UDC 664.66
DOI: 10.15587/2706-5448.2025.323829

Olena Bilyk,
Iurii Bogachov,
Yulia Bondarenko,
Albina Fain,
Volodymyr Bilokhatniuk

USING REHEATING OF BAKED PRODUCTS TO PROLONG THEIR FRESHNESS

The object of research is the technological process of reheating bakery products after cooling. The study is devoted to the development of technological methods for extending the freshness of bakery products to reduce bread waste into the environment. Traditional methods for extending the freshness of bakery products require the use of high-quality raw materials, packaging materials, food additives, non-traditional raw materials, and the use of rational methods of storing finished products which in turn leads to an increase in the cost of products.

This work considers the possibility of using reheating of bakery products after a certain storage period, which may allow them to be produced with an extended shelf life without the use of additional ingredients, food additives, and technological equipment. It was established that to slow down the staling process, the optimal temperature for reheating of bakery products weighing 0.060 kg is heating the finished products to 75 °C. It was established that reheating reduces the friability of products compared to the control by 27.0 % under the condition of storage for 48 hours. Along with this, it was found that the water binding of the crumb of products after reheating also decreases during storage, but this decrease after 48 h of storage compared to the control is 15.5 % greater, which indicates a slowdown in the aging of the hydrocolloids of the products. It was found that the lightness (color L) of the bakery product after reheating significantly decreased from 66.81 to 59.38, which indicates darkening due to the Maillard reaction. Due to reheating, the formation of the subcrust layer of bakery products occurs more slowly and the crust to crumb ratio is 57.5 % less compared to the control. Thus, the use of reheating is an effective technological measure for extending the freshness of bakery products.*

Keywords: *bakery product, reheating, staling, crumb hardness, subcrust layer.*

Received: 04.12.2024
Received in revised form: 04.02.2025
Accepted: 16.02.2025
Published: 28.02.2025

How to cite
Bilyk, O., Bogachov, I., Bondarenko, Y., Fain, A., Bilokhatniuk, V. (2025). Using reheating of baked products to prolong their freshness. Technology Audit and Production Reserves, 1 (3 (81)), 39–44. https://doi.org/10.15587/2706-5448.2025.323829

1. Introduction

Worldwide, about 30–40 % of food produced is wasted, resulting in the loss of valuable nutrients. Food waste is a social paradox, as it exacerbates the problem of food security and harms the environment by increasing greenhouse gas emissions [1, 2].

Bakery products are discarded in significant volumes, in some cases accounting for 30 % of waste by weight. They are among the food waste categories with the most negative impact on the environment [3, 4].

An effective solution to reduce the share of bread waste is to extend the shelf life of bakery products. This can be achieved:

– at the production and retail levels – by establishing better logistics and management tools;
– at the production level – by choosing recipe ingredients or technological solutions that extend the shelf life;
– at the consumer level – by adjusting eating behavior and consumption habits [5–7].

A bakery product is a dynamic system that undergoes physicochemical, organoleptic and microbiological changes that determine the period of its consumption. Physicochemical and organoleptic changes cause the process of product staling, which leads to the gradual hardening of the crumb and its loss of the desired texture and taste [8, 9]. Microbiological spoilage of bakery products is manifested in the visible damage to the surface of the product or its crumb by mold fungi and the invisible accumulation of mycotoxins in the product with the formation of foreign flavors [10].

Scientists consider the process of staling as two separate phenomena:
– the transfer of moisture from the crumb to the crust during storage, which causes the crumb to harden;
– the recrystallization of starch during storage, which causes the internal strengthening of the cell wall material [11].

In the first phenomenon, the crust easily absorbs moisture from the interior of the crumb, which has a humidity of about 45 %. The author claims that during 100 hours of storage, the humidity of the crust can increase from 20 to 28 % [12]. In the second phenomenon, bread staling is a more complex and less understood process, which is the main obstacle to developing a strategy for preventing bread staling.

The staling process cannot be stopped, but its rate of progress can be slowed. To do this, it is necessary to use high-quality raw materials, packaging materials, food additives, non-traditional raw materials, apply rational methods of storing finished products and manufacture products by steaming methods [9, 12–14].

Both scientists and manufacturers give the greatest preference to the use of food additives, complex improvers. The authors [15] studied the effect of hydrocolloids on the process of stale bread from wheat flour. It was found that the use of hydrocolloids significantly reduces the rate of hardening of the crumb of products. This is explained by the formation of complexes of flour lipids with starch amylose, which were formed during the first two days of storage. It turned out that they reduce the maximum level of starch retrogradation.

ISSN-L 2664-9969; E-ISSN 2706-5448

To slow down starch retrogradation (the transition of partially gelatinized starch from an amorphous to a crystalline state), the authors [16] suggest using maltogenic amylase. The enzyme preparation Novamil 1500 MG contributes to a significant accumulation of maltose in the dough, which has a positive effect on the process of slowing down staling due to the formation of thin-walled homogeneous porosity. The authors [17] confirm the positive effect of phosphatide concentrates on the porosity structure of bakery products, increasing the specific volume and extending the shelf life.

It is more expedient for manufacturers to use complex baking improvers. Since they simultaneously correct deviations in the quality of flour, technological process management and ensure the extension of the freshness of finished products [18, 19].

To slow down the development of mold, the authors [20, 21] recommend using sorbates or propionates, but their use affects the organoleptic quality indicators of bread. In addition, prolonged use of sorbates or propionates can lead to the development of mold resistance to them.

To extend the shelf life of bakery products, active packaging is used, which absorbs oxygen and releases antimicrobial substances [22, 23]. There are different types of active packaging systems, but mainly these are absorption and release systems. The absorption system includes those types that remove oxygen from the packaging environment. Release systems include those that release compounds such as antioxidants, preservatives, and antimicrobials into the packaged food or into the headspace of the package. Absorbers and releasers are manufactured in the form of sachets, labels, or films. They are usually placed at the top of the package so that there is no direct contact with the baked product.

Nanotechnology has also enabled the creation of polymers with improved barrier function against oxygen. Using nanocomposites, which are the fusion of traditional packaging polymers with nanoparticles, improves the mechanical strength of food packaging materials and reduces their weight [24]. Such packaging materials have improved barrier properties against oxygen, carbon dioxide, ultraviolet radiation, moisture, and volatiles. In addition, they can allow air and other enzymes to pass out but not in, destroy ripening gases such as ethylene, and have antimicrobial effects [25, 26].

Among the technological methods for slowing down the process of staling, such processes as freezing of bakery products after final baking are effective; carrying out the first partial stage of baking with subsequent cooling and storage at room temperature or storage in freezing conditions with subsequent baking at retail outlets or at home [27]. To implement these technological schemes, additional equipment is required, which significantly increases the cost of production.

The baking process plays a crucial role in the production of bakery products, as it affects the quality of the finished product. During the baking process, as a result of heat and mass transfer, the dough system undergoes an irreversible transition from a liquid to a solid state. This leads to an increase in volume, the formation of pores and starch gelatinization [28, 29].

There is considerable interest among scientists and manufacturers of bakery products in the reheating of bread after a certain storage period, which may allow the production of bakery products with an extended shelf life. There are very few literary sources on this topic, so such studies are relevant.

Considering all of the above, reducing bread waste becomes a priority. *The aim of this research* is to establish the reheating parameters of bread from wheat flour to increase its shelf life. This will allow manufacturers to reduce the shortage of finished products, consumers to reduce waste, which will contribute to reducing the negative impact on the environment.

2. Materials and methods

The object of the research was the reheating process of bakery products after cooling.

The subject of the research was the quality indicators of bakery products that were subjected to reheating.

To assess the quality of bakery products that were subjected to reheating, a trial laboratory baking was carried out. The control was a bakery product made according to the recipe [30]:

– premium wheat flour – 100 kg;
– pressed baking yeast – 4.0 kg;
– table salt – 1.5 kg;
– white sugar – 5.0 kg;
– sunflower oil – 3.0 kg.

The dough was kneaded in an Esher dough mixer (Italy) at the first speed for 10 min. The dough was prepared in a non-mixed way with a mass fraction of dough moisture – 42.0 %. The fermentation process was carried out for 90 min. The dough was processed manually, the dough pieces were proofed in a proofing cabinet at a temperature of 38±2 °C and a relative humidity of 78±2 % until ready. The products were baked in a cabinet oven at a temperature of 180–200 °C with humidification of the baking chamber.

The crumb hardness was measured 24 and 48 hours after baking using a JJ Lloyd LR5K texture analyzer (Lloyd Instruments Ltd., Great Britain). Seven 10 mm thick slices were used for each compression study. The slices were taken from the middle of the product. The crust of the slices was removed to measure only the crumb texture parameters. The samples were compressed using a cylindrical probe with a diameter of 20 mm, moving at a speed of 20 mm/min. A constant degree of deformation (40 % of the total height) was applied. Displacement was recorded when the force exceeded 0.1 N. 50 N load cell was mounted on the movable head of the device. The maximum force (N) was extracted from the force-strain curve [29].

To determine the porosity, two pieces in the shape of a parallelepiped, each weighing 5 g, are cut from the crumb and transferred to a conical flask with a volume of 250 cm^3. The contents of the flask are shaken for 5 min on a vibrating mixer. The crumb formed as a result of the friction of the two pieces is collected and weighed on a scale with an accuracy of 0.01 kg.

The porosity X, % of the mass of the bread crumb, is determined by the formula:

$$X = \frac{G_1}{G_2} \cdot 100, \qquad (1)$$

where $G1$ – crumb mass, g; $G2$ – bread sample mass, g [31].

To determine the amount of water absorbed by the bread, the bread crumb is crushed and 3 g of the crumb is weighed. The sample is transferred to a sieve (12 cells per 1 cm^3) and 17 cm^3 of distilled water is added dropwise from a pipette over 5 min. The moistened crumb is collected from the sieve and weighed again.

The amount of water absorbed by the bread V, % on the CP, is calculated by the formula:

$$V = \frac{10000(G_1 - G_2)}{(100 - W) \cdot G_2}, \qquad (2)$$

where $G1$ – bread mass after wetting, g; $G2$ – bread sample mass before wetting, g; W – mass fraction of moisture in the bread, % [31].

One day later, 48 h after baking, water activity (aW) was measured by placing 1 g of each sample in a laboratory water activity analyzer Pre-Aqua (Meter Group Inc., WA, USA) at 25 °C. The water activity analyzer was calibrated for W0.984, close to the expected for normal bread of 0.91–0.93 [32].

The mass fraction of moisture was determined by a standard accelerated method [33].

Surface color was measured to assess the degree of browning of the bread crust during baking. Bread surface and dough color were measured using a Chroma meter CR-200 (Minolta, Osaka, Japan) with a Hunter $L*a*b*$ system. The $L*$ color describes the lightness of the sample with values ranging from 0 (black) to 100 (white). The color $a*$ describes the green ($-a*$) and red ($+a*$) of the scale, while the color $b*$ defines the blue ($-b*$) and yellow ($+b*$). The colors $a*$ and $b*$ are limited by the white calibration. The numerical value ΔE describes the total color difference and is given by the formula:

$$\Delta E = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right) + \left(b^* - b_0^*\right)^2}, \quad (3)$$

where $L_0^*=82.14\pm0.31$, $a_0*=-4.43\pm0.01$; $b_0*=17.43\pm0.41$ are the measured lightness, greenness and yellowness of the dough, respectively. The color of each bread was averaged over three measurements on the surface of the product.

When studying the staling degree, it is necessary to organoleptically establish the boundary of the transition of the crumb into the subcrust layer. The subcrust layer is formed from the compacted crumb. The established boundary is marked with a marker. The thickness of the subcrust layer is established by measuring with a ruler the width of the subcrust layer from the crust to the boundary marked with a marker [31].

The crust/crumb ratio was calculated as the crust mass divided by the dry crumb mass [29]. The crust to crumb ratio was determined by separating the crust from the product with a razor blade; the separation criteria were based on a dry and denser layer on the surface of the bread, which has a color from brown to white. They were then placed in aluminum cups and placed in a drying oven at 103 °C for 16 h (three replicates). Three bread samples were used for each analysis. The samples were cooled in a desiccator and weighed on an analytical balance with a sensitivity of ±0.01 g.

The results of the experimental studies were subjected to statistical processing implemented using standard Microsoft Office software packages.

3. Results and Discussion

The first stage of the research concerned the establishment of parameters for the reheating of the products, which was carried out after 4 h of their cooling. During this duration of cooling of the products, the processes that occur during staling do not yet begin. In production conditions, this process precedes the packaging operation. We studied samples weighing 0.060 kg, which were baked at a temperature of 180–200 °C for 10–11 min, cooled to a temperature of 20 °C for up to 4 h. It is known from literature that stable amylose crystals do not melt during reheating to 100 °C [34]. Therefore, it is possible to choose the temperature of the heating of the products so that the inside of the crumb was from 65–85 °C with a step of 5 °C, which corresponds to the pasteurization temperature of food products. The reheating effect on the freshness of bakery products was determined by changes in structural and mechanical properties during 4 days of storage using the "Texturometer" device (Table 1).

Table 1

The effect of repeated baking on the structural and mechanical properties of the crumb

Samples	Force, g					
	11 min of baking	Crumb temperature after reheating, min				
		65	70	75	80	85
After 24 hours of baking						
Control	1218	–	–	–	–	–
Test sample	–	1188	1155	1106	1128	1147
After 48 hours of baking						
Control	1836	–	–	–	–	–
Test sample	–	1648	1615	1583	1608	1627

Notes: $n=3$, $p\geq0.95$, $\delta=3-5$ %

A decrease in the "hardness" index, which is recorded by a texturometer, indicates an extension of the freshness of baked goods. Therefore, a significant increase in the indicators for the control sample indicates a faster aging and loss of freshness compared to the test sample. The control sample demonstrates significantly greater changes in texture than the test sample, which may indicate that the test sample retains its freshness better over time. This is due to the melting of amylopectin crystals that formed in the baked goods during storage as a result of the recrystallization of glycan chains in gelatinized starch, during which the dispersed starch molecules begin to re-associate via H-bonding [34, 35]. The data obtained indicate that the sample with a crumb temperature of 75 °C during reheating has the lowest "Hardness" index. So, the optimal temperature of the crumb of products during reheating of bakery products weighing 0.060 kg is 75 °C. Therefore, further studies were conducted with this sample.

The second stage of the research was to confirm the positive effect of reheating on slowing down the staling process.

During the process of staling, the physicochemical properties of the crumb change, the pore walls lose their strength, which is accompanied by an increase in the crumb's porosity. Therefore, further studies were concerned with determining the effect of reheating on the crumb's porosity. The results of the research show (Fig. 1) that the porosity value decreases in the case of reheating compared to the control – by 27.0 % under the condition of storage for 48 hours.

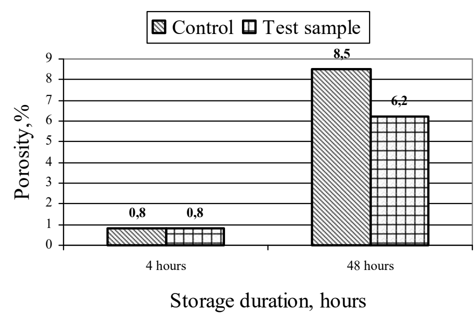

Fig. 1. The effect of reheating on the crumb coating of products, %

To confirm the obtained data, the effect of reheating on the hydrophilicity of the crumb was studied. During the storage of bakery products, the hydrophilicity of their crumb decreases. The decrease in the hydrophilicity of the crumb affects its ability to swell and absorb water, as well as the ability of colloids and other substances in the crumb to pass into an aqueous solution. In our studies, we determined the amount of water absorbed by the crumb as a percentage of the dry matter of the product (water absorption capacity of the crumb). The determination was carried out 4 and 48 hours after baking and reheating. The results of the studies are presented in Fig. 2.

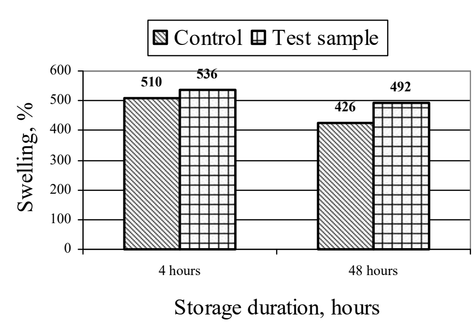

Fig. 2. The reheating effect on the swelling of the crumb of products, %

It was established that during the storage of bakery products, the processes of staling lead to a decrease in the swelling of the crumb of products. This is due to a decrease in the ability of colloidal substances to absorb water due to the compaction of the structure of starch and proteins during their aging. However, this decrease is significant in the control sample for the same storage period. The binding of water by the crumb of products after reheating also decreases during storage, but this decrease after 48 h of storage compared to the control is 15.5 % greater, which indicates a slowdown in the aging of hydrocolloids of products.

Further studies concerned the effect of reheating on the activity of water, the mass fraction of moisture in the crust and crumb, the surface color indices *L**, *a**, *b** and the crust to crumb ratio after 48 h of storage. The results obtained are given in Table 2 and Fig. 3.

Table 2

Reheating effect on quality indicators of bakery products

Indicator	Control	Experimental sample
Water activity, *a*w crust	0.92	0.89
Crumb	0.97	0.96
Moisture mass fraction, % crust	21.93	20.10
Crumb	41.60	40.20
Surface color: *L**	64.81	59.38
*a**	5.31	6.31
*b**	22.83	19.6
Δ*E*	18.2	22.9
Crust to crumb ratio:		
4 h after baking	0.08	0.08
48 h after baking	1.2	0.51

Notes: n=3, p≥0.95, δ=3–5 %

Analysis of the obtained results (Table 2) on water activity showed that re-baking reduced the amount aw in the crust from 0.92 to 0.89, and in the crumb from 0.97 to 0.96. This is due to the release of free moisture, which is confirmed by the lower moisture content in both the crumb and crust of the finished products.

Fig. 3. Photos of products heat treated for crumb swelling, %: *a*, *c*, *e* – control sample; *b*, *d*, *f* – test sample; *a*, *b* – after 4 h after baking; *c*, *d* – after 48 h after baking; *e*, *f* – surface color

During storage of baked goods, water migrates from the crumb to the crust, which leads to a further decrease in the moisture content of the crumb. In particular, the moisture content of the denatured gluten framework decreases to a critical point at which the plasticity of gluten proteins is lost. As a result, the rigidity of the gluten network increases, which also contributes to an increase in the hardness of the crumb and its transition to the sub-crust layer during storage [34]. A study of the change in the crust to crumb ratio showed that in the sample subjected to reheating, the crust to crumb ratio was 57.5 % lower compared to the control. This confirms the slowing down of the staling process, namely, a slower migration of moisture from the crumb of the products to the crust and the formation of a smaller sub-crust layer. The results obtained are confirmed by the photo in Fig. 3. The Maillard reaction is mainly responsible for color development at temperatures below 150 °C. Caramelization and carbonization reactions occur at temperatures above 150 °C. The Maillard reaction is influenced by the composition of reducing sugars and amino acids, as well as temperature, pH, and moisture content [36]. It was therefore of interest to investigate the effect of reheating on the surface color of the products. The results show that the lightness (*L** color) decreased significantly from 66.81 to 59.38, indicating darkening. Comparisons of color values with conventional bread were made because abrupt color changes, especially browning, can affect the perception of potential products. Bakery products have *L** color values in the range of 50–65, *a** in the range of 14–18, and *b** in the range of 30–35 [37]. Importantly, the lightness (*L** color) is within the range of commercial wheat bread, indicating that the reheating has little effect.

Practical significance. The conducted research opens up prospects for extending the freshness of bakery products through technological measures, without the use of additional ingredients, food additives and technological equipment.

Research limitations. The lack of the ability in Ukraine to establish the effect of repeated baking on the glass transition temperature, which would allow for a more substantiated establishment of its effect on biopolymers.

The influence of martial law conditions. The war in Ukraine prevents industrial testing and implementation of the results obtained at bakery enterprises.

Prospects for further research. The subject of further research is the selection of packaging materials for the possibility of reheating of packaged products and the establishment of final storage times according to the passage of the staling process and microbiological purity.

4. Conclusions

As a result of the research, it was found that to slow down the process of staling, the optimal temperature for reheating of bakery products weighing 0.060 kg is heating the finished products to 75 °C. This is due to the melting of amylopectin crystals that formed in the baked products during storage.

It was found that reheating reduces the friability of the products compared to the control by 27.0 % under the condition of storage for 48 hours. It was also found that the water binding of the crumb of the products after reheating also decreases during storage, but this decrease after 48 hours of storage compared to the control is 15.5 % greater, which indicates a slowdown in the aging of the hydrocolloids of the products.

The formation of the subcrust layer of bakery products was studied and it was found:

– that in the sample subjected to reheating, the crust to crumb ratio is 57.5 % less compared to the control;

– the photograph confirmed the formation of a smaller sub-crust layer by highlighting the transition of the crumb into the sub-crust layer with a marker.

It was found that the luminance (color L^*) of the bakery product after reheating significantly decreased from 66.81 to 59.38, which indicates darkening due to the Maillard reaction.

Acknowledgments

The work was carried out within the framework of the state budget research project "Scientific justification and development of resource-efficient technologies for food products of specific purpose as an imperative of food security" 0123U102060.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

Financing

The study was conducted without financial support.

Availability of data

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

References

1. Gómez, M., Martinez, M. M. (2023). Redistribution of surplus bread particles into the food supply chain. *LWT, 173,* 114281. https://doi.org/10.1016/j.lwt.2022.114281
2. Priss, O. P., Yevlash, V. V., Tovma, L. F. (2024). Skorochennia prodovolchykh vtrat i kharchovykh vidkhodiv, yak zasib dosiahnennia stiikoi prodovolchoi systemy v umovakh voiennoho stanu ta pisliavoiennoho vidnovlennia. *Prodovolchi systemy Ukrainy: povoienne vidnovlennia ta zabezpechennia staloho rozvytku*. Kharkiv, 74–76.
3. Brancoli, P., Bolton, K., Eriksson, M. (2020). Environmental impacts of waste management and valorisation pathways for surplus bread in Sweden. *Waste Management, 117,* 136–145. https://doi.org/10.1016/j.wasman.2020.07.043
4. Brancoli, P., Rousta, K., Bolton, K. (2017). Life cycle assessment of supermarket food waste. *Resources, Conservation and Recycling, 118,* 39–46. https://doi.org/10.1016/j.resconrec.2016.11.024
5. Garrone, P., Melacini, M., Perego, A. (2014). Opening the black box of food waste reduction. *Food Policy, 46,* 129–139. https://doi.org/10.1016/j.foodpol.2014.03.014
6. Bilyk, O., Kochubei-Lytvynenko, O., Bondarenko, Y., Vasylchenko, T., Pukhliak, A. (2020). Developing an improver of targeted action for the prolonged freshness of bread made from wheat flour. *Eastern-European Journal of Enterprise Technologies, 5 (11 (107)),* 62–70. https://doi.org/10.15587/1729-4061.2020.214934
7. Papargyropoulou, E., Lozano, R., K. Steinberger, J., Wright, N., Ujang, Z. bin. (2014). The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production, 76,* 106–115. https://doi.org/10.1016/j.jclepro.2014.04.020
8. Bianchi, A., Venturi, F., Palermo, C., Taglieri, I., Angelini, L. G., Tavarini, S., Sanmartin, C. (2024). Primary and secondary shelf-life of bread as a function of formulation and MAP conditions: Focus on physical-chemical and sensory markers. *Food Packaging and Shelf Life, 41,* 101241. https://doi.org/10.1016/j.fpsl.2024.101241
9. Taglieri, I., Macaluso, M., Bianchi, A., Sanmartin, C., Quartacci, M. F., Zinnai, A., Venturi, F. (2020). Overcoming bread quality decay concerns: main issues for bread shelf life as a function of biological leavening agents and different extra ingredients used in formulation. A review. *Journal of the Science of Food and Agriculture, 101 (5),* 1732–1743. https://doi.org/10.1002/jsfa.10816
10. Galić, K., Ćurić, D., Gabrić, D. (2009). Shelf Life of Packaged Bakery Goods – A Review. *Critical Reviews in Food Science and Nutrition, 49 (5),* 405–426. https://doi.org/10.1080/10408390802067878
11. Melini, F., Melini, V., Luziatelli, F., Ruzzi, M. (2017). Current and Forward-Looking Approaches to Technological and Nutritional Improvements of Gluten-Free Bread with Legume Flours: A Critical Review. *Comprehensive Reviews in Food Science and Food Safety, 16 (5),* 1101–1122. https://doi.org/10.1111/1541-4337.12279
12. Melini, V., Melini, F. (2018). Strategies to Extend Bread and GF Bread Shelf-Life: From Sourdough to Antimicrobial Active Packaging and Nanotechnology. *Fermentation, 4 (1),* 9. https://doi.org/10.3390/fermentation4010009
13. Ottenhof, M.-A., Farhat, I. A. (2004). The effect of gluten on the retrogradation of wheat starch. *Journal of Cereal Science, 40 (3),* 269–274. https://doi.org/10.1016/j.jcs.2004.07.002
14. Iorhachova, K. H., Lebedenko, T. Ye. (2015). *Khlibobulochni vyroby ozdorovchoho pryznachennia z vykorystanniam fitodobavok*. Kyiv: K-Pres, 463.
15. Ferrero, C. (2017). Hydrocolloids in wheat breadmaking: A concise review. *Food Hydrocolloids, 68,* 15–22. https://doi.org/10.1016/j.foodhyd.2016.11.044
16. Sylchuk, T. A., Drobot, V. I., Bondarenko, Yu. V. (2012). Doslidzhennia vplyvu dobavok na protses cherstvinnia khliba. *Kharchova nauka i tekhnolohiia, 1,* 56–58.
17. Teplov, V. I. (2008). *Funktcionalnye produkty pitaniia.* A-Prior, 240.
18. Ben Hmad, I., Mokni Ghribi, A., Bouassida, M., Ayadi, W., Besbes, S., Ellouz Chaabouni, S., Gargouri, A. (2024). Combined effects of α-amylase, xylanase, and cellulase coproduced by Stachybotrys microspora on dough properties and bread quality as a bread improver. *International Journal of Biological Macromolecules, 277,* 134391. https://doi.org/10.1016/j.ijbiomac.2024.134391
19. Tebben, L., Shen, Y., Li, Y. (2018). Improvers and functional ingredients in whole wheat bread: A review of their effects on dough properties and bread quality. *Trends in Food Science & Technology, 81*, 10–24. https://doi.org/10.1016/j.tifs.2018.08.015
20. Levinskaite, L. (2012). Susceptibility of food-contaminating Penicillium genus fungi to some preservatives and disinfectants. *Annals of agricultural and environmental medicine, 19 (1),* 85–89.
21. Stratford, M., Nebe-von-Caron, G., Steels, H., Novodvorska, M., Ueckert, J., Archer, D. B. (2013). Weak-acid preservatives: pH and proton movements in the yeast Saccharomyces cerevisiae. *International Journal of Food Microbiology, 161 (3),* 164–171. https://doi.org/10.1016/j.ijfoodmicro.2012.12.013
22. Commission Regulation (EC) No 450/2009 of 29 May 2009 on active and intelligent materials and articles intended to come into contact with food (2009). *Official Journal of the European Union, 135,* 3–11.
23. Ahvenainen, R. (Ed.) (2003). *Novel food packaging techniques.* Elsevier. https://doi.org/10.1201/9780203507698
24. Priyanka, S., Namasivayam, S. K. R., Kennedy, J. F., Moovendhan, M. (2024). Starch-chitosan-Taro mucilage nanocomposite active food packaging film doped with zinc oxide nanoparticles – Fabrication, mechanical properties, anti-bacterial activity and eco toxicity assessment. *International Journal of Biological Macromolecules, 277,* 134319. https://doi.org/10.1016/j.ijbiomac.2024.134319
25. Azeredo, H. M. C. de. (2009). Nanocomposites for food packaging applications. *Food Research International, 42 (9),* 1240–1253. https://doi.org/10.1016/j.foodres.2009.03.019
26. Mihindukulasuriya, S. D. F., Lim, L.-T. (2014). Nanotechnology development in food packaging: A review. *Trends in Food Science & Technology, 40 (2),* 149–167. https://doi.org/10.1016/j.tifs.2014.09.009
27. Poinot, P., Arvisenet, G., Grua-Priol, J., Colas, D., Fillonneau, C., Le Bail, A., Prost, C. (2008). Influence of formulation and process on the aromatic profile and physical characteristics of bread. *Journal of Cereal Science, 48 (3),* 686–697. https://doi.org/10.1016/j.jcs.2008.03.002
28. Waldert, K., Bittermann, S., Martinović, N., Schottroff, F., Jäger, H. (2025). Ohmic baking of wheat bread – effect of process parameters on physico-chemical quality attributes. *Journal of Food Engineering, 392,* 112493. https://doi.org/10.1016/j.jfoodeng.2025.112493
29. Dessev, T., Lalanne, V., Keramat, J., Jury, V., Prost, C., Le-Bail, A. (2020). Influence of Baking Conditions on Bread Characteristics and Acrylamide Concentration. *Journal of Food Science and Nutrition Research, 3 (4),* 291–310. https://doi.org/10.26502/jfsnr.2642-11000056
30. Drobot, V. I. (2019). *Dovidnyk z tekhnolohii khlibopekarskoho vyrobnytstva.* Kyiv: Prof Knyha, 580.
31. Bilyk, O., Bondarenko, Y. (2024). Methods of determining the freshness of bakery products using the example of the influence of an improvement on the freshness of bran bread. *Innovative scientific research.* Toronto, 104–107. https://doi.org/10.5281/zenodo.12548671
32. Schmidt, S. J., Fontana, A. J. (2007). Appendix E: Water Activity Values of Select Food Ingredients and Products. *Water Activity in Foods*, 407–420. https://doi.org/10.1002/9780470376454.app5
33. Drobot, V. I. (Ed.) (2015). *Tekhnokhimichnyi kontrol syrovyny ta khlibobulochnykh i makaronnykh vyrobiv*. Kyiv: NUKhT, 902.

ISSN-L 2664-9969; E-ISSN 2706-5448

34. Bosmans, G. M., Lagrain, B., Fierens, E., Delcour, J. A. (2013). The impact of baking time and bread storage temperature on bread crumb properties. *Food Chemistry, 141 (4),* 3301–3308. https://doi.org/10.1016/j.foodchem.2013.06.031

35. Roman, L., Gomez, M., Hamaker, B. R., Martinez, M. M. (2019). Banana starch and molecular shear fragmentation dramatically increase structurally driven slowly digestible starch in fully gelatinized bread crumb. *Food Chemistry, 274,* 664–671. https://doi.org/10.1016/j.foodchem.2018.09.023

36. Conceição, L. dos S., Almeida, B. S. de, Souza, S. F. de, Martinez, V. O., Matos, M. F. R. de, Andrade, L. L. et al. (2024). Critical conditions for the formation of Maillard Reaction Products (MRP) in bread: An integrative review. *Journal of Cereal Science, 118*, 103985. https://doi.org/10.1016/j.jcs.2024.103985

37. Jusoh, Y. M., Chin, N. L., Yusof, Y. A., Rahman, R. A. (2008). Bread crust thickness estimation using LAB colour system. *Pertanika Journal of Science & Technology, 16 (2),* 239–247.

✉***Olena Bilyk,** PhD, Professor, Department of Bakery and Confectionary Goods Technology, National University of Food Technologies, Kyiv, Ukraine, e-mail: bilyklena@gmail.com, ORCID: https://orcid.org/0000-0003-3606-1254*

***Iurii Bogachov,** PhD Student, Department of Bakery and Confectionary Goods Technology, National University of Food Technologies, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0001-6411-9890*

***Yulia Bondarenko,** PhD, Associate Professor, Department of Bakery and Confectionary Goods Technology, National University of Food Technologies, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-3781-5604*

***Albina Fain,** Lecturer, Department of Fundamental Disciplines, Separate Structural Subdivision Kamianets-Podilskyi Professional College of Educational and Rehabilitation Institution of Higher Education "Kamianets-Podilskyi State Institute", Kamianets-Podilsky, Ukraine, ORCID: https://orcid.org/0000-0002-9107-7198*

***Volodymyr Bilokhatniuk,** Department of Bakery and Confectionary Goods Technology, National University of Food Technologies, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0008-1116-0241*

✉*Corresponding author*