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

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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-

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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.

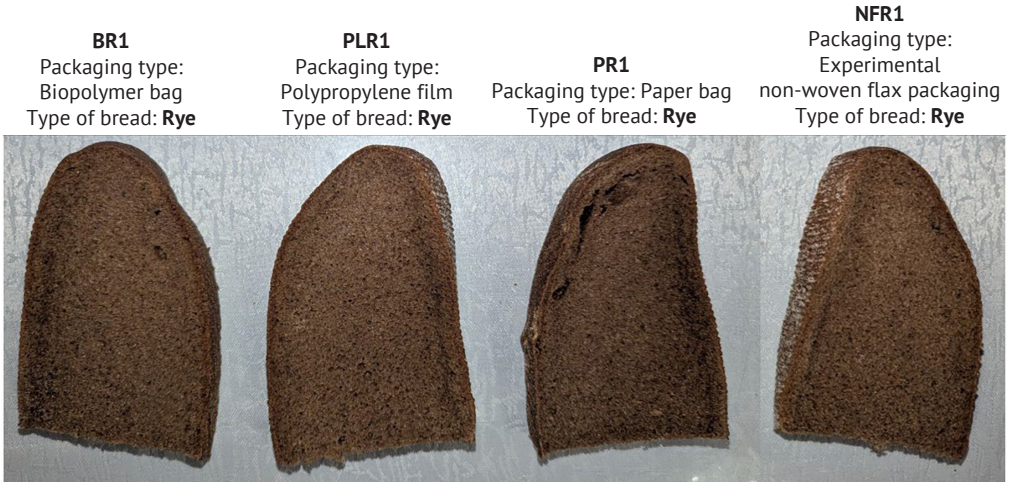

Figure 1. *Samples of rye bread after 1 day of packaging*

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.

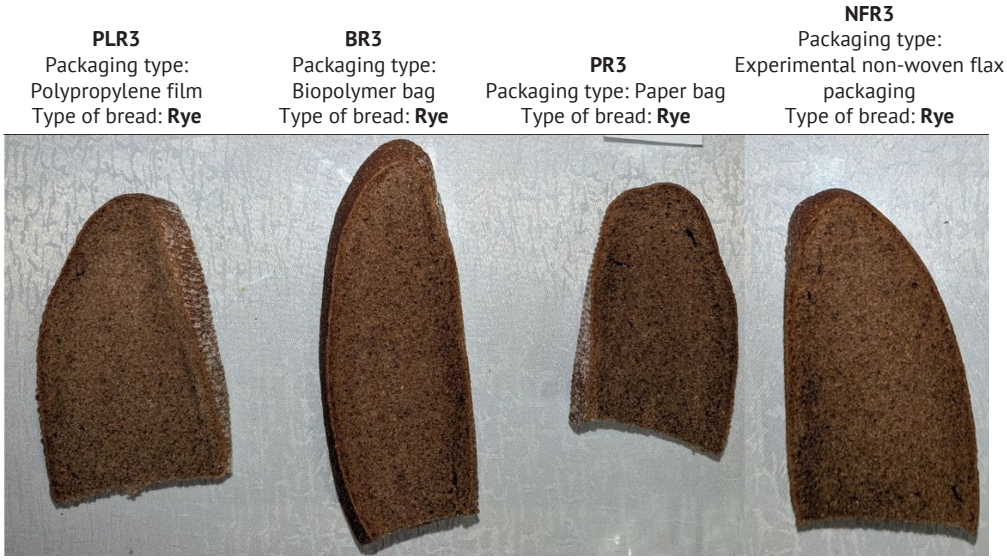

Figure 2. *Samples of rye bread after 3 days of packaging*

Source: *compiled by the authors*

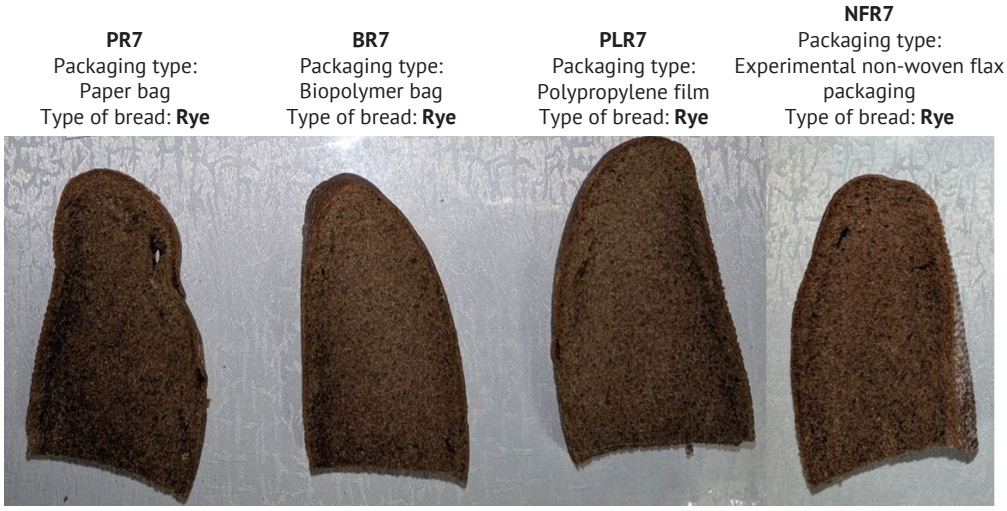

Figure 3. *Samples of rye bread after 7 days of packaging*

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.

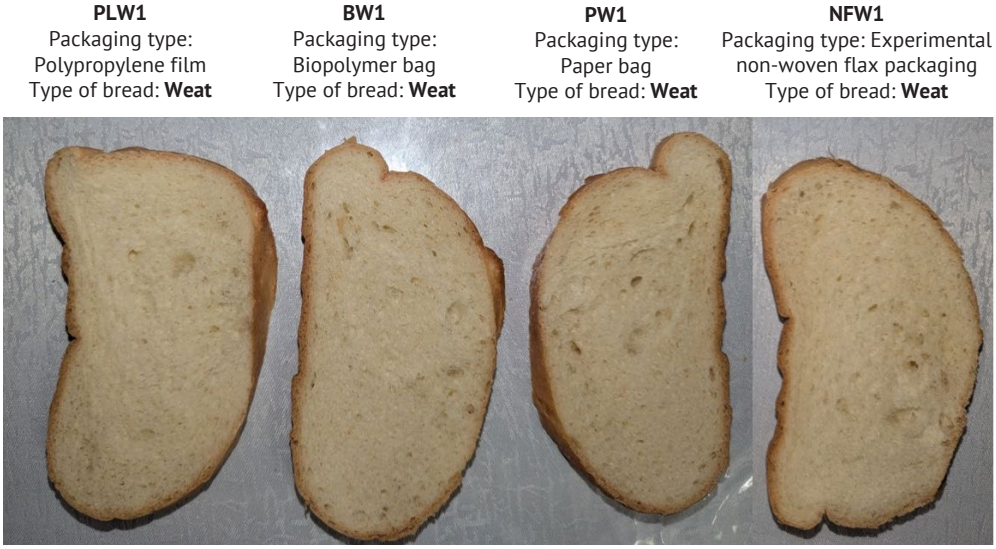

Figure 4. *Samples of wheat bread after 1 day of packaging*

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.

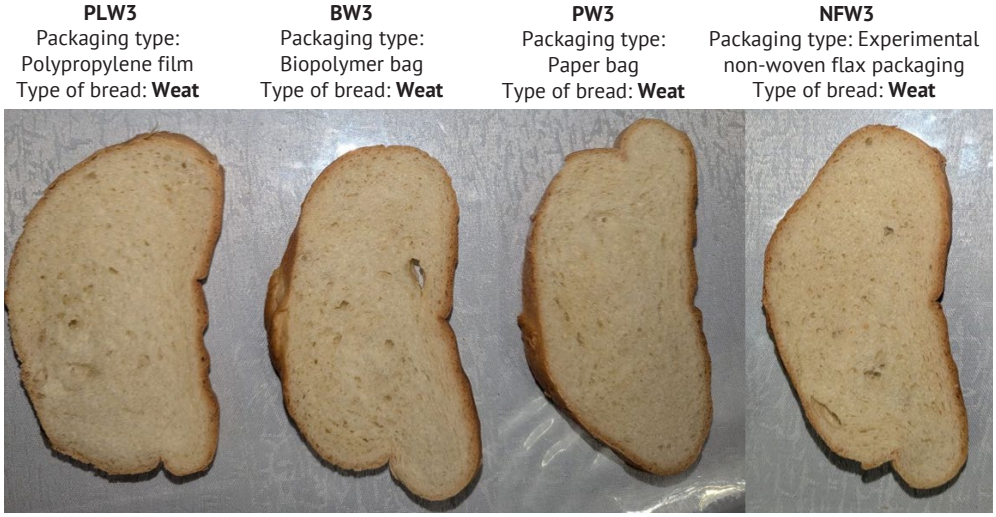

Figure 5. *Samples of wheat bread 3 days after packaging*

Source: *compiled by the authors*

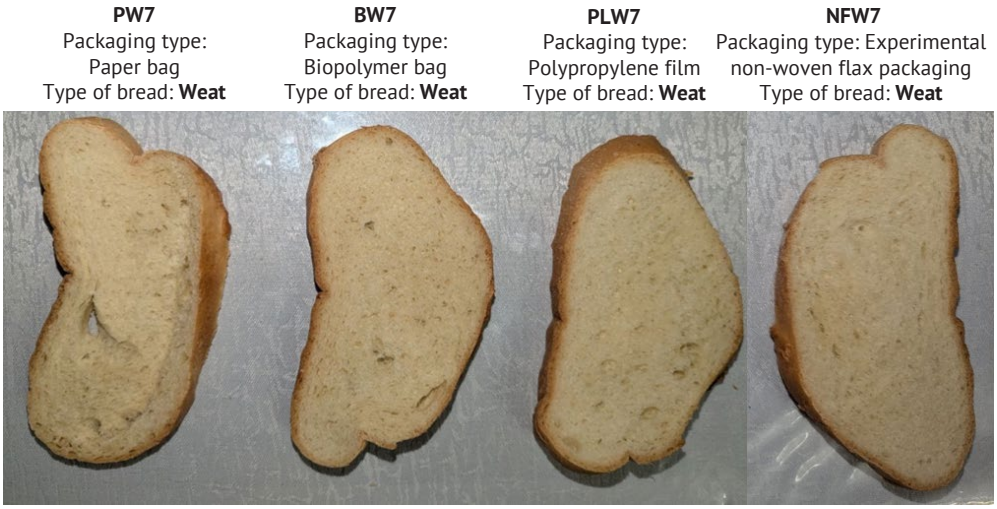

Figure 6. *Samples of wheat bread 7 days after packaging*

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.

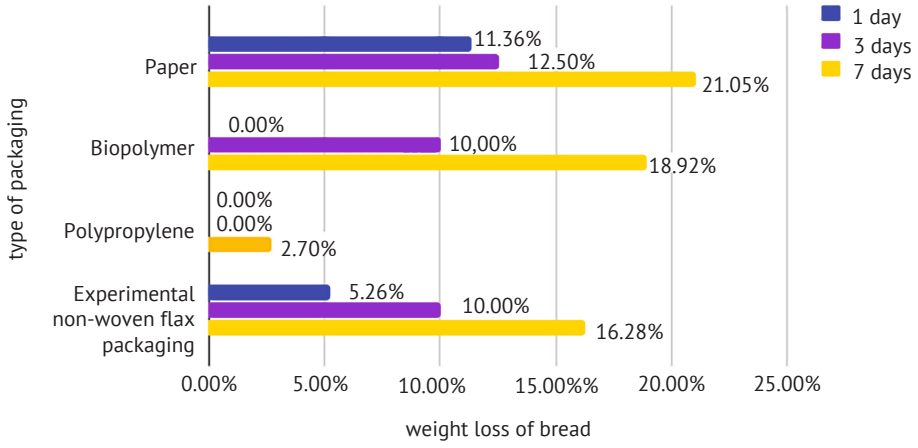

Figure 7. *Dynamics of average weight loss of rye bread in different types of packaging*
Source: *compiled by the authors based on experimental data*

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.

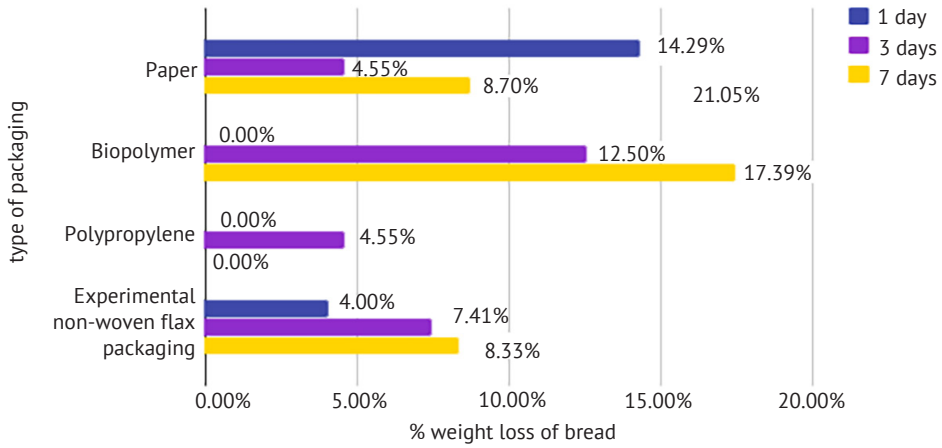

Figure 8. *Dynamics of average weight loss of wheat loaf in different types of packaging*
Source: *compiled by the authors based on experimental data*

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.

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Conflict of Interest

None.

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

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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