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YEASTS IN SOURDOUGH: FUNDAMENTAL INSIGHTS AND THEIR ROLE IN FUNCTIONAL PROCESSES

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Sourdough are unique microbiological systems with a symbiotic interaction between lactic acid bacteria and yeasts. Yeasts, together with lactic acid bacteria, play a significant role in fermenting starters and are crucial for shaping the technological and functional properties of the product.

Aim. To analyze scientific data regarding the importance of yeasts in shaping the properties of sourdough and final products.

Methods. Searching and analyzing the relevant scientific literature, systematizing, and summarizing the results of available publications.

Results. It was highlighted the significant role of yeasts in formation the properties of sourdough and final bakery products, particularly for dough leavening, the development of flavor and aromatic characteristics, enrichment of bread with biologically active compounds, enhancement of bioavailability and shelf-life extension.

Conclusion. It was emphasized the importance of this knowledge for improving bakery production technologies using starter compositions for sourdough fermentation and the rational selection of yeast strains to regulate the organoleptic and functional-technological properties of the finished products.

Key words: sourdough, yeasts, fermentation, organoleptic properties, nutritional value, adaptation mechanisms.

Fermentation is one of the oldest manifestations of biotechnology, which has been used for daily human needs, particularly in bread production. The history of bread fermentation dates back to ancient times. There is evidence of its use since Ancient Egypt [1], and according to some sources [2], the first appearance of fermentation was more than 5,000 years ago. However, the principles of creating and using sourdough have fundamentally remained unchanged since then. Originally, sourdough was used to preserve and enhance the quality of bread made from wheat and rye flour. It has been discovered that sourdough not only maintains the freshness of the product but also enhances its texture, flavor, and nutritional value. The main purpose of using sourdough is to achieve bread with greater porosity and volume [3].

The popularity of traditional sourdough production has been rapidly increasing recently, as many consumers are shifting towards healthier eating habits and choosing organic and/or gluten-free products. This trend is attracting a new category of consumers, primarily younger and more knowledgeable about proper nutrition. Additionally, the use of not only traditional wheat or rye flour but also other varieties such as buckwheat and quinoa [4], rice, corn, oats, etc., is stimulating interest in products and expanding the palette of flavors available to consumers.

It is worth noting that sourdough and products made from it can also be produced using gluten-free cultures, which is quite limited in conventional baking. This provides an additional stimulus to the sourdough production industry, as gluten-free diets rank third in popularity worldwide and are consumed by 11% of the population [5]. This not only keeps manufacturers "on trend" but also contributes to the development of inclusivity for people with digestive disorders such as celiac disease, gastrointestinal sensitivity, and other conditions [6].

Interest in sourdough significantly increased after 2018. One possible explanation for this sharp rise in popularity is the COVID-19 pandemic, which allowed people to dedicate more attention and time to their hobbies and share their bread-baking experiences with sourdough on social media. In [7], it was noted that the daily routine of maintaining sourdough starters and baking bread from them reduced stress during lockdowns. According to statistics, the number of menu items featuring fermented products in dining establishments has increased by 149% since then [8].

The forecast for the global sourdough market indicates it will reach USD 3.11 billion by 2027. According to this information, Europe will emerge as the dominant region, with Germany leading as the largest sales market. Currently, significant competition is already observed among manufacturers, with the top five brands being Ernst Böcker GmbH & Co KG (Germany), IREKS GmbH (Germany), GoodMills Group GmbH (Austria), Puratos (Belgium), and Lesaffre (France). Unfortunately, Ukraine has not yet made any notable contribution to this sector of the economy, as there are currently no commercial producers of sourdoughs in the country. However, this industry is rapidly evolving, making research in this field relevant, as Ukraine's market potential remains open for exploration.

The scientific literature traditionally emphasizes lactic acid bacteria and their role in fermentation processes in the context of sourdoughs. However, other organisms in the microbiota of sourdoughs, particularly yeasts, receive much less attention. Their contribution often remains either entirely unmentioned or briefly referenced, despite playing a significant role in shaping sourdough and the properties of the final product. Therefore, the aim was to analyze scientific data regarding the influence of yeasts on the quality of bread sourdough and the final products.

Materials and Methods

The scientific literature search was conducted using keywords in Ukrainian and English languages on Google Scholar, NCBI archives, ResearchGate, electronic publications, and other sources. The search results were analyzed according to the chosen topic and utilized in this review.

Results and Discussion

Sourdough is a complex microbiological system based on the interaction of yeasts and lactic acid bacteria, both among themselves and with the main matrix consisting mainly of water and flour [9]. This unique symbiosis, which may seem simple at first glance, creates the distinctive taste and aroma of freshly baked bread.

Fermentation of dough offers numerous advantages, including improvement of bread's organoleptic properties, alteration of functional characteristics, and enhanced bioavailability of bioactive compounds [10]. For instance, increased synthesis of B vitamins (thiamine, riboflavin, folic acid) occurs; the shelf life of the product is prolonged; consumption of such bread is permissible for individuals on diets due to medical reasons or gastrointestinal disorders. The low pH of fermentation activates phytase enzymes naturally present in grains, facilitating the absorption of nutraceutical compounds in the body. Phytases dephosphorylate phytic acid, which has strong chelating properties. Phytic acid forms insoluble complexes with cations, thereby impairing their absorption [11, 12]. Another significant factor is the reduction in glycemic index [13] and fluctuations in blood glucose levels [14], observed specifically with the consumption of products baked with sourdough. This list is not exhaustive and may continue.

Flour as the Main Component of Sourdough

Traditional sourdough consists of only two components: water and flour. It is the flour that primarily determines the properties of the resulting mixture. Flour serves not only as the main source of microorganisms but also as a nutrient provider essential for their growth and reproduction.

Usually, wheat (*Triticum aestivum*) or rye (*Secale cereale*) flour is used for preparing sourdoughs. Dough made from these types of flour exhibits superior textural properties, such as excellent rising and a fluffy texture. This characteristic is linked to the protein content in these grains: glutenins and gliadins in wheat, and secalins and secalinins in rye [2]. These protein fractions form the gluten network in the dough, where glutenins contribute to its elasticity and strength, while gliadins impart viscosity and extensibility. This structure traps carbon dioxide produced by yeasts, creating bubbles that become the pores in bread crumb.

However, a significant portion of the population suffers from gluten-related disorders. Approximately 3% have celiac disease, or a gluten allergy, and an additional 10–15% experience non-celiac gluten sensitivity [15]. Consequently, there is a growing popularity in producing sourdoughs using gluten-free types of flour, including rice, corn, sorghum, millet, and others [16]. This addresses the issue of gluten consumption and supports local businesses and food security in less protected regions. However, these products often exhibit lower technological quality, such as reduced volume, crumbliness, altered taste, and aroma, among other drawbacks [17]. Thus, widespread market entry for sourdough products made from alternative flours has not yet occurred.

There is a significant amount of research available describing the microbiological composition of sourdoughs in correlation with the type of flour; however, these relationships are not stable. Microorganisms native to each type of flour are adapted to specific environmental conditions, therefore the composition of flour determines factors such as temperature and fermentation duration, which depend on the microbiota inhabiting the flour [18, 19]. Thus, the variety of flour determines biodiversity [20], the ecology of microbial cultures [21, 22], the rheological properties of the dough obtained from it [23, 24], and finally, the organoleptic characteristics of bakery products [22, 25].

The quality of flour is another factor influencing the species diversity in sourdoughs. It is determined by the degree of milling — the level of grain grinding. Higher-grade flours contain only endosperm, thus having fewer proteins, mineral components, and microelements that are present in other parts of the grain. Therefore, using lower grades of flour may be better for sourdough fermentation, as they have higher buffering capacity, preventing rapid acidification of the medium and promoting the development of greater biodiversity and a stable microbial consortium [26].

Species Diversity of Yeast Microflora Associated with Sourdoughs

Yeasts belong to the division *Ascomycota*. These unicellular fungi are reproduced by budding and are facultative aerobes [27]. They are adapted to exist in various nutrient mediums and are unpretentious in terms of trophic preferences. Despite their microscopic size, they play a significant role in human life. In the fields of biotechnology and the food industry, yeast activity contributes to production of various foods and drinks such as beer, wine, cider, coffee, chocolate, and traditional dishes [28, 29].

Arora et al. analyzed scientific publications over a period of 30 years and found that a total of 80 yeast species were identified or mentioned in sourdoughs during that time (Figure). These species belong to the genera *Candida, Kazachstania, Torulopsis, Yarrowia, Pichia,* and, of course, *Saccharomyces*. The species *S. cerevisiae* is the most frequently found in the microflora of sourdoughs (in 68% of cases), even in controlled laboratory studies of spontaneous sourdoughs [30, 31].

Interesting hypotheses exist regarding the origin of the species *S. cerevisiae*. One of the leading and most substantiated theories is that it originated from the wild species *S. paradoxus* as a result of domestication processes. This hypothesis was described by Vaughan-Martini and Martini in 1993 [32]. *S. paradoxus* is closely related to *S. cerevisiae* — they share about 50% of their nucleotide sequences. *S. paradoxus* is found in nature on fruits, trees, soil, etc., and can ferment plant substrates. These wild yeasts were likely involved in the initial episodes of natural fermentation of grape juice or other plant materials. Over time, humans began to use *S. paradoxus* for beverage production through controlled fermentation, gradually selecting strains with better fermentative properties. Eventually, through genetic changes under the

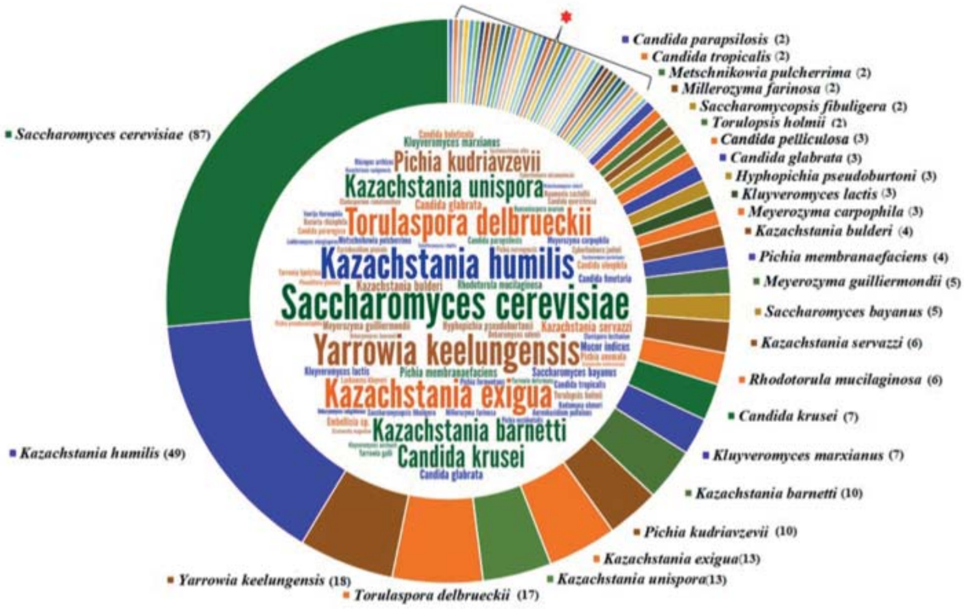

Fig. **The ratio of yeast species that were isolated from starter cultures**
Number of the articles indicating the identification of a given species is highlighted in parentheses; species that appeared in only 1 article are marked with an asterisk [30]

pressure of artificial selection, a separate species, *S. cerevisiae,* emerged, better suited to human needs in the production of fermented products. Several factors support this hypothesis [33]:

1) The close genetic relationship between *S. cerevisiae* and *S. paradoxus*, indicating their common origin, has been demonstrated by other studies as well [34].

2) Greater genetic diversity in *S. paradoxus*, a marker of an older species that is the predecessor of *S. cerevisiae*.

4) The presence of enzymes in *S. paradoxus* for fermenting plant substrates.

5) Historical evidence of yeast usage for producing fermented foods and beverages dates back to ancient times.

Thus, although the domestication of *S. paradoxus* remains a hypothesis, many pieces of evidence suggest a high probability that *S. cerevisiae* may have evolved from its wild ancestor *S. paradoxus* under the influence of artificial selection by humans during the early stages of winemaking and brewing.

Other theories propose the "natural" origin of this species from plant sources, as well as cross-contamination of *S. cerevisiae* environments due to human activity over centuries [30]. While these theories explain the widespread presence of *S. cerevisiae*, a definitive answer to its origin and dissemination remains elusive [34].

However, it is clear that the source of microorganisms for sourdough fermentation can be not only flour (which plays a leading role) but also air, surfaces in the environment where the baker or researcher works, fruits, and other possible ingredients, and even the skin of the bakers themselves [20]. There is insufficient evidence to establish correlational links between the geographic location of bakeries and the types of yeasts predominant in local sourdoughs to confidently predict the composition of the microbiome, and all existing matches may simply be coincidences [35]. Nevertheless, some species occur more frequently in certain regions: in Italy, these include *S. cerevisiae* and *K. humilis*, along with regular reports of *T. delbrueckii*, *Wickerhamomyces anomalus*, *K. exigua*, and *P. kudriavzevii*; in France, *K. bulderi* and *K. humilis* are common, while *S. cerevisiae* appears with variable frequency [36]; in Belgium, *S. cerevisiae* and *W. anomalus* are prevalent [37]. For sourdoughs from Turkey, differences were observed even within a single region: in the city of Safranbolu, in the north-central part of the country, *T. delbrueckii* was the most common, while in Trabzon, in the northeast, *S. cerevisiae* was predominant, despite both cities being located on the Black Sea coast [24].

Yeast Adaptation to Fermentation Conditions

It is worth noting that not all yeast species can be used during sourdough fermentation, as the conditions they encounter are quite harsh. Yeasts are subjected to acidic, osmotic, and temperature stresses, as well as nutrient deficiencies, high cell population densities of lactic acid bacteria (which outnumber the yeasts), and oxidative stress. Therefore, species typical for sourdough microflora have developed phenotypic responses that allow them to adapt to these harsh conditions. One of these responses is gene repression or induction. For instance, the transcription factors Msn2 and Msn4 determine yeast behavior under most stress conditions, including high or low temperatures, oxidative stress, carbohydrate starvation, osmotic shock, and high ethanol concentrations. They alter cell metabolism by activating genes involved in heat shock proteins, mitochondrial respiration, glycogen synthesis, trehalose synthesis, and the pentose phosphate pathway [38]. Another response pathway is the synthesis of metabolites that are not suppressed even when the cell is under stress. For example, glycerol is produced as an osmoprotector in response to high salt concentrations [31]. Takagi reported that some yeast strains that accumulated proline showed better survival under osmotic stress or low temperatures. Succinic acid was produced by yeasts at high acidity levels [39].

Overall, the strains associated with sourdoughs exhibit high tolerance to the low pH that fermentation entails. Yeasts are adapted to the presence of lactic, acetic, and other organic acids in the environment. Moreover, it has been found that yeast stress is induced not by the level of acidity, but by the degree of dissociation of organic acids, known as pKa. For example, the growth of *K. humilis* does not cease at pH 3.5–5.5; however, its ability to leaven dough decreases in the presence of undissociated acetic acid [2].

The Role of Yeast in Sourdough Fermentation Processes

The primary function of yeasts in sourdough fermentation is the "rise" of the dough. This is achieved through the release of carbon dioxide in anaerobic conditions, where oxygen is absent or present in very limited quantities. This occurs during glycolysis when glucose is broken down into two molecules of pyruvate, which are converted into two molecules of ethanol and two molecules of CO_2 [28]. The overall equation of this process is as follows:

$$C_6H_{12}O_6 \rightarrow 2\,C_2H_5OH + 2\,CO_2\,.$$

This process is highly inefficient for the cell because only 2 molecules of ATP are produced from one molecule of glucose compared to 38 molecules of ATP that can be generated from the same amount of glucose during the tricarboxylic acid cycle. Additionally, the rate of carbon dioxide release is not constant and depends on the activity of the glycolytic pathway enzymes [40]. Retaining this gas is another crucial part of the leavening process, directly determining how much the dough will rise. As mentioned earlier, this depends on the content and composition of gluten proteins in the flour, which form a protein network in the dough that traps and holds carbon dioxide. When the dough becomes saturated with it, the number of bubbles (alveoli) does not increase, but their diameter does. The stretching ability of the gluten network is crucial here. A larger loaf volume correlates with better crumb characteristics: softness, airiness, and longer shelf life [2].

Looking again at the fermentation equation, it is evident that alongside carbon dioxide, yeast cells also produce ethanol. Despite much of it evaporating during baking, ethanol still affects the rheology of the dough. The aqueous solution of ethanol formed in the dough promotes the development of the gluten network because it is a better solvent for the prolamin fraction proteins than water. Additionally, low ethanol content increases the dough's strength but negatively impacts its extensibility [41].

Yeasts is capable of producing a significant amount of other metabolites. For instance, glycerol enhances dough stiffness by influencing the gluten network [42]. Additionally, yeasts can produce small amounts of organic acids, including lactic and acetic acids, contributing to the overall acidity of the sourdough [43]. Generally, these secondary metabolites do not play a major role in fermentation per se, but nevertheless influence the texture and consistency of the dough to some extent.

Yeasts contribute significantly to the flavor and aroma profile of bakery products. They are capable of producing a wide variety of aromatic compounds through several metabolic pathways, with the Ehrlich pathway being prominent, involving amino acids. The main substances influencing the development of aromatic characteristics in baked goods are higher alcohols, aldehydes, esters, and ketones [44]. Aldehydes and alcohols are formed during the breakdown of branch-chained amino acids. For instance, 3-methyl-1-butanol is derived from leucine, and 2-phenylethanol from phenylalanine. Studies have shown that fermentation with added yeasts leads to higher levels of methylpropanol, methylbutanol, ethyl acetate, and diacetyl compared to fermentations without yeasts, indicating their involvement in the synthesis of these compounds. Amino acids ornithine and citrulline, typical for yeasts, are associated with a popcorn-like aroma during fermentation [45]. Some yeast species even specifically impart certain aromas to bread. For example, *S. cerevisiae* produces balsamic, honey-like, floral, buttery, and malty aromas, while *K. humilis* contributes fruity and herbal flavors [22, 46]. Additionally, melanoidin formation (Maillard reaction) and caramelization reactions, affecting the color and crust of bread, rely on yeast enzymes that hydrolyze carbohydrates [40].

The synthesis of aromatic compounds is influenced by the interaction of yeasts with lactic acid bacteria (LAB). This interaction often results in lower levels of aromatic compounds compared to pure yeast cultivation, indicating a symbiotic relationship between the cultures. Furthermore, the production of certain substances occurs only in the presence of symbiotic species in the starter culture [43]. A notable example of mutualistic relationships is the interaction between *K. exigua*, which is maltose-negative, and *L. sanfranciscensis*, which hydrolyzes complex sugars and consumes maltose, releasing glucose for the symbiotic species [47].

The Impact of Yeasts on the Nutritional and other Characteristics of the Final Product

Overall, among the advantages of using sourdough for baking bread, one can highlight increased nutritional value, lower glycemic index and starch digestibility, extended shelf life, reduced bread spoilage rate, and its use as a natural alternative to chemically-based preservatives. Yeast contributes to these properties at least as part of the microbiological consortium of sourdough.

However, they also have a direct impact on the formation of most of the mentioned benefits. Specifically, yeast produce B vitamins, including niacin, riboflavin, biotin, and folic acid [48]. It has been shown that the levels of folic acid, riboflavin, and thiamine increase during prolonged fermentation processes involving yeasts [49]. While strains vary in their production levels of folic acid, the use of high-productivity yeast strains can replace the artificial addition of vitamins [2].

Furthermore, flour is a source of essential minerals necessary for human functioning; however, their absorption through bread consumption is severely limited due to the presence of phytic acid. Phytic acid binds ions such as Ca^{2+}, K^{+}, Mg^{2+}, $Fe^{2+/3+}$, Zn^{2+}, and others into insoluble complexes, hindering their absorption [50]. Phytase enzymes, which release mineral components, are naturally present in flour but can only be activated in acidic environments provided by sourdough fermentation. Moreover, yeasts also possess phytase activity, although the optimum pH for yeast enzymes is around 3.5, compared to pH 5.0 for wheat phytases [18]. It is also possible that some yeast strains with high phytase activity could colonize our gastrointestinal tract [51], potentially enhancing nutrient absorption from food. Some yeast strains may exhibit probiotic properties, promoting gut microbiota health [52]. The use of such strains would be a significant advantage for individuals with gastrointestinal disorders.

During sourdough fermentation of whole grain flour, there is also an increase in the bioavailability of compounds with antioxidant properties, such as phenolics. Yeast plays a crucial role in releasing polyphenols from the cell wall matrix where they are bound [53, 54]. This process has been utilized during pizza dough fermentation, where a reduction in reactive oxygen species (ROS), particularly hydroxyl radicals, was observed alongside an increase in free ferulic acid content. Ferulic acid is known for its antioxidant properties and is characterized by its anti-inflammatory, neuroprotective, and anticancer effects [51, 55]. Additionally, yeasts has been found to produce specific enzymes and peptides that positively impact the antioxidant properties of bakery products [56].

The safety of bread and other bakery products is another important characteristic of the final products. Even before scientific studies, it was noted that using sourdough prevents rapid spoilage and delays staling. Later research revealed that the low pH created by sourdough acts as a barrier against foreign microorganisms. However, this is not the only protective mechanism. Some yeast species are capable of producing protein compounds that have cytotoxic effects on microorganisms. For instance, *Pichia anomala* produces ethyl acetate, that exhibits antagonistic activity [57]. Moreover, certain strains of lactic acid bacteria and yeast produce hydrogen peroxide and ethanol, which have antifungal properties and inhibit the synthesis of mycotoxins [58]. Coda et al. successfully extended the shelf life of bread by up to 14 days by adding *Candida guilliermondii* (formerly known as *Meyerozyma guilliermondii*) yeast to the sourdough fermentation. This yeast species showed fungistatic activity and was combined with *Wickerhamomyces anomalus,* previously known as *Pichia* *anomala*, 1695 and *Lactobacillus plantarum* 1A7, already known for their antifungal properties. Together, they prevented spoilage even when intentionally introducing mold at high concentrations [59].

The moisture content of sourdough is an important indicator that affects both the microbial composition and the properties of the sourdough, and consequently, the final product. Sourdoughs with high moisture content (around 70%) or high dough yield (DY) (around 200 % and above) are more liquid and practical for industrial use due to their lower viscosity, which facilitates automation, mechanization of processes, transportation, and dosing [60]. Sourdoughs with lower moisture content (around 50%) or lower DY (around 150–160%) are more demanding in terms of handling and control. Their advantages include an increased buffering capacity of flour, which prevents rapid acidification of the dough, even during high production of organic acids [25].

The consistency of sourdough also influences the diversity of microbiota it contains. This is likely related to the uniform distribution of nutrients in the sourdough environment, their availability to cells, and the rate of acid accumulation [22]. In liquid sourdoughs, the ratio of lactic acid bacteria (LAB) to yeast tends to favor LAB, as they are more tolerant to acidic conditions. On the contrary, in dense sourdoughs, the balance shifts towards yeast [25].

Lower moisture content in sourdough correlated with improved dough and final product characteristics. In dough preparations, there was accelerated acidification, reflected in an increase in titratable acidity by 4.6 degrees and a decrease in pH by 1.11. The dough's lifting capacity of the leavening power increased by 15 minutes, and the resting period decreased by 10 minutes. The final products had a larger specific volume, and their acidity decreased more significantly, likely due to a greater conversion of acids into volatile forms. Additionally, besides yeast predominance, dense sourdoughs were characterized by a higher content of heterofermentative LAB, which were prone to producing volatile acids: 13–34%, unlike homofermentative bacteria. Assessment of products from denser sourdoughs also showed better results compared to other products [60].

Conclusions

Sourdoughs in bread baking represent complex microbiological systems characterized by symbiotic interactions between lactic acid bacteria and yeast. Yeasts associated with sourdoughs constitute a diverse group, encompassing over 80 species predominantly belonging to various genera. Among them, *Saccharomyces cerevisiae* stands out as the most prevalent species. The composition of yeast microflora can vary depending on geographic origin, flour type, and other environmental factors.

Yeasts associated with sourdoughs have developed a range of adaptive mechanisms to survive stressful fermentation conditions such as high acidity, nutrient scarcity, oxidative stress, and others. Their primary function in sourdoughs is to facilitate the leavening process by producing carbon dioxide during ethanol fermentation. However, their contribution extends beyond leavening. Yeasts play a crucial role in shaping the flavor and aromatic characteristics of bakery products by synthesizing a wide array of aromatic compounds.

They are capable of increasing the nutritional value of products by enriching them with vitamins of the B group and improving the availability of mineral substances. Yeasts also contribute to the release and enhanced bioavailability of antioxidant compounds from enhancement grain crops. Certain yeast strains may exhibit antimicrobial activity, extending the shelf life of bread and preventing spoilage. Some types can produce substances with probiotic properties, making them promising for use in baking with additional health benefits.

Considering the functional importance of yeasts, a promising direction of work is screening and identifying new yeast strains from spontaneous sourdoughs with unique properties, and developing new compositions of starter cultures based on their abilities for the production of a wide range of bakery products with improved organoleptic, functional, and health-promoting properties.

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Authors' contribution

Ye.R.H. — prepared the manuscript and analyzed data; O.V.N. — author and project manager; I.V.L. — data collection and analysis; V.O.H. — data analysis, conceptualization and edited the manuscript; L.V.M. — suggested the study and project administration.

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ДРІЖДЖІ У ХЛІБОПЕКАРСЬКИХ ЗАКВАСКАХ: ЗАГАЛЬНІ ВІДОМОСТІ ТА РОЛЬ У ФУНКЦІОНАЛЬНИХ ПРОЦЕСАХ

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Хлібопекарські закваски — унікальні мікробіологічні системи із симбіотичною взаємодією молочнокислих бактерій та дріжджів. Дріжджі разом з молочнокислими бактеріями відіграють значну роль у ферментації заквасок та є важливими для формування технологічних і функціональних властивостей продукту.

Мета. Аналіз наукових даних щодо значення дріжджів у формуванні властивостей хлібопекарських заквасок та готової продукції.

Методи. Пошук та аналіз релевантної наукової літератури, систематизація та узагальнення результатів доступних публікацій.

Результати. Показано вагому роль дріжджів у формуванні властивостей закваски та кінцевих хлібопекарських виробів, зокрема, для розпушування тіста, формування смакових і ароматичних характеристик, збагачення хліба біологічно активними сполуками, підвищення біодоступності та терміну зберігання.

Висновок. Наголошено на важливості цих знань для вдосконалення технологій виробництва хлібобулочних виробів із застосуванням стартерних композицій для ферментації заквасок і раціонального добору штамів дріжджів з метою регулювання органолептичних і функціонально-технологічних властивостей готової продукції.

Ключові слова: хлібопекарські закваски, дріжджі, ферментація, органолептичні властивості, поживна цінність, адаптаційні механізми.

активність *L. officinalis* вивчали за допомогою когерентного монохроматичного лазерного світла низької інтенсивності із заданими спектральними та інтенсивними характеристиками. В експерименті використовувалися водні колоїдні розчини наночастинок біогенних металів, таких як FeNPs, MgNPs і AgNPs, отримані методом об'ємного електроіскрового диспергування металів у рідині.

Результати. Оброблення інокулюму *L. officinalis* колоїдними розчинами наночастинок усіх використаних металів посилює ріст на 31–54% , а опромінення інокулюму гриба лазерним світлом у середовищі з наночастинками знижує ростову активність міцелію на 14,4–22,6% . Усі наночастинки металів пригнічували біосинтез позаклітинних полісахаридів, тоді як оброблення посіву колоїдними розчинами FeNPs та MgNPs стимулювало синтез ендополісахаридів. Водночас опромінення лазерним світлом у присутності AgNPs збільшувало кількість ендополісахаридів, тоді як FeNPs та MgNPs дещо пригнічувало їх синтез. Оброблення посівного матеріалу колоїдними розчинами металів і лазерним випромінюванням впливало на кількість загальних фенольних сполук (TPC) у міцеліальній масі. Найвищі значення TPC зафіксовано у етанольних екстрактах міцеліальної маси з AgNPs та опромінених лазерним світлом становлять 97,31±3,7 мг еквівалента галової кислоти на 1 г сухої маси (мг ЕГК/г). Найнижчі значення у розчинах метанолу з MgNPs без опромінення становили 58,12±3,2 мг ГКЕ/г сухої маси.

Висновки. Результати досліджень дають підстави розглядати наночастинки біогенних металів (AgNPs, FeNPs, MgNPs) та низькоінтенсивне лазерне світло як перспективний регулятор біосинтетичної активності *L. officinalis* у біотехнології його культивування.

Ключові слова: лазер, міцелійна маса, полісахариди, загальні фенольні сполуки, антиоксидантна активність.