss of 4.5% (1 g). The bread remains quite soft (5 points – excellent quality) and retains the active pleasant aroma of a fresh product (5 points – excellent quality), with no signs of mould. Experimental non-woven flax packaging (NFW3) demonstrated moderate moisture loss after 3 days of wheat bread storage. The sample showed a 7.4% weight loss (2 g), indicating gradual moisture migration through the breathable structure of the non-woven flax material. Compared to paper packaging, the bread did not become as dry and brittle, although noticeable staling occurred. The aroma and crumb condition were rated at 3 points (satisfactory quality), indicating a perceptible reduction in freshness and crumb elasticity; however, the bread remained acceptable for consumption at this stage of storage. No mould development was observed. The visual appearance and weighing results of the wheat bread control samples after 7 days of storage in different types of packaging are presented in Figure 6.

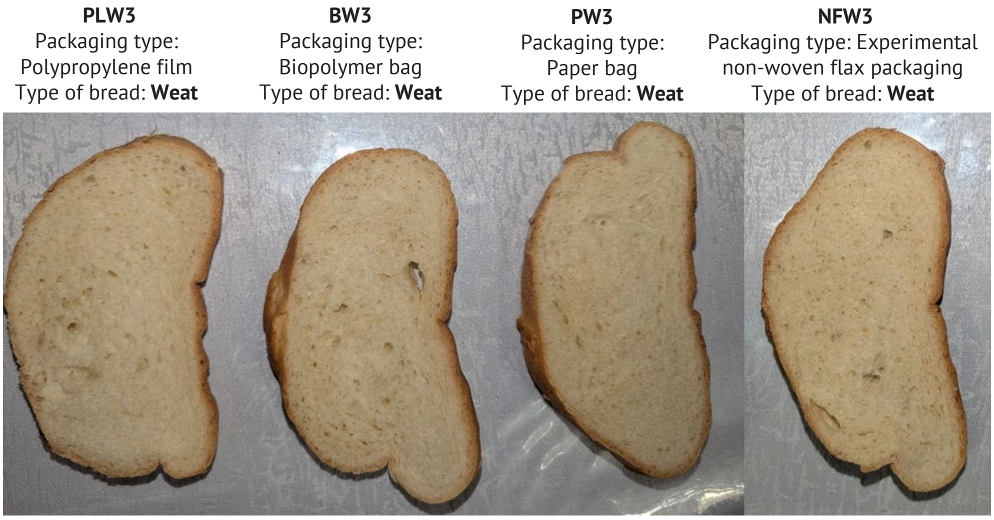

Figure 5. *Samples of wheat bread 3 days after packaging*

Source: *compiled by the authors*

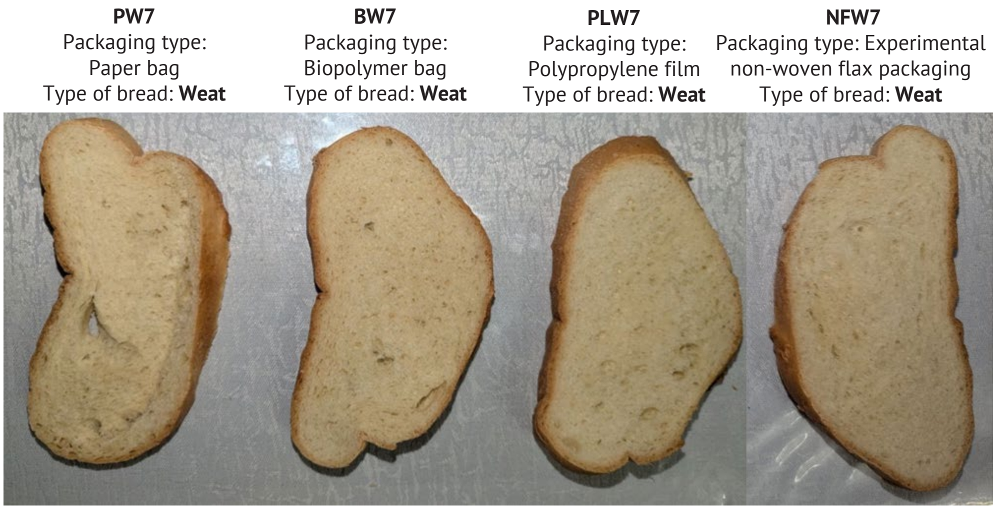

Figure 6. *Samples of wheat bread 7 days after packaging*

Source: *compiled by the authors*

In paper packaging (PW7), a loss of 8.7% of mass (2 g) relative to the stabilised weight was recorded after the paste dried. Due to prolonged moisture exchange with the environment, the product finally turned into a cracker. Organoleptic indicators reached minimum values: there was no aroma (1 point – poor quality), and the crumb became hard and inflexible (1 point – poor quality). No mould was detected. The biopolymer bag (BW7) showed the most intense dehydration – the weight loss was 17.4% (4 g). Despite the presence of a slight bread aroma (2 points – unsatisfactory quality), the condition of the crumb is characterised as "dry," which corresponds to 1 point (poor quality) on the organoleptic evaluation scale. The high vapour permeability of the material at this stage did not provide adequate protection against staling. The polypropylene film (PLW7) once again confirmed its high barrier properties: the weight of the sample did not change (0% loss) throughout the observation period. The bread retained a soft structure suitable for consumption and a pronounced aroma. The condition of the crumb and the aroma were rated at 4 points (good quality), which is the best result among all packaging options on the seventh day. No traces of mould were found. The experimental non-woven flax packaging (NFW7) demonstrated a moderate moisture loss of 8.3% (2 g) after 7 days of storage. Despite relatively moderate dehydration compared to paper and biopolymer packaging, significant staling occurred. The aroma was rated at 2 points (unsatisfactory quality), and the crumb condition declined to 1 point (poor quality), indicating a substantial loss of structural integrity and sensory properties. No mould development was observed during the storage period.

The quantitative data regarding mass loss (as an indicator of moisture dynamics) and the organoleptic evaluation of wheat bread samples over the seven-day storage period across different packaging types are summarised in Table 3.

Table 3. *Dynamics of weight change (as an indicator of moisture loss) and organoleptic indicators of wheat bread over 1, 3, and 7 days depending on packaging*

Indicator	PW1	PW3	PW7	BW1	BW3	BW7	PLW1	PLW3	PLW7	NFW1	NFW3	NFW7
Initial weight, g	28/24*	27/22*	28/23*	22	24	23	24	22	21	25	27	24
Weight after storage, g	24	21	21	22	21	19	24	21	21	24	25	22
Moisture loss (weight loss), g	4	1	2	0	3	4	0	1	0	1	2	2
Aroma, points	3	2	1	4	2	2	5	5	4	4	3	2
Crumb texture, points	3	2	1	4	3	1	5	5	4	4	3	1

Note: **weight loss in paper packaging after 1 day is due to the drying of the paste. Abbreviations: PW1, PW3, PW7 –wheat bread stored in paper packaging for 1, 3 and 7 days, respectively; BW1, BW3, BW7 – wheat bread stored in biopolymer packaging for 1, 3 and 7 days, respectively; PLW1, PLW3, PLW7 – wheat bread stored in polypropylene packaging for 1, 3 and 7 days, respectively; NFW1, NFW3, NFW7 – wheat read stored in experimental non-woven flax packaging for 1, 3 and 7 days, respectively. Separate samples were used for each storage period*

Source: *compiled by the authors based on experimental data*

The results of the statistical analysis showed the stability of the moisture-retaining properties of wheat bread during storage, which was evaluated using the sample standard deviation (*s*). At the initial stage of storage (after 1 day), samples of wheat bread were analysed for paper, biopolymer and polypropylene packaging, as well as for experimental non-woven flax packaging. In the case of polypropylene film, the average weight loss was 0 g with a standard deviation of $s \approx 0$ g. A zero standard deviation indicates a complete absence of variability within the sample at this stage: the material demonstrated high airtightness and completely eliminated moisture loss during the first 24 hours. For biopolymer packaging, the average weight loss was 0.33 g with a standard deviation of $s \approx 0.58$ g (losses for the samples were 0 g, 1 g, and 0 g, respectively). Experimental non-woven flax packaging demonstrated small but measurable moisture loss at this stage, indicating limited moisture exchange due to the breathable structure of the material. Paper packaging was not included in the statistical analysis after 1 day due to additional mass loss associated with paste drying rather than only moisture migration. Therefore, the statistical analysis was continued for the 3-day storage period. The comparative analysis of average values ($\bar{x}$) after three days of storage reveals distinct patterns of dehydration. Biopolymer packaging exhibited the highest intensity of uniform moisture loss, with an average value of 3 g and a standard deviation of *s*. Similarly, paper packaging showed a highly uniform but lower average loss of 1 g (*s*), which is explained by the critical dehydration already reached in the first days, after which further weight change stabilised. Polypropylene film continued to demonstrate the best protective properties with a minimal average loss of 0.5 g and a deviation of $s \approx 0.71$ g, indicating high structural stability and resistance to staling. Experimental non-woven flax packaging demonstrated intermediate average moisture loss values between paper and biopolymer packaging, confirming its moderate barrier properties and controlled moisture permeability. The organoleptic assessment documented in Tables 2 and 3 correlates directly with the physical dynamics of moisture loss. A comparative analysis of Domashnii Zhytnii rye bread and Molochnyi loaf reveals distinct patterns in their staling processes, likely related to the specific structural characteristics of the crumb. In general, the rye samples exhibited higher texture stability and a more gradual decline in softness compared to the wheat loaf, suggesting superior resistance to structural degradation during storage. To provide a clear quantitative visualisation of these changes, the dynamics of weight loss for rye bread (expressed as a percentage of initial mass) are presented in Figure 7.

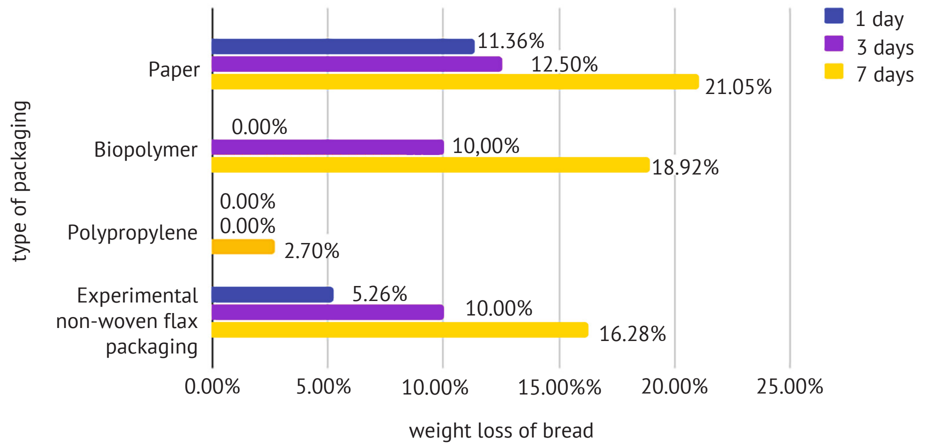

Figure 7. *Dynamics of average weight loss of rye bread in different types of packaging*
Source: *compiled by the authors based on experimental data*

While rye bread showed a more gradual decline in quality, the Molochnyi wheat bread was characterised by a more intense loss of softness and a faster deterioration of aromatic properties, which was already evident in the early stages of storage (Table 3). This accelerated staling is closely associated with a lower initial moisture content and the faster rate of wheat starch retrogradation compared to rye samples. To analyse the physical manifestation of these changes, the dynamics of weight loss for the wheat loaf in different packaging materials are illustrated in Figure 8.

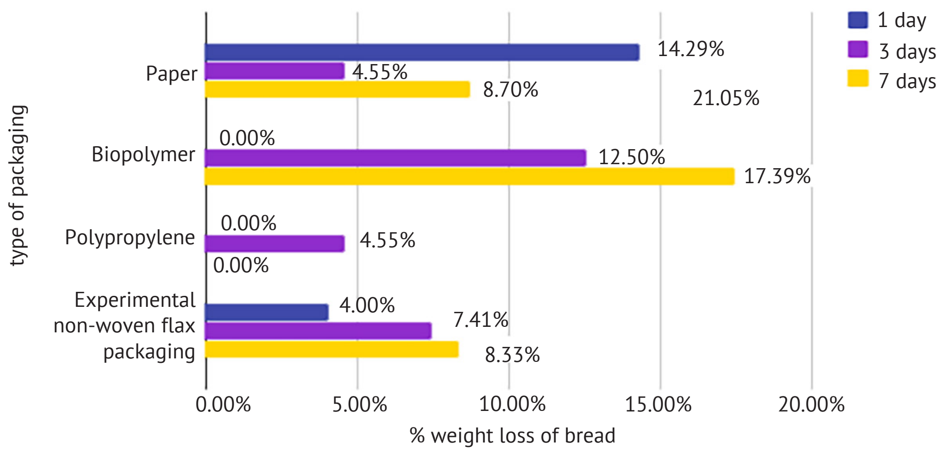

Figure 8. *Dynamics of average weight loss of wheat loaf in different types of packaging*
Source: *compiled by the authors based on experimental data*

The data presented in Figure 7 and Figure 8 confirm that bread type is an important factor in resistance to staling. The marked difference in the rate of loss of consumer properties between the rye and wheat samples is fundamentally rooted in their distinct physical and chemical characteristics. These findings underscore the necessity of accounting for specific recipe components and the structural features of the crumb when assessing aging processes and predicting the shelf life of bread during storage. Ultimately, for both bread types, the choice of packaging – specifically high-barrier materials like polypropylene – remains the primary defence against moisture loss and quality degradation. The results clearly demonstrate a direct correlation between the type of packaging material and the preservation of bread freshness, expressed in minimised weight loss as an indicator of moisture loss.

Paper packaging demonstrated the weakest protective performance across both bread types, a result fully consistent with established knowledge on the capillary-porous structure of cellulose-based materials. As V.A. Osyka *et al.* (2019) established, the microstructural characteristics of paper fibres – specifically their through-pore network – directly limit the material's resistance to water vapour diffusion, accelerating starch retrogradation and staling. The experimental data of the present study confirmed this mechanism: rye bread in paper packaging underwent the most intensive dehydration among all tested materials at both the three- and seven-day timepoints. The contrast with wheat bread was particularly informative from a physicochemical standpoint: wheat bread reached a state of critical dehydration earlier and at lower absolute moisture losses, as its lower initial moisture content was exhausted more rapidly. This differential response between bread types in paper packaging was closely connected to their fundamental compositional differences. Research by T. Alpers *et al.* (2021) comparing rye and wheat bread staling demonstrated that the relative crystallinity of starch in rye sourdough bread increased more slowly than in wheat bread. Additionally, the higher content of non-starch polysaccharides – including pentosans, β-glucan, and arabinoxylan – in rye flour led to higher water-absorbing properties. This provides a structural explanation for the greater moisture-retaining capacity and slower quality decline of rye bread during storage.

Biopolymer packaging exhibited intermediate barrier properties – performing comparably to polypropylene during the first 24 hours but showing substantial moisture migration over the longer term. This pattern of good short-term protection followed by progressive barrier failure aligned with the general limitations attributed to biodegradable packaging materials in the scientific literature. Most biodegradable biopolymers have lower moisture barrier properties than conventional plastics due to their chemical structure, as noted by B. Mishra *et al.* (2024), which places them in an inherently intermediate position between polypropylene and uncoated paper. N.M. Samoilenko & Yu.S. Hadayeva (2025) reached an analogous conclusion, noting that despite the high potential of PLA-based materials, performance limitations in moisture-sensitive food applications remain a critical constraint on their adoption. Across all timepoints, rye bread consistently exhibited greater absolute moisture losses than wheat bread under identical biopolymer packaging conditions, further highlighting the role of bread-intrinsic factors – such as higher initial moisture content and the acidity of rye bread – in modulating the rate of dehydration. Although the biopolymer material demonstrated adequate vapour barrier capacity in the short term, its protective properties deteriorated significantly beyond the three-day threshold, limiting its practical suitability to short retail cycles.

Experimental non-woven flax packaging occupied a position between biopolymer and paper packaging in terms of moisture retention, with notable performance differences between bread types. For wheat bread, its protective capacity was broadly comparable to that of biopolymer packaging, whereas for the more moisture-rich rye bread, losses at the final timepoint approached those observed in the biopolymer variant. The inherent breathability of the non-woven flax substrate, while contributing to moisture exchange with the environment, simultaneously prevented the condensation and humidity accumulation that represents a recognised spoilage risk in hermetically sealed polypropylene packaging. Importantly, no microbiological spoilage was observed in flax-packaged samples across either bread type throughout the experiment – an outcome that may be attributable, at least in part, to the phenolic compounds including lignans present in flax, whose antimicrobial and antioxidant properties have been documented by F. Gai *et al.* (2023). This functional characteristic distinguishes flax-based packaging from conventional synthetic alternatives and is particularly relevant for fresh bakery products, where the balance between moisture retention and microbial safety is critical. The higher inter-sample variability observed for this material, in comparison to the more homogeneous synthetic options, reflected the structural heterogeneity inherent to a first-generation, unoptimised non-woven substrate and indicated that targeted improvements in fibre processing and web density could substantially enhance barrier consistency in subsequent development stages. The experimental non-woven flax packaging, taken as a whole, demonstrated sufficient functional potential to justify continued research as a sustainable short-term bakery packaging material. Its plant-based origin, biodegradable character, and the natural bioactivity of its constituent fibres collectively position it as a candidate for the fresh bread retail segment, where a balance between environmental sustainability and functional adequacy is increasingly required by both regulators and consumers.

Given Ukraine's significant agricultural potential and the possibility of using plant residues as raw materials, flax paper can be considered a promising packaging material for food products, particularly bakery products. Environmental and economic feasibility: oil flax is a renewable agricultural crop with a short growth cycle (1 year versus 30-50 years for trees). Ukraine has a huge amount of unused flax straw, which is a cheap and accessible raw material. Using these residues reduces the cost of packaging and solves the problem of deforestation (Yaheliuk *et al.*, 2022).

Flax-based paper can be considered a promising compromise between breathability and moisture resistance. It may help reduce the disadvantages of conventional plastic and ordinary paper packaging, while contributing to longer freshness preservation and compliance with environmental requirements. The technology for producing biodegradable kraft paper from oilseed flax waste combines affordable Ukrainian raw materials, environmentally friendly processes, and the necessary operational properties, forming a real alternative to plastic for the large-tonnage segment of bakery product packaging. Scaling up such packaging can significantly reduce plastic waste in the bakery product supply chain and provide a resource-saving alternative for high-quality packaging. Other innovative approaches discussed by A. Pasqualone (2019) included modified materials and nanotechnology to reduce moisture loss.

The results of the experiment clearly indicated that the type of packaging material plays a crucial role in preserving the freshness of bakery products and slowing down the staling process. It was found that polypropylene film exhibited the best barrier properties, maintaining the quality of bread throughout the storage period due to its high impermeability. This is consistent with the findings of J. Cheng *et al.* (2024), who emphasised the importance of polymer materials as the most effective barriers to moisture and gases in food packaging. Biopolymer packaging, while effective during the initial stages of storage, failed to maintain its barrier properties over the long term, which aligns with the limitations of such materials when compared to traditional plastics. This is in agreement with the work of A. Panou & I.K. Karabagias (2023), who noted that biopolymers generally exhibit poorer moisture vapour permeability compared to polypropylene, limiting their effectiveness for long-term storage.

Additionally, P.M. Junaid *et al.* (2025) highlighted the need for improvements in biopolymer systems to enhance their functionality, particularly in packaging moisture-sensitive foods. Experimental flax-based packaging, despite high variability between samples due to the material's heterogeneity, showed significant potential for sustainable short-term bakery packaging. Flax packaging also demonstrated promising moisture retention for wheat bread, supporting the findings of S. Roy & J.-W. Rhim (2022), who highlighted the natural antimicrobial properties of flax fibre, which could help in preventing microbial spoilage. The study also demonstrated that the composition of the bread was an important factor in determining the rate of quality loss during storage. Rye bread exhibited better structural stability and slower organoleptic deterioration compared to wheat, which was likely due to the higher content of non-starch polysaccharides in rye flour, providing greater water-binding capacity. Such compositional effects have also been acknowledged in research comparing moisture behaviour in diverse food polymer systems (Venkatesan, 2025).

The obtained results demonstrated that the experimental non-woven oil flax material occupied an intermediate position between conventional paper and biopolymer packaging in terms of moisture retention, while showing no signs of microbiological spoilage throughout the 7-day storage period for both rye and wheat bread. This performance can be partly attributed to the natural phenolic compounds, particularly lignans, present in flax fibres, which are known for their antimicrobial and antioxidant properties. Comparative studies confirm that the choice of packaging material significantly influences moisture migration and the kinetics of bread staling. V. Gigante *et al.* (2023) reviewed innovative cellulose- and lignin-based materials for bread packaging and highlighted that such biobased substrates, despite their inherent porosity, can provide a balanced moisture and gas exchange when properly designed, often outperforming uncoated paper while avoiding excessive condensation typical of highly impermeable synthetic films. An important intrinsic factor modulating these effects is bread composition itself. Rye bread exhibited greater structural stability and slower loss of organoleptic quality compared to wheat bread, consistent with the higher content of non-starch polysaccharides (pentosans, arabinoxylans, and β-glucans) in rye flour, which enhance water-binding capacity and slow starch retrogradation. E. Nordlund *et al.* (2016) demonstrated that these compositional and structural differences lead to distinct disintegration patterns and moisture distribution behaviours between rye and wheat breads, explaining the observed slower staling kinetics in rye samples across all packaging types in the present study. The absence of mould growth in flax-packaged samples is particularly noteworthy. Similar effects have been reported with active cellulose-based materials. N. Noshirvani *et al.* (2017) developed a carboxymethyl cellulose-chitosan-ZnO nanocomposite film that effectively extended bread shelf life by suppressing microbial growth through controlled release of antimicrobial agents while regulating moisture exchange. Their findings support the potential of cellulose-derived matrices enriched with bioactive compounds to simultaneously address moisture loss and microbiological spoilage.

These characteristics – bioactivity, biodegradability, and accessible raw material base – positioned flax-based packaging as a candidate for the short-term fresh bread retail segment, where a balance between environmental sustainability and functional adequacy was increasingly required. Further research focused on standardising substrate structure and evaluating performance under variable storage conditions appeared both scientifically warranted and practically relevant.

Conclusions

Based on the results of the experimental study of the influence of different types of packaging materials on the dynamics of moisture content changes and organoleptic characteristics of rye and wheat bread during 7 days of storage at a temperature of 12°C, the following conclusions were obtained. The type of packaging material was confirmed as a critical determinant of moisture retention and the rate of physical staling in bakery products. The four materials tested formed a clear performance hierarchy, with polypropylene film providing the most effective moisture barrier and conventional paper the least, while biopolymer and experimental non-woven flax packaging occupied intermediate positions with distinct functional profiles. Polypropylene film ensured the highest preservation of both weight and organoleptic quality across the full storage period for both bread types, demonstrating exceptional uniformity and predictability of barrier performance. Its primary limitation was the hermetic character of the material, which may create conditions favouring condensation and microbiological spoilage under elevated temperature or humidity – an aspect that requires further investigation. Paper packaging proved inadequate for storage beyond one to two days, producing the most severe dehydration and complete loss of consumer properties by day 7. Its high vapour permeability accelerated starch retrogradation and led to irreversible structural degradation of the crumb in both bread types. Biopolymer packaging demonstrated adequate short-term protection, effectively comparable to polypropylene within the first 24 hours, but failed to sustain its barrier properties over the longer term.

The experimental non-woven flax packaging, as a first-generation prototype substrate, showed promising results that warranted further research. Despite higher inter-sample variability reflecting the structural heterogeneity of the unoptimised material, it demonstrated functional moisture retention for wheat bread comparable to biopolymer packaging, and recorded no microbiological spoilage across either bread type throughout the experiment. Combined with its biodegradable nature and plant-based origin, these characteristics positioned it as a candidate for sustainable short-term bakery packaging, subject to improvements in substrate homogeneity and fibre processing. The comparative analysis of rye and wheat bread revealed that bread composition was an independent factor influencing the rate of quality loss. Rye bread exhibited greater structural stability and slower organoleptic deterioration, attributable to its higher non-starch polysaccharide content and water-binding capacity, while wheat bread was more sensitive to dehydration due to its lower initial moisture content and faster starch retrogradation. The results obtained provided a scientific basis for the informed selection of packaging materials for fresh bakery products. Further research should focus on improving the structure and processing of flax material to enhance its uniformity and stability, which will significantly improve its barrier properties for extended bread storage.

Acknowledgements
None.

Funding
None.

Conflict of Interest
None.

References
[1] Alpers, T., Kerpes, R., Frioli, M., Nobis, A., Hoi, K.I., Bach, A., Jekle, M., & Becker, T. (2021). Impact of storing condition on staling and microbial spoilage behavior of bread and their contribution to prevent food waste. *Foods*, 10(1), article number 76. doi: 10.3390/foods10010076.
[2] Aravindan, M., Selvam, P., Subramaniyan, V., Subramanian, S., & Sathiavelu, M. (2022). Bread packaging techniques and trends. *Italian Journal of Food Safety*, 11(4), article number 10771. doi: 10.4081/ijfs.2022.10771.
[3] Cheng, J., Gao, R., Zhu, Y., & Lin, Q. (2024). Applications of biodegradable materials in food packaging: A review. *Alexandria Engineering Journal*, 91, 70-83. doi: 10.1016/j.aej.2024.01.080.
[4] DSTU 4583:2023. (2023). *Bread made from rye and a mixture of rye and wheat flour. General technical conditions*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=104866.
[5] DSTU 4587:2023. (2023). *Buns and bakery products. General technical conditions*. Retrieved from https://zakon.isu.net.ua/sites/default/files/normdocs/dstu_4587_2023.pdf.
[6] DSTU 9188:2022. (2022). *Bakery products. Organoleptic evaluation of quality indicators*. Retrieved from https://zakon.isu.net.ua/sites/default/files/normdocs/dstu_91882022.pdf.
[7] Gai, F., Janiak, M.A., Sulewska, K., Peiretti, P.G., & Karamać, M. (2023). Phenolic compound profile and antioxidant capacity of flax (*Linum usitatissimum* L.) harvested at different growth stages. *Molecules*, 28(4), article number 1807. doi: 10.3390/molecules28041807.
[8] Gigante, V., Aliotta, L., Ascrizzi, R., Pistelli, L., Zinnai, A., Batoni, G., Coltelli, M.-B., & Lazzeri, A. (2023). Innovative biobased and sustainable polymer packaging solutions for extending bread shelf life: A review. *Polymers*, 15(24), article number 4700. doi: 10.3390/polym15244700.
[9] Junaid, P.M., Saikumar, A., Islam, R.U., Patel, M.K., Eranda, D.H.U., Islam, M., Zaidi, S., & Badwaik, L.S. (2025). Polysaccharide-based biopolymers: exploring film fabrication techniques, molecular interactions, and their potential food applications. *Quality Assurance and Safety of Crops & Foods*, 17(4). doi: 10.15586/qas.v17i4.1581.
[10] Kumar, V., Vinayak, A.K., Venkatachalam, S., & Muruganandam, L. (2022). Moisture barrier behavior of polymer films on food packaging plastic materials. *International Journal for Technological Research in Engineering*, 9(5), 6-11. doi: 10.5281/zenodo.6348202.
[11] Kyivkhlib. (n.d.a). *"Domashnii Zhytnii" bread*. Retrieved from https://kyivkhlib.ua/t-product/khlib-domashniy-2/.
[12] Kyivkhlib. (n.d.b). *"Molochnyi" loaf*. Retrieved from https://kyivkhlib.ua/t-product/baton-molochnyy/.
[13] Mishra, B., Panda, J., Mishra, A.K., Nath, P.C., Nayak, P.K., Mahapatra, U., Sharma, M., Chopra, H., Mohanta, Y.K., & Sridhar, K. (2024). Recent advances in sustainable biopolymer-based nanocomposites for smart food packaging: A review. *International Journal of Biological Macromolecules*, 279(4), article number 135583. doi: 10.1016/j.ijbiomac.2024.135583.

[14] Mohammadi-Moghaddam, T., Morshedi, M., Ansari, R.M., Golmohamadi, A., Morshedi, A., & Kariminejad, M. (2024). Bread staling measurement techniques: A review. *Journal of Food Chemistry & Nanotechnology*, 10(2), 85-93. doi: 10.17756/jfcn.2024-178.

[15] Nordlund, E., Katina, K., Mykkänen, H., & Poutanen, K. (2016). Distinct characteristics of rye and wheat breads impact on their *in vitro* gastric disintegration and *in vivo* glucose and insulin responses. *Foods*, 5(2), article number 24. doi: 10.3390/foods5020024.

[16] Noshirvani, N., Ghanbarzadeh, B., Mokarram, R.R., & Hashemi, M. (2017). Novel active packaging based on carboxymethyl cellulose-chitosan-ZnO NPs nanocomposite for increasing the shelf life of bread. *Food Packaging and Shelf Life*, 11, 106-114. doi: 10.1016/j.fpsl.2017.01.001.

[17] Osyka, V.A., Koptiukh, L.A., Komakha, V.O., & Shulha, O.S. (2019). Formation of the quality of base paper for the manufacture of water- and greaseproof packaging materials. *Bulletin of Cherkasy State Technological University*, 3, 76-82.

[18] Panou, A., & Karabagias, I.K. (2023). Biodegradable packaging materials for foods preservation: Sources, advantages, limitations, and future perspectives. *Molecules*, 13(7), article number 1176. doi: 10.3390/coatings13071176.

[19] Pasqualone, A. (2019). Bread packaging: Features and functions. In *Flour and breads and their fortification in health and disease prevention* (pp. 211-222). Amsterdam: Academic Press. doi: 10.1016/B978-0-12-814639-2.00017-4.

[20] Perreard, S., Boucher, J., & Gallato, M. (2025). *Plastic overshoot day – report 2025*. Lausanne: EA-Earth Action.

[21] Roy, S., & Rhim, J.-W. (2022). Genipin-crosslinked gelatin/chitosanbased functional films incorporated with rosemary essential oil and quercetin. *Materials,* 15(11), article number 3769. doi: 10.3390/ma15113769.

[22] Samoilenko, N.M., & Hadayeva, Yu.S. (2025). Actual aspects of development and use of biopolymer materials for disposable packaging. *Environmental Sciences*, 2(59), 330-336. doi: 10.32846/2306-9716/2025.eco.2-59.49.

[23] State Statistics Service of Ukraine. (2022). *Population size and composition*. Retrieved from https://stat.gov.ua/uk/publications/chyselnist-ta-sklad-naselennya.

[24] UNEP. (2023). *UN roadmap outlines solutions to cut global plastic pollution*. Retrieved from https://www.unep.org/news-and-stories/press-release/un-roadmap-outlines-solutions-cut-global-plastic-pollution.

[25] Venkatesan, R., Alrashed, M.M., Vetcher, A.A., & Kim, S.-C. (2025). Next-generation food packaging: Progress and challenges of biopolymer-based materials. *Polymers*, 17(17), article number 2299. doi: 10.3390/polym17172299.

[26] Yaheliuk, S.V., Fomych, M.I., & Yaheliuk, O.O. (2022). The modern technologies of bast crops biomass processing. *Agricultural Machines*, 48, 59-66. doi: 10.36910/acm.vi48.841.

[27] Zhang, Y., *et al.* (2024). Effects of wheat oligopeptide on the baking and Retrogradation properties of bread rolls: Evaluation of crumb hardness, moisture content, and starch crystallization. *Foods*, 13(3), article number 397. doi: 10.3390/foods13030397.

Втрата вологи хлібом в різних пакувальних матеріалах та потенціал матеріалів на основі льону

Світлана Ягелюк
Доктор технічних наук, професор
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0000-0002-7428-0848
Владислав Часніков
Аспірант
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
https://orcid.org/0009-0004-4008-9502

Анотація. Накопичення пластикових відходів, зокрема від одноразової упаковки для продуктів харчування, є значною екологічною проблемою, що робить необхідним пошук альтернативних, сталих пакувальних матеріалів для зменшення екологічного впливу та збереження якості продуктів. Метою дослідження було порівняльне оцінювання ефективності паперової, біополімерної, поліпропіленової та експериментальної нетканої лляної упаковки в збереженні свіжості пшеничного та житнього хліба, використовуючи втрату маси як індикатор обміну вологою. У роботі було проаналізовано екологічне навантаження в Україні, спричинене використанням полімерних матеріалів в пекарській промисловості, де споживання упаковки досягає близько 9 млрд одиниць на рік. Експериментально встановлено, що поліпропіленова плівка забезпечує найкращі бар'єрні властивості, зберігаючи стабільну масу і високі органолептичні показники протягом 7 днів. Традиційне паперове пакування виявилось найменш ефективним через високу паропроникність, що призводить до втрати до 21 % вологості та швидкого старіння продуктів. Біополімерні пакети продемонстрували здатність утримувати вологу лише короткий період (до 3 днів), після чого їх захисні властивості значно знижуються. Як екологічно безпечна та функціональна альтернатива, папір на основі лляної целюлози може бути перспективним. Завдяки щільній структурі довгих волокон та наявності природних антисептичних сполук (лігнани), таке пакування може допомогти продовжити свіжість хліба, відповідаючи принципам циркулярної економіки. Практична цінність дослідження полягає в науковому обґрунтуванні вибору біорозкладних пакувальних матеріалів на основі лляної целюлози для хлібобулочних виробів, що можуть бути використані в харчовій промисловості для зменшення пластикових відходів при збереженні якості продуктів

Ключові слова: хлібобулочні вироби; кінетика старіння; термін зберігання; біорозкладні матеріали; лляна целюлоза; органолептична якість; бар'єрні властивості

Журнал
«ТОВАРОЗНАВЧИЙ ВІСНИК»

Том 18, № 2
2025

(Англійською мовою)

Відповідальний редактор:
О. Передрій

Підписано до друку з оригінал-макета 26.12.2025
Ум. друк. арк. 8,1
Наклад 100 прим.

Контактна адреса:
Луцький національний технічний університет
43018, вул. Львівська, 75, м. Луцьк, Україна
Тел.: (0332) 746 103
E-mail: info@c-bulletin.com.ua
https://c-bulletin.com.ua/uk

Journal
“COMMODITY BULLETIN”

Volume 18, No. 2
2025

Managing editor:
O. Peredriy

Signed to the print with the original layout 26.12.2025
Conventional Printed Sheet 8.1
Circulation 100 copies

Address for contacts:
Lutsk National Technical University
43018, 75 Lvivska Str., Lutsk, Ukraine
Tel.: (0332) 746 103
E-mail: info@c-bulletin.com.ua
https://c-bulletin.com.ua/en