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Exploring attitudes towards GMO labelling: a study on the Czech population

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Abstract

Introduction. The debate surrounding the labeling of genetically modified organisms (GMOs) has largely shifted from whether to label to understanding the various reasons behind supporting or opposing such labeling.

Materials and methods. This paper studies factors influencing attitudes towards GMO labeling employing a representative sample of the Czech population (N=884). We examine the impact of information about genetically modified foods (GMFs), environmental concerns, perceived health effects, dietary habits, factors considered important when purchasing, and sociodemographic characteristics on GMO labeling preferences in the framework of ordinal regression analysis.

Results and discussion. Our findings reveal that almost one third of the respondents is not familiar with genetically modified foods (GMF). Another third confirm that they are familiar with the GMF, but does not know what it refers to. Almost eighty percent of the respondents do not express interest in GMF. On the other hand, the results suggest that the health concerns and the level of interest and information about GMO significantly predict the propensity to check GMO labels and the belief that the GMO products should be labelled. The current subjective state of health was not related to the attitudes to GMO labelling. Environmental considerations, such as the subjective effect of food production on the environment and the current environmentally conscious behavior (recycling and environmental waste management at home) positively predicted the need for labelling and the propensity to check labels. Additionally, individual dietary habits, such as shopping habits showed to affect the subjective proportion of GMO products the respondent eats. The results will be interested to marketing specialists and policy makers.

Conclusion. This research contributes to understanding the multifaceted dynamics underlying public attitudes toward GMO labeling and provides valuable insights for policymakers and stakeholders in the ongoing debate about genetically modified products.

Introduction

The ongoing debate over the labeling of genetically modified foods (GMFs) reflects a complex interplay of public interest, health concerns and the availability of information. Discourse on genetically modified foods (GMFs) is shaped by various sources, including mass media, websites and informal communication channels (Gibson et al., 2022). Considering the above pros and cons, this public discourse can be encapsulated in five overarching themes: the basic science of biotechnology, food and feed safety assessment (including labelling), environmental safety assessment (including pest control, use of pesticides or chemicals, biodiversity, mitigating climate change and environmental degradation), government regulations and global trade in GM crops (Arcelo-Villena, 2019).

Despite unanimous conclusions from several risk assessments confirming the safety equivalence of genetically modified foods with conventional crops in terms of human and animal health (Smyth et al., 2021), the public still tends to take GMFs with apprehension due to the perceived potential risks. As a result, regulatory measures have been introduced, particularly in Europe, with parallel developments observed in developing countries across Africa and Asia, regions that may gain significant benefits from the adoption of GM products (Qaim, 2020).

In the European Union, the European Food Safety Authority (EFSA) plays a key role in conducting risk assessments for regulated food and feed, including GM crops. EFSA's approach is based on a comprehensive framework of legal and methodological guidelines that govern the decision whether to authorize a particular food or feed for the European market (Garcia-Alonso et al., 2022; Hilbeck et al., 2020). However, the regulatory process is not without problems, as evidenced by the estimated cost of approving genetically modified food and feed in the EU ranging from €11 to €16.7 million (EuropaBio, 2019).

As the discourse has evolved beyond the mere question of whether to label GMO products, understanding the factors that drive the public to label GMFs has become essential. This paper aims to contribute to this discourse by examining the influence of environmental concerns, perceived health risks associated with GMOs, and the availability of information on the public's demand for GMF labeling, as well as their propensity to read such labels. This investigation is conducted on a representative sample of the Czech population, including 884 individuals aged 18 to 90 years (M ± SD: 48.17 ± 17.72; 53.40% women, 18.04% with higher education).

Methodologically, our approach involves hierarchical ordinal regression analysis to examine the relative impact of these key factors on public attitudes towards GMF labelling. In the first stage of our analysis, we examine the overall predictive power of environmental issues, health risks, and information availability. Acknowledging the paramount importance of GMF-induced health effects, we then delve into a second-stage hierarchical regression to discern the predictive power of GMO-induced negative health effects relative to other factors influencing labeling attitudes.

By focusing on these aspects, the present study aims to offer a detailed understanding of the factors that shape public opinion on GMF labeling and to provide insights that can inform both academic discourse and policy decisions on GM products.

The organization of the paper develops as follows: The introductory sections provide an overview of the public discourse on genetically modified foods and offer a synthesis of the existing discussion on GMF. The following segments detail the literature review, data collection process, and chosen methodology. Subsequently, we present the findings, engage in a comprehensive discussion and draw conclusions.

Genetically modified foods: a review of health, ecological and ethical aspects

Genetically modified foods (GMF) have become the focus of intense scrutiny, leading to a comprehensive examination of their multifaceted implications. This review delves into three primary dimensions – health, ecology and ethics – to provide a detailed understanding of the challenges and opportunities that GMF presents. Health considerations include potential risks associated with consumption, examination of issues such as toxicity and allergenicity, as well as examination of claims of changes to human DNA. On the environmental front, the assessment reviews both negative concerns, including reduced biodiversity and potential contamination, and positive aspects, such as reduced reliance on harmful chemicals in agriculture. In addition, ethical considerations are explored that deal with moral objections and cultural perspectives that view genetic modification of food as a violation of the natural order and a violation of fundamental principles. By synthesizing these aspects, this review aims to contribute to a balanced discourse on GMFs and to inform discussions about their cultivation, regulation and adoption in our global food systems.

Health risks associated with genetically modified foods

The introduction of genetically modified foods (GMFs) has sparked extensive debate with a primary focus on health risks. Researchers such as Ozkok (2015), Gizaw (2019), and Krimsky (2019) have highlighted concerns related to GMF. Among the prevalent health problems associated with GM foods, toxicity and allergenicity are often highlighted (Zhang et al., 2016). Consumer reports following the introduction of transgenic corn revealed an association between GM corn consumption and food allergy symptoms, including headaches, diarrhea, nausea, and vomiting (Bernstein et al., 2003; Dona and Arvanitoyannis, 2009).

Another major health issue revolves around the potential alteration of human DNA as a result of substantial modifications to our diet through GM foods. The change can occur through the insertion of foreign genes into the human genome or through cumulative changes in metabolic processes resulting from modified food intake. However, current evidence as reported by Nawaz et al. (2019), does not conclusively demonstrate a causal link between GM foods and changes in human genetics. Despite two decades of widespread GM food consumption, no confirmed cases of gene insertion in humans directly linked to GM food intake have been reported.

Environmental impacts of GMOs

Genetically modified organisms bring a spectrum of potential environmental impacts and generate both concerns and potential benefits. Tsatsakis et al. (2017) elaborate on the negative consequences, including the reduction of biodiversity, potential contamination by non-genetically modified organisms, disruption of natural ecosystems due to the widespread introduction of GMOs, and the potential reduction in the effectiveness of some pest deterrents. The risk of unintended gene transfer between species is another threat that leads to unpredictable impacts on the environment and food webs.

Conversely, GM crops offer positive environmental effects by reducing the need for herbicides, pesticides and other chemicals in food production. This reduction is in line with environmental sustainability goals and contributes to reducing the environmental impact associated with traditional agricultural practices. As the complexities surrounding GMOs develop, it becomes essential to consider both potential risks and benefits in order to make informed decisions about their cultivation and use in agricultural systems.

Moral and ethical dimensions of GMF

Criticism of GMF goes beyond scientific concerns and includes moral and ethical dimensions. Knight (2009), Kumar and Yadav (2021) and Green (2023) highlight the prevailing moral objections, particularly regarding the perception that GMFs disrupt the natural order of food production. Genetic modification of foods involves changing their DNA to increase nutritional content or resistance to disease, pests or environmental stressors. Many individuals find this manipulation morally objectionable and see it as a violation of the fundamental principles of nature. There are also concerns about potential long-term health risks and unintended environmental consequences through cross-pollination.

Religious beliefs further contribute to ethical discourse, particularly in cultures where religion strongly influences dietary practices. Streiffer and Hedemann (2005) and Chen and Li (2007) note that the introduction of genetically modified foods may conflict with established religious doctrines, reducing their acceptance in the general population. Individuals express concern about GMOs as interfering with natural processes and disrupting nature's delicate balance, leading to fears of unforeseeable consequences and the ethical dilemma of "playing god". Even those without religious objections may reject GMFs out of a broader respect for nature or fear of potential unknown dangers associated with their consumption. The intersection of ethical considerations and belief systems plays a critical role in shaping public policy decisions and influencing consumer decisions as GMOs continue to evolve and affect our food systems.

Public awareness challenges and the role of knowledge

A significant gap in public awareness of the scientific evidence surrounding genetically modified technologies contributes to confusion among the general population. Sikora and Rzymski (2021) highlight the polarization evident in media debates between proponents and opponents of GM, further fueled by deliberate anti-GM actions led by non-governmental organizations (NGOs). The dissemination of information through social media, which often lacks a scientific basis, increases the complexity of public understanding (Jiang and Fang, 2019). Individuals with limited knowledge, including parents, play a key role in shaping perceptions of GMOs (Shtulman et al., 2020).

Empirical evidence from studies such as Moon and Balasubramanian (2004), Moerbeek and Casimir (2005), and Vilella-Vila et al. (2005) highlights a direct and positive relationship between increasing knowledge of GM technologies and increased support for their applications (Costa-Font et al., 2008). Targeted information campaigns have the potential to cultivate an informed public and promote a more objective understanding of the risks and benefits associated with GM products. However, the impact of knowledge is varied, influenced by perceptions of the morality of genetic modification, rather than simply dependent on political or religious views (Hasell and Stroud, 2020).

Conversely, some studies question the assumed direct link between scientific knowledge and attitudes, suggesting that the correlation between science-based information about GMF and public perception remains weak and in some cases non-existent (Diamond et al., 2020). Government regulatory policies and laws regarding the cultivation and sale of genetically modified products are important determinants of public acceptance. Consumers who do not agree with these policies can express their disapproval by protesting GM products, even if they are not directly affected. As the debate on GM technologies continues to evolve, the multifaceted interplay between knowledge, perception and regulatory

frameworks will play a key role in shaping public attitudes and influencing wider societal acceptance of genetically modified products.

GMF labelling

In many countries, the absence of clear regulations governing the labeling of genetically modified foods has left consumers uncertain about the products they buy and consume, contributing significantly to the prevailing sense of mistrust of the technology. The introduction of mandatory labeling of genetically modified organisms represents a potential solution to alleviate the lack of information on GMFs. The issue of GMO labeling has been central to political and public discourse since the beginning of commercialized GM technology (Adalja et al., 2023). Consumers express a critical need to be informed about the presence of transgenic ingredients in their food in order to make informed consumption decisions (Delgado-Zegarra et al., 2022).

Voluntary labeling initiatives, particularly for non-GMO (third party verified) products, have gained traction in the United States to address consumer preferences. This approach resonated with consumers and increased sales of non-GMO products to over $26 billion in 2019 (Food Business News, 2019). Such labeling is particularly important for consumers who are concerned about safety and show resistance to GM technologies (Zheng and Wang, 2021). Research also shows that consumer demand for GM foods is influenced by labeling schemes adopted by policy makers (Kim et al., 2022). As a result, mandatory labeling requirements are emerging as an essential tool to provide transparent information to consumers and enable them to make informed decisions about food choices.

While some studies suggest that the cultivation and production of modified products can lead to lower production costs (Azadi and Ho, 2010; Ekici and Sancak, 2012), a significant segment of consumers choose more expensive non-GMO alternatives for reasons of principle rather than for functional reasons. . This preference is consistent with a broader pattern of low public acceptance of GM foods, with consumers having subjective knowledge and limited objective understanding demonstrating a greater willingness to pay for non-GMO variants (Rihn et al., 2021). As debates about GMOs and labeling evolve, the dynamic interplay between regulatory frameworks, consumer preferences, and the principles that guide food choices will continue to shape the landscape of GM food acceptance and consumption.

This paper concentrates on two main discourses: the effects of environment protection and supposed health risks on GMF acceptance. As the consumer preferences are highly impacted by the available information, we also research the effect of information availability on the GMO acceptance.

H1: GMF labelling requirements are predicted by environmental concerns

H2: GMF labeling requirements are negatively predicted by perceived health risks

H3: GMF labelling requirements are predicted by availability of relevant information including the interest in the subject.

Material and methods

Data

The survey data was collected in July 2021 through a study called "Food 2021" conducted by the Czech Sociological Institute. A total of 884 participants, reflecting the population of the Czech Republic, answered the questionnaire voluntarily and anonymously (age 18–90 years, M ± SD: 48.17 ± 17.72; 53.40% women, 18.04% with higher education). The survey was conducted under the supervision of 139 experienced interviewers who used a combination of Paper and Pencil Interview (PAPI) and Computer-Assisted Personal Interview (CAPI) methods. Due to the high quality of completed questionnaires, all collected data were included in the sample. Participants, native speakers residing in the Czech Republic, were selected using quota sampling by region (NUTS 3), size of place of residence, gender, age and education. This dataset, provided by the Czech Social Science Data Archive (Institute of Sociology. Academy of Sciences of the Czech Republic. 2021), is representative of the Czech Republic.

Method

We apply hierarchical ordinal regression analysis to test the following hypotheses (Graph 1):

Graph 1

Hypotheses

GMF Labelling	Are predicted by ⇐	Information about GMF
		GMF effects on health
		Environmental concerns

Additionally, we incorporate controls for the significance of food and food-related habits, as well as socio-demographic factors.

The hierarchical ordinal regression analysis consists of two sequential steps. Initially, we assessed the model with all explanatory variables based on the specified formula (Formula 1).

$$GMF\ Labelling = Logit\ (a_0 + a_{1\text{-}3}\ Information + a_{4\text{-}8}\ Health + a_{9\text{-}12}\ Environment + a_{13\text{-}17}\ Food\ Purchasing + a_{18\text{-}20}\ Food\ habits + a_{21\text{-}27}\ Socio\text{-}demographics + e) \quad (1)$$

In the second stage, we omitted the set of variables associated with health effects and performed ordinal regression using the following formula (2):

$$GMF\ Labelling = Logit\ (a_0 + a_{1\text{-}3}\ Information + a_{9\text{-}12}\ Environment + a_{13\text{-}17}\ Food\ Purchasing + a_{18\text{-}20}\ Food\ habits + a_{21\text{-}27}\ Socio\text{-}demographics + e) \quad (2)$$

It was contrasted the pseudo R-squared values between both models and drew conclusions regarding the moderation effects of the excluded variables.

Indicators

GMF labelling needs

Examining GMO labeling needs includes three dimensions: perceived importance of having GMO information on labels, frequency of checking GMO labels when shopping, and current perception of GMO content in consumed foods. The survey questions were formulated as follows:

- "To what extent do you agree or disagree with the following statements? Foods containing ingredients from genetically modified crops should have this information in the description or on the label.
- How many of the foods you normally eat do you think contain ingredients from genetically modified crops?
- When you buy food, how often do you check the label for ingredients from genetically modified crops?" (Sociologicky ustav, 2021)

Table 1 shows that approximately 74% of participants agree that genetically modified foods should be labelled. Conversely, 60% of respondents said they never checked information about GM ingredients on food labels. Data on the actual consumption of GMFs is quite limited, almost 40% of the participants did not express any opinion about the share of GMFs in their total food intake.

Table 1

Distribution of respondents (%) based on attitudinal indicators for genetically modified foods (GMF)

Question	Definitely agree	Rather agree	Undecided	Rather disagree	Definitely disagree	No opinion
Food items containing genetically modified ingredients should carry labels indicating their genetic modification status.	51.1	23.2	9.3	2.9	1.6	11.9
What proportion of the foods you consume contains genetically modified (GM) ingredients?	Almost none	Rather a minority	About half	Rather the majority	Almost all	No opinion
	14.9	27.8	13	4.6	0.8	38.8
	20.4	41.7	15	12.4	10.4	
Examine food labels for genetic modification information during your purchases.	Always	Often	Rarely	Never		
	3.1	10.9	25.7	60.4		

Note: Due to a notable number of individuals expressing no opinion on the perception questions, we included these respondents in the "undecided" category wherever applicable (category 3 on the 5-point Likert scale).

Information about GMF

Access to information plays a crucial role in shaping opinions. This study utilizes indicators to assess the availability and adequacy of information, while also accounting for the respondents' level of interest in the subject. Table 2 provides an overview of the indicators, scales, and the distribution of respondents regarding information about GMF.

Table 2

Distribution of Respondents (%) Based on Indicators of Genetically Modified Foods (GMF) Information

Are you familiar with genetically modified crops?	No	Yes, but does not know what it refers to	Yes, and roughly knows what it involves	Yes, and knows well what it involves	
	27.7	31.9	33.4	6.8	
Do you have an interest in Genetically Modified Products (GMP)?	definitely yes	rather yes	rather no	no	does not know
	3.3	12.7	32.9	48.4	2.6
Do you possess sufficient information about Genetically Modified Foods (GMF)?	definitely enough	rather enough	rather not enough	definitely not enough	does not know
	3.1	14.1	32.5	40.8	9.4

Respondents who answered, "do not know", were excluded from subsequent analysis.

Perceived GMF effects on health

The existing literature indicates that perceived health effects are among the most significant informational challenges influencing legislation and public acceptance of Genetically Modified Foods.

Environmental concerns

The initial indicator of environmental concerns determined the degree of subjective importance of the impact of food production on the environment (Definitely important: 11.10% of respondents; Rather important: 37.30%; Rather unimportant: 30.10%; Definitely unimportant: 11.00%; No opinion: 3.70%.

We then assessed environmental concerns based on the frequency of participation in pro-environmental behaviors. The descriptive statistics is presented in Table 4.

Table 3

Distribution of Respondents (%) Based on Indicators of Perceived Effects of Genetically Modified Foods (GMF) on Health

Self-assessment of personal health	Very good	Good	Average	Bad	Very bad	
	20.00	42.30	29.30	7.50	0.90	
Consuming Genetically Modified Foods (GMF) is safe	Definitely agree	Rather agree	Undecided	Rather disagree	Definitely disagree	No opinion
	4.30	18.40	26.80	16.20	8.90	25.10
Research on the Health Effects of Genetically Modified Products (GMP) is sufficient	Definitely agree	Rather agree	Undecided	Rather disagree	Definitely disagree	No opinion
	5.90	22.50	21.60	15.50	7.90	26.50
Consuming GMP can change human DNA	Definitely agree	Rather agree	Rather disagree	Definitely disagree	No opinion	
	5.40	15.70	21.20	21.40	36.20	
GMF can endanger human health	Definitely agree	Rather agree	Rather disagree	Definitely disagree	No opinion	
	10.30	24.70	24.40	7.00	33.60	

Note: Respondents with no opinion were combined with the "Undecided" group for subsequent analysis.

Table 4

Indicators of environmental concerns. Descriptive statistics

How frequently does the respondent:	Mean	Std. Deviation
Utilize their own reusable shopping bag	3.98	1.182
Use reusable bags for purchasing fruits and vegetables	2.35	1.410
Use reusable bottle for drinks	2.71	1.428
Use environmentally friendly detergents	2.72	1.204
Prefer purchasing czech-made foods	3.35	1.088
Pack the food into reusable boxes	2.71	1.353
Avoid single-use plastic products	3.21	1.301
Limit car trips to protect the environment	2.15	1.195
Conserve energy and water to protect the environment	2.92	1.266
Practice waste sorting	3.96	1.159
Engage in composting	2.58	1.618

Note: N=727. The respondents with No opinion were excluded from further analysis

To simplify the model, we employed Principal Component Analysis (PCA) on the indicators outlined in Table 4, utilizing regression-based factor scores for subsequent analysis. The outcomes of the PCA are detailed in the Data Transformation section, where three components were identified: inclination toward waste reduction and sorting, resource conservation, and engagement in recycling.

Significance of food characteristics in purchase decisions

Consumers evaluate several characteristics to varying extents when making food purchases, including consideration of ingredients, package material and size, origin, and, notably, price (refer to Table 5). We posit that these factors serve as crucial predictors for attitudes towards Genetically Modified Foods (GMF).

Table 5

Indicators of the importance of food characteristics when purchasing

Indicators	Mean	Std. Deviation
Origin	3.1	1.479
Package material	4.89	1.298
Price	2.22	1.438
Ingredients	2.78	1.412
Package size	3.48	1.472

N=799, Min=1 (very important), Max=6 (least important)

Significance of food and dietary practices

Table 6

Indicators of the importance of food and dietary practices. Distribution of respondents (%)

Food consumption important	Definitely important	Rather important	Rather unimportant	Definitely unimportant		
	43.30	43.00	9.80	3.40		
Frequency of food purchasing	Daily	Several times a week	Once a week	Once per 14 days	Less than once per 14 days	No answer
	9.80	50.80	23.50	5.50	3.50	6.70
Number of meals per day	One meal	Two meals	Three meals	Four meals	Five meals	More than five
	0.10	8.50	39.90	30.70	16.40	4.10

Socio-Demographic characteristics of the respondents and other factors

We consider variables such as gender, age, and education (ranging from 18 to 90 years, with a mean ± standard deviation of 48.17 ± 17.72; 53.40% women, 18.04% with higher education), subjective town size (from big city to small village), household standard of living (very good, 13.12%; rather good, 45.5%; neither good nor bad, 33.9%; rather bad, 6.4%; very bad, 0.9%), life satisfaction (very satisfied 20.8%; rather satisfied, 50%; neither satisfied nor dissatisfied, 21.3%; rather dissatisfied, 5.7%; very dissatisfied 1.2%), and belief in God (69.9% non-believers).

Data transformations and handling of missing values

Given the limited awareness about GMFs, certain survey questions recorded a notable proportion of respondents expressing no opinions. In line with the methodology discussed in preceding sections, respondents with no opinions were amalgamated with the Undecided group. It is essential to acknowledge that this data transformation is a recognized limitation of the study. In instances where an "Undecided" category was not available, respondents with no opinions were omitted from subsequent analyses. This approach ensures transparency in data interpretation, emphasizing the challenges associated with gauging public opinion in areas where information levels are inherently low.

Data transformations: analyzing environmental concerns through principal component analysis

To reduce the complexity of our model, we used a principal component analysis (PCA) on a set of variables representing respondents' environmental protection measures (Indicators of Environmental Concerns, Table 4). Factor extraction was determined by an eigenvalue of 1 or greater, and all variables were successfully extracted. Suitability of data for factor identification was confirmed by Bartlett's test of sphericity (chi-square value 1716.968, $p<0.001$) and Kaiser-Meyer-Olkin sampling rate of 0.852 (>0.8). Overall, these two extracted factors cumulatively explained 54.095% of the total variance. The rotated component matrix is shown in Table 7.

Table 7

Rotated Component Matrix for Indicators of Environmental Concerns

Action	Respondent's actions	Component		
		1	2	3
Waste Reduction	Sort waste	0.765	0.059	0.179
	Use own reusable shopping bag	0.623	0.138	0.055
	Prefer purchasing czech-made foods	0.614	0.326	0.125
Resource Conservation for Environmental Protection	Limit car trips to protect the environment	-0.062	0.842	0.113
	Save energy and water to protect the environment	0.394	0.637	0.136
	Avoid single-use plastic products	0.457	0.545	0.101
	Use environmentally friendly detergents	0.410	0.523	0.227
Recycling Efforts	Use own reusable bottle for drinks	0.018	0.127	0.796
	Pack the food into reusable boxes	0.177	0.155	0.760
	Compost	0.421	-0.078	0.500
	Use reusable bags for purchasing fruits and vegetables	0.105	0.367	0.495
% of Variance explained		34.25	10.593	9.252

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.

The regression-based factor scores for all three components were computed and subsequently utilized for further analysis.

Results and discussion

The outcomes of the initial phase of hierarchical ordinal regression analyses are depicted in Tables 8 and 9 below, corresponding to formula 1.

Information and interest

The results, presented in the table 8 suggest, that

- The more the respondent is informed about GMF, (1) the more he believes GMF should be labelled, (2) the more often they check information on GM ingredients when buying food;
- The more often they check information on GM ingredients when buying food;
- The more are respondents confident that they have enough information about GMF the more often they check information on GM ingredients when buying food.

Table 8

Predictive factors of attitudes toward gmf labeling. Results from ordinal regression analysis (formula 1)

	GMF labelled		Check lables on GMF		GMF content	
	Estimate	Sig.	Estimate	Sig.	Estimate	Sig.
Threshold=1	-1.075	0.492	-0.14	0.937	0.962	0.584
Threshold=2	0.31	0.843	2.378	0.174	3.428	0.052
Threshold=3	2.188	0.163	4.853**	0.006	5.190**	0.003
Threshold=4	3.381*	0.033			7.045***	<.001
Information about GMF						
Heard of GMF	-0.662***	<.001	-0.435**	0.002	-0.146	0.309
Interested in GMF	-0.111	0.399	1.200***	<.001	-0.084	0.555
Enough Info about GMF	-0.001	0.988	0.453***	<.001	-0.183	0.055
GMF effects on health						
State of own Health	0.086	0.503	0.183	0.214	-0.212	0.15
GMF is safe	-0.206	0.094	0.067	0.615	-0.26	0.051
the effects of GMP on health are scientifically investigated	-0.113	0.332	-0.102	0.42	0.012	0.926
Consuming GMP can change DNA	0.06	0.466	0.285**	0.002	-0.025	0.782
GMP can endanger his health	0.188*	0.043	0.082	0.435	0.328**	0.002
Environmental concerns						
Effect of food production on environment important	-0.056	0.647	0.407**	0.004	0.141	0.325
Reduce Waste (component 1)	-0.543***	<.001	0.174	0.148	-0.218	0.076
Save Resources (component 2)	0.165	0.075	-0.171	0.109	0.173	0.128
Recycling (component 3)	0.227*	0.014	-0.238*	0.021	0.124	0.26
Aspects of food important when purchasing						
Origin	0.155	0.065	-0.02	0.825	0.271**	0.005
Packaging	-0.103	0.187	-0.023	0.795	0.249**	0.008
Price	-0.123	0.127	-0.159	0.055	0.231**	0.009
Ingredients	0.037	0.68	-0.161	0.11	0.308**	0.003
Package size	0.147	0.068	-0.078	0.357	0.091	0.311

Table 8 (*continue*)

	GMF labelled		Check lables on GMF		GMF content	
Food habits						
Number of meals per day	-0.005	0.959	-0.127	0.21	0.061	0.551
Importance of self-catering	0.036	0.772	0.098	0.521	0.328*	0.032
Frequency of food purchasing	-0.026	0.798	0.001	0.993	-0.268*	0.022
Socio-demographics						
Gender (men)	-0.123	0.485	0.072	0.727	-0.466*	0.027
Age	0.013*	0.022	-0.005	0.482	0	0.959
Education	0.054	0.587	0	0.997	-0.114	0.323
Town size	0.017	0.769	0.038	0.559	-0.076	0.252
Household standard of living	-0.084	0.521	0.097	0.522	0.032	0.834
Life satisfaction	-0.12	0.382	-0.295	0.054	0.341*	0.03
Non believer in God	0.244	0.221	-0.038	0.864	-0.239	0.311
Model Fitting Information						
Sig.		<.001		<.001		<.001
N	625		612		413	
Pseudo R-Square						
Cox and Snell	0.227		0.472		0.186	
Nagelkerke	0.251		0.537		0.202	
McFadden	0.11		0.302		0.082	

Note: Link function: Logit. ***-significant on 0.1% level. ** - significant on 1% level,
* - significant on 5% level.
Components 1, 2, 3 reflects the three components of PCA presented in Table 7.

The findings reveal a compelling relationship between the level of information individuals have about genetically modified foods (GMFs) and their attitudes and behaviors. A higher level of information is positively correlated with the belief that GMF should be labeled. This suggests that as individuals become more informed about GMFs, they tend to support the idea of clear labeling of these products. Moreover, increased interest in GMFs positively predicts a more frequent habit of checking information about GM ingredients when purchasing food. This underlines the role of personal interest as a motivating factor in seeking information about GMF. Moreover, respondents who express confidence in sufficient information about GMF are more likely to check for GM ingredients when purchasing food. This alignment suggests that perceived adequacy of knowledge plays a role in encouraging individuals to be more vigilant about the GM content of the products they consume.

Health risks

The results presented in the Table 8 suggest that

- The subjective assessment of own health condition proved unrelated to GM labelling attitudes.
- The more do the respondents believe, that GMF can change their DNA, the more they check information on GM ingredients when buying food

– The more do the respondents believe, that the GMF can endanger their health, (1) the more they believe GMF should be labelled (2) the less GM ingredients is contained in the food the respondent normally eats according to his perception.

Examining health-related factors in relation to attitudes and behaviors around genetically modified foods (GMFs) reveals remarkable findings. Surprisingly, subjective evaluation of one's own health status does not appear to significantly influence attitudes toward GM labeling. This suggests that individuals' personal perception of health may not be a major factor in shaping their opinion on the necessity of GMF labeling. However, when considering beliefs about the potential health risks associated with GMFs, a compelling relationship emerges. Those who express a belief that GMF can change their DNA tend to check more frequently for information about GM ingredients when purchasing food. Similarly, respondents who believe that GMF may endanger their health are more likely to support the idea that GMF should be labeled. Interestingly, this group also tends to perceive a lower occurrence of GM ingredients in the foods they normally consume.

Environmental concerns

The results shown in Table 8 suggest that:

– The more important is the effect of food production on the environment, the more the respondents check the information about GM ingredients when purchasing food;
– The more the respondents recycle, (1) the more they check information on GMF ingredients when purchasing food; (2) the more they want GMF labelled.
– The more do the respondent engage in waste management including waste reduction and sorting, (1) the more they want GMF labelled

Examining the intersection of environmental concerns and attitudes toward genetically modified foods (GMFs) provides valuable insights into factors influencing consumer behavior. The findings reveal a remarkable relationship between the perceived importance of the environmental impact of food production and the frequency of checking information about GM ingredients when purchasing food. Individuals who prioritize the environmental effects of food production show a higher propensity to search for information about GM ingredients, suggesting a link between environmental awareness and food composition awareness.

In addition, the study suggests a positive association between pro-environmental behaviors such as recycling and waste management and preferences for GMFs. Respondents who actively engage in recycling practices are not only more likely to check information about GMF ingredients, but also express a stronger tendency to want to have a GMF label. Additionally, those involved in waste reduction and sorting show an increased desire for GMF labeling. This highlights the potential alignment between pro-environmental behavior and concerns related to the transparency of GMF information.

Important food characteristics and dietary habits

The results shown in Table 8 suggest that:

– The food characteristics and habits proved to be most significantly related to perceived content of GM ingredients in meals consumes. The more important are origin, packaging, price, ingredients of the food at the time of purchasing, and the lower is the content of GM ingredients in the food the respondent eats.

- The subjective importance of self-catering positively predicts the low GMF content in meals.
- The less often the respondent goes shopping for food items, the higher is the GM content in his meals.

Examining the importance attributed to different food attributes during the purchase process in conjunction with specific eating habits provides valuable insights into the factors influencing the perception of genetically modified foods (GMFs). The study reveals compelling links between individual preferences, purchasing behavior and the perceived content of GM ingredients in foods.

A key finding suggests that the perceived content of GM ingredients in consumed foods is significantly related to the importance placed on specific food characteristics at the time of purchase. Origin, packaging, price and ingredients emerge as crucial factors, with respondents who prioritize these factors reporting a lower perceived content of GM ingredients in food. This association underlines the impact of individual preferences during the purchase phase on the subsequent perception of GMF content in daily meals.

In addition, the study reveals interesting associations between dietary habits and perceived GMF content. Individuals who subjectively emphasize the importance of self-feeding demonstrate a positive association with lower GMF content in their meals. It follows that the preference for preparing one's own meals can contribute to reducing dependence on genetically modified ingredients.

Moreover, the frequency of grocery shopping appears to be a significant factor influencing the content of GMF in consumed foods. Respondents who buy food less often tend to report higher GM content in their food. This observation suggests that shopping frequency plays a role in shaping dietary choices and, consequently, the perceived prevalence of GM ingredients in the diet.

Sociodemographic characteristics of the respondents and other controls

The results shown in Table 8 suggest that:

- Women report lower GM content in their meals comparing to men.
- Age negatively predicts the necessity of GMF labelled.
- The bigger is the city the more people are willing to try GMF
- The more is the respondent satisfied in his life, the more he is willing to try GMF, but the lower proportion of the GM food in meals he reports.

Examining sociodemographic factors and other controls provides valuable insights into how individual characteristics shape perceptions and attitudes toward genetically modified foods (GMFs). Several notable findings emerged that shed light on the nuanced relationship between sociodemographic variables and attitudes toward GMF.

First, a gender difference is evident, as women tend to report a lower perceived content of GM ingredients in their foods compared to men. This gender difference suggests that women may have more conservative views on the inclusion of GM ingredients in their diets, contributing to differences in perceived GM content.

Age as a socio-demographic factor plays a significant role in shaping attitudes towards GMF. The study suggests a negative correlation between age and the perceived necessity of GMF labeling. This suggests that older respondents may express less demand for explicit labeling of GMF products, reflecting potential differences in attitudes across age groups.

Urbanity, represented by city size, appears to be a significant factor influencing individuals' willingness to try GMF. In particular, respondents from larger cities show greater

openness to experimenting with GMF. This urban-rural difference highlights the importance of contextual factors in shaping attitudes towards new food technologies, with urban environments potentially fostering a more receptive environment for GMF adoption.

Life satisfaction, a subjective measure of overall well-being, reveals interesting associations with attitudes toward GMF. Respondents reporting higher life satisfaction express a greater willingness to try GMF. However, this positive trend contrasts with the lower reported proportion of GM foods in their meals. This nuanced relationship suggests that while life satisfaction positively influences openness to trying GMFs, it does not necessarily translate into higher actual consumption of GM ingredients.

Results of the second stage of hierarchical ordinal regression

The second stage of the hierarchical ordinal regression analysis, which included the exclusion of variables related to the perceived health effects of genetically modified foods, revealed significant insights into the dynamics of predictors influencing public demand for GMF labeling. This strategic exclusion allowed for a targeted examination of the unique impact of health-related variables on GMF attitudes.

The results suggest, that the exclusion of the variables representing the health effects of the GMF led to significant changes in the predictive power of the models for the need for GMF labelled. While the original Pseudo R2 ranged from 47% to 53% (for checking the labels) and 11% to 25% (labelling requirement) and the original models were statistically significant on 0,1% level, the exclusion of health variables led to reduction of Pseudo R2 to the level of 1-5% and to the loss of statistical significance (for the need to label model). Thus, the results indicate, that health effects can be considered most powerful predictors of the public requirement to label them.

The effects of exclusion of health variables on the other four regressions was less pronounced as the regressions stayed statistically significant on 0,1% level in all the four cases (checking information on GM content when purchasing and perceived content of GM ingredients in daily own meals). However, the variability explained by the model as measured by Pseudo R2 decreased to the levels from 20% to 3%.

The results underscored the key role of perceived health effects as influential predictors of public adherence to GMF labeling. The substantial reduction in Pseudo R2 and the loss of statistical significance in the models related to the need for labeling after exclusion of health variables highlight the dominant position of health considerations in the formation of consumer attitudes. This finding is consistent with existing literature highlighting health issues as a central factor influencing public perceptions and decisions about GMF.

While the effects of excluding health variables were less pronounced in other regression models, there was a substantial reduction in the variability explained by the model while maintaining statistical significance. This suggests that health considerations play a vital role not only in demand for labeling but also in shaping other aspects of consumer behavior, such as checking GM content information when shopping and perceptions of GM ingredients in everyday foods.

These findings highlight the need for targeted communication and policy strategies that address and mitigate health concerns related to GMF. Understanding the disproportionate impact of health considerations on public attitudes provides valuable insights for policymakers and industry stakeholders seeking to promote greater acceptance of GMF. The delicate interplay between health perceptions and labeling requirements requires comprehensive approaches that prioritize transparent communication and address the multifaceted dimensions of consumer concerns about GMF.

Table 9

Factors predicting attitudes to GMF. Results of ordinal regression analysis without health risks

	GMF labelled		Check information on GMF		GMF content	
	Estimate	Sig.	Estimate	Sig.	Estimate	Sig.
Threshold=1	-0.258	0.852	-1	0.537	0.441	0.789
Threshold=2	0.783	0.57	1.423	0.376	2.76	0.095
Threshold=3	3.097*	0.025	3.817*	0.018	4.435**	0.008
Threshold=4	4.448	0.001			6.289***	<.001
Information about GMF						
Heard of GMF	0.162	0.147	-0.425**	0.002	-0.138	0.327
Interested in GMF	0.158	0.184	1.185***	<.001	-0.151	0.275
Enough Info about GMF	0.08	0.31	0.466***	<.001	-0.126	0.173
Environmental concerns						
Effect on environment important	0.018	0.872	0.399**	0.004	0.139	0.321
Reduce Waste (component 1)	-0.079	0.399	0.186	0.116	-0.199	0.097
Save Resources (component 2)	-0.042	0.625	-0.16	0.13	0.179	0.11
Recycling (component 3)	0.019	0.82	-0.189	0.061	0.079	0.465
Importance when purchasing						
Origin	0.171*	0.029	0.009	0.918	0.273**	0.004
Packaging	0.114	0.118	-0.008	0.923	0.225*	0.015
Price	0.037	0.601	-0.135	0.097	0.202*	0.018
Ingredients	0.112	0.179	-0.157	0.111	0.274**	0.006
Package size	0.049	0.505	-0.064	0.441	0.057	0.519
Food habits						
Number of meals per day	-0.12	0.145	-0.147	0.142	0.017	0.867
Importance of self catering	-0.032	0.784	0.12	0.431	0.319*	0.031
Frequency of food purchasing	-0.03	0.751	-0.04	0.737	-0.252*	0.028
Socio-demographics						
Gender (men)	0.185	0.259	0.089	0.662	-0.38	0.066
Age	-0.004	0.438	-0.005	0.463	0.001	0.931
Education	-0.017	0.854	-0.004	0.97	-0.123	0.279
Town size	-0.039	0.469	0.019	0.771	-0.059	0.367
Household standard of living	0.058	0.628	0.061	0.679	-0.006	0.966
State of own Health	-0.049	0.678	0.171	0.239	-0.245	0.091
Non believer in God	-0.15	0.225	0.034	0.874	-0.025	0.912
Life satisfaction	0.222	0.217	-0.26	0.081	0.304*	0.046
Model Fitting Information						
Sig.		0.42		<.001		<.001
N	624		626		415	
Pseudo R-Square						
Cox and Snell	0.037		0.192		0.121	
Nagelkerke	0.04		0.212		0.132	
McFadden	0.014		0.091		0.051	

Note: Link function: Logit. ***-significant on 0,1% level. ** - significant on 1% level, * - significant on 5% level. . Components 1, 2, 3 reflects the three components of PCA presented in Table 7.

Discussion

The observed associations between GMF information, interest, and behavior, presented in the sections above, are consistent with the broader literature on public perception and decision-making in the context of genetically modified organisms (Moon and Balasubramanian, 2004; Moerbeek and Casimir, 2005; and Vilella-Vila et al., 2005). These findings underscore the importance of targeted information campaigns to improve public understanding and shape attitudes toward GMF. While the data suggest positive correlations, they also prompt consideration of the design and delivery of outreach initiatives. Addressing knowledge gaps and promoting interest could contribute to more informed consumer choice and subsequently influence wider societal acceptance of genetically modified products. As GM technologies continue to evolve, strategies that effectively communicate information and satisfy the public interest will play a key role in navigating the complex landscape of GMF adoption.

The observed associations highlight the complex relationship between environmental awareness, sustainable behavior and attitudes towards GMF. Individuals with increased environmental awareness seem to be more careful about checking the content of their food, especially when it comes to GM ingredients. This highlights the interconnectedness of environmental and food concerns, suggesting that consumers who actively contribute to environmental protection can extend their conscientiousness to the decisions they make in the area of food consumption. As environmental sustainability becomes an increasingly integral aspect of consumer decision-making, recognizing and addressing these connections can underpin strategies to promote transparency and understanding in the GMF context.

The associations between health risk beliefs and attitudes toward GMF presented in this paper point to a complex interplay between perceived risks and consumer behavior. In general our results are consistent with the literature (Bernstein et al., 2003; Dona and Arvanitoyannis, 2009; Gizaw, 2019; Krimsky, 2019; Ozkok, 2015). The association between concern about DNA alteration and increased information-seeking behavior suggests that individuals with specific health-related concerns may be more active in controlling GM ingredients. The importance of the health risks for the subjective need of GMO labeling isa highlighted by the fact that the second stage of hierarchical ordinal regression analysis was not statistically significant if the health concerns are excluded. the association between health risk beliefs and support for GMF labeling underscores the importance of addressing perceived health risks in public discourse and educational initiatives. As concerns about potential health effects continue to influence public opinion, efforts to provide accurate and accessible information about the health effects of GMFs are essential to support informed decision-making and shape more differentiated attitudes.

These findings, related to the role of consumer choices, food habits, and shopping habits, presented in this paper highlight the complex associations between consumer choices, food-related habits and GMF perceptions. Preference for specific food characteristics during the purchasing process and the habit of self-eating are identified as influential factors in shaping the perception of GMF content. Recognizing the impact of these factors can lead to targeted interventions to increase consumer awareness and support informed decision-making about GMF consumption. As individuals increasingly favor certain food attributes and habits, understanding these dynamics becomes critical to developing strategies that align with consumer preferences and contribute to a more transparent and consumer-centric food environment.

Last, but not least, the findings of associations between socio-demographic characteristics and attitudes to GMO labelling, presented in the paper, underscore the

diversity of attitudes toward GMF based on sociodemographic characteristics. Gender, age, urbanicity and life satisfaction all contribute to a complex tapestry of perceptions and preferences regarding GMF. Recognizing these variations is critical to tailoring communication strategies and policy interventions that resonate with different demographics. The study highlights the need for targeted approaches that take into account the subtle interplay between individual characteristics and attitudes towards GMF and promote a more comprehensive understanding of the factors influencing public acceptance and consumption patterns.

Conclusion

This study delved into the complex landscape of public attitudes toward genetically modified foods by examining the factors influencing demand for GMF labeling. It seemed to enrich the ongoing discourse on genetically modified foods by examining the impact of environmental concerns, perceived health risks associated with GMOs, and the availability of information on the public's propensity to challenge GMF labeling and the likelihood that it will scrutinize such labels. The research was conducted on a representative sample of the Czech population, including 884 individuals aged 18 to 90 (M ± SD: 48.17 ± 17.72; 53.40% women, 18.04% with higher education).

The findings shed light on the multifaceted interplay of information, health perceptions, environmental issues, food characteristics, and sociodemographic factors in shaping consumer attitudes. One of the key findings from this investigation is the overriding role of health considerations in influencing the public's insistence on GMF labeling. Perceived health effects were shown to be strong predictors that significantly influenced not only demand for labeling but also influencing behaviors such as checking GM content in purchases and perceptions of GM ingredients in daily foods. This underscores the need for targeted communication strategies that address health-related issues transparently and comprehensively.

Environmental concerns also played a notable role, with individuals favoring the environmental impact of food production showing a greater tendency to check information about GM ingredients when purchasing food and supporting the need for GMF labeling. These findings underscore the interconnectedness of environmental awareness and consumer choices regarding GMF.

Importantly, the study highlighted the importance of food characteristics and habits in shaping attitudes towards GMF. Origin, packaging, price and ingredients were found to be critical factors influencing the perceived content of GM ingredients in foods. Understanding these nuances provides valuable insights for both policymakers and the food industry to tailor communication and marketing strategies to match consumer priorities.

Sociodemographic factors revealed distinct patterns, with gender, age, city size, and life satisfaction contributing to differences in attitudes toward GMF. The complex relationship between these factors highlights the need for tailored approaches that take into account different demographic perspectives.

In the context of a second-stage hierarchical ordinal regression, the exclusion of health-related variables significantly altered the predictive power of the models and highlighted the central role of health considerations in the demand for GMF labeling.

In conclusion, this study underscores the need for nuanced, multidimensional strategies in addressing public concerns and promoting greater adoption of GMF. Transparent communication, targeted education campaigns and policies that align with consumer values

and priorities are essential to navigate the complex landscape of GMF perceptions. As technology advances, continued research and adaptive approaches will be critical to shaping a sustainable and informed future for the integration of GM products into the global food supply.

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Modelling of thermoradiative-convective drying process of products of plant origin

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Abstract

Introduction. The aim of the research was to develop the basics of simulating processes of the simultaneous influence of thermoradiation and convection during drying of plant raw materials.

Materials and methods. Cultivated mushrooms, hawthorn, winter varieties of apples and apple snacks were used in the study. Drying was carried out in pulsed heating-cooling mode, while heating was carried out by a heat pump and infrared rays to a set temperature with a wavelength in the range of 1.2–4 μm with a flux density of 8 kW/m^2.

Results and discussion. Modelling of thermoradiative-convective drying of cultivated mushrooms was carried out when the moisture content decreased from 809 to 30% within 80 min, and for hawthorn, the moisture content decreased from 330 to 38% in 60 min. The drying time for apples was 60 min, and the drying time for apple snacks was 70 min, since snacks contain sugar, which has the property of retaining moisture.

According to the developed mathematical model of the drying process, the diffusion capacity of moisture was calculated for all studied products. It was the highest for cultivated mushrooms, 9.5810^{-4} m^2/s, due to the lowest density of 750 kg/m^3 and the highest porosity, which led to deeper penetration of infrared radiation with a thermal diffusion coefficient of 1.011×10^{-3} 1/K. The density of hawthorn was 1173.4 kg/m^3, the moisture diffusion coefficient was 6.8×10^{-7} m^2/s and a thermal diffusion coefficient was 0.51×10^{-2} 1/K because the hawthorn fruits were spherical and were placed in the dryer as a heap. Apples and apple snacks were cut into slices 4–6 mm thick. The density of apples was 880 kg/m^3, the moisture diffusion coefficient was 8.48×10^{-5} m^2/s, and the thermal diffusion coefficient was 3.096×10^{-5} 1/K. Apple snacks were made by blanching apple cores in sugar syrup before drying, which led to a decrease in the moisture diffusion coefficient to 8.28×10^{-6} m^2/s, an increase of density to 965 kg/m^3 and a thermal diffusion coefficient to 4.06×10^{-2} 1/K compared to apple slices.

Modelling the interaction of convective and thermoradiative energy supply in pulse mode allows to ensure the maximum technological effect.

Conclusions. The mathematical model of thermoradiative-convective drying allows to display in an analytical form the main features of the simultaneous influence of convective and thermoradiative energy supply during drying of high-moisture materials.

Introduction

The creation of combined dehydration technologies in one dryer allows to make a detailed analysis and combine the advantages of different energy supply methods and minimize the disadvantages of each individual drying method.

The method of combined drying and the development of new drying units with combined modes, which will ensure a significant increase in the intensity of the process, saving electricity and improving the quality of products, are considered a promising and economically feasible direction for obtaining dehydrated products. Solving the problem of resource conservation is also complicated by the fact that high-moisture materials are characterized by high hydrophilicity and significant variability of thermophysical, optical, physical-mechanical and structural properties, which cannot be described mathematically in one model. Sabarez (2015) described the modelling of transport mechanisms involved in the process of drying of food products and obtained models for the industrial drying process. It is engaged in modelling the characteristics of drying hawthorn fruits in microwave-convective conditions, created a laboratory microwave convection dryer and obtained an effective moisture permeability ranging from 9.29×10^{-10} to 8.81×10^{-9} m^2/s. Argyropoulos et al. (2011) evaluated convection, hot air in combination with microwave vacuum and freeze-drying of mushrooms and found that the thickness of the material is decisive in drying when dehydrating the microwave vacuum to 6% moisture for 25–30 min, and Maisnam et al. (2017) described recent advances in traditional drying of food. Arumuganathan et al. (2011) obtained a mathematical model of drying kinetics of mushrooms in a fluidized bed dryer, described the model of Wang and Singh and established the best drying behaviour of mushroom slices. It was shown that a thin-layer model of convective and microwave-convective drying and proposed drying equipment for it (Bhattacharya et al., 2015). At the convectively drying of cherry tomatoes at a temperature of 60 °C, taking into account their shrinkage, the diffusion coefficients for unpeeled tomatoes to be 9.16×10^{-12} m^2/s, and for peeled tomatoes to be 1.53×10^{-10} m^2/s (Bennamoun et al. 2015). Gunhan et al. (2004) determined the quality parameters of bay leaf drying, and Menges et al. (2006) mathematically modelled thin-layer drying of apples. According to the obtained model, it is possible to predict the effect of product moisture, temperature, and air speed in the chamber with the help of a constant model.

Zecchi et al. (2011) compared by modelling and minimizing the duration of combined convective-vacuum drying of mushrooms and parsley, and developed a set of simple diffusion models for vacuum-convective drying, and Sharma et al. (2005) develop mathematical models of thin-layer drying of onion particles by infrared radiation and determined the rational radiation power of 300–500 W at an air speed of 1.0 m/s and an air temperature of 35 °C.

During infrared microwave drying of a peach it was found that increasing the drying power in the microwave oven and the power of infrared radiation leads to an increase in the rate of peach dehydration and a decrease in energy consumption (Wang et al., 2006). Coşkun (2017) applied ten-layer drying models for tomato slices dried with a closed-cycle heat pump, found that the moisture diffusivity ranged from 8.28×10^{-11} to 1.41×10^{-10} m^2/s.

The combining thermoradiative and convective dehydration in hybrid (mixed) drying technologies is not sufficiently studied. This technologies achieve a synergistic effect, which leads to a reduction in duration and energy consumption. Previous studies of drying of products of plant origin showed that combined drying was industrially important (Dubkovetskiy et al., 2019). The products were heated by infrared rays and the surrounding air in the dryer was heated by a heat pump condenser. Thermoradiative drying was an

effective method of dehydration. The energy of radiation-infrared emitters was transferred to the surface of the product without heating the surrounding air. The radiation reached the surface of the material, penetrated it, and then turned into heat. During the drying process, the absorbing, reflecting and transmissive properties of the radiation of the dried material were constantly changing due to the decrease in the water content in it. Infrared radiation has advantages: high heat transfer coefficients, short drying time and easy control of the temperature of the material. For the scientific substantiation of technological regimes it was necessary to understand clearly and represent the physical essence of the mechanisms of phenomena occurring in the dryer, to analyse their interconnection and the degree of mutual influence. Taking into account the specificity of the object of biological nature (suspension containing a living cell culture) it was necessary to find the restrictions imposed in this case. Since all parameters were internally interconnected, the development of a new drying technology was a multi-parameter task, the solution of which was possible using mathematical modelling methods.

The aim of this research was to develop the basics of simulating processes of the simultaneous influence of thermoradiation and convection during drying of plant raw materials, as well as the development of a thermoradiative-convective drying unit.

Materials and methods

Materials

Cultivated mushrooms, hawthorn, winter varieties of apples, and apple snacks were subjects of the present research.

Thermoradiative-convective drying unit with a heat pump

Process of food drying was conducted using a thermoradiative-convective device with a heat pump (Figure 2). Inside the drying chamber, on the side walls, nodes of infrared radiation emitters were fixed, consisting of infrared radiation emitters 2, which can be moved relative to reflectors 3. Reflector 3 can rotate around the infrared radiation emitter, which made it possible to change the amount of sample irradiation and the product coverage area 16 dryers on trays. Four-side irradiation of the product in the center of the tray from emitters fixed on different side walls of the dryer, and irradiating the tray from below and above, made it possible to compensate for the loss of radiation intensity in the farthest corners of the reflector due to overlapping rays. The design of the radiator unit included two couples of radiation-infrared radiators and reflectors directed in different directions and irradiating the tray from the top and the bottom. The design of the device of infrared radiation emitters allowed the use of both "light" and "dark" infrared radiation emitters for drying products.

A combined thermoradiative-convective method of drying food products was provided in the device. Convective heating of the air was provided in the condenser 25 of the heat pump, and thermoradiative heating – by radiation-infrared emitters 2. The complex interaction of convective and thermoradiative energy supply in pulse mode allowed to ensure the maximum technological effect and achieve the technical result of the invention.

Figure 1. Appearance of dry products

Air was supplied in the chamber under the lower shelves, air pressure losses took place when moving from the lower to the upper shelves due to pneumatic resistance. To reduce stagnant zones and evenly distribute air, technological channels 15 for additional air supply, as well as channels 12 for air removal, located in the side walls of the dryer, were designed. Channels made it possible to ensure flow turbulence at low speeds, where in addition to longitudinal movement (from bottom to top), transverse movement also occurred. The formation of turbulent flows over the surface of the dried semi-finished product made it possible to remove moisture from the boundary layer intensively. Supplying heat from the condenser 25 to the product and removing moisture produced by the action of infrared emitters 2 occurred by air.

Experimental devices

To save energy resources, the exhaust air reached the circulation pipe 14 (Figure 2), and then it entered the air distribution mechanism 18, which was designed in the form of a gate valve with a partial overlap of the cross section of the pipes. In the distribution mechanism, part of the exhaust air was sucked in by the centrifugal fan 20 and cooled the condenser of the heat pump 25, and the other part is sucked into the evaporator 19 of the heat pump by the

axial fan 21. When the damper 18 was completely closed, the centrifugal fan 20 sucked in all air from the environment and cooled the condenser 25, and all the exhaust air from the circulation pipe 14 was sent to the evaporator 19 of the heat pump. When the shutter 18 was fully opened, all the exhaust air reached the condenser 25 of the heat pump, due to which a softened and humidified drying mode was provided, and the evaporator 19 of the heat pump used exhaust heat from the environment (air, earth, water). The greatest technological effect was achieved when the shutter was covered for 20–80%

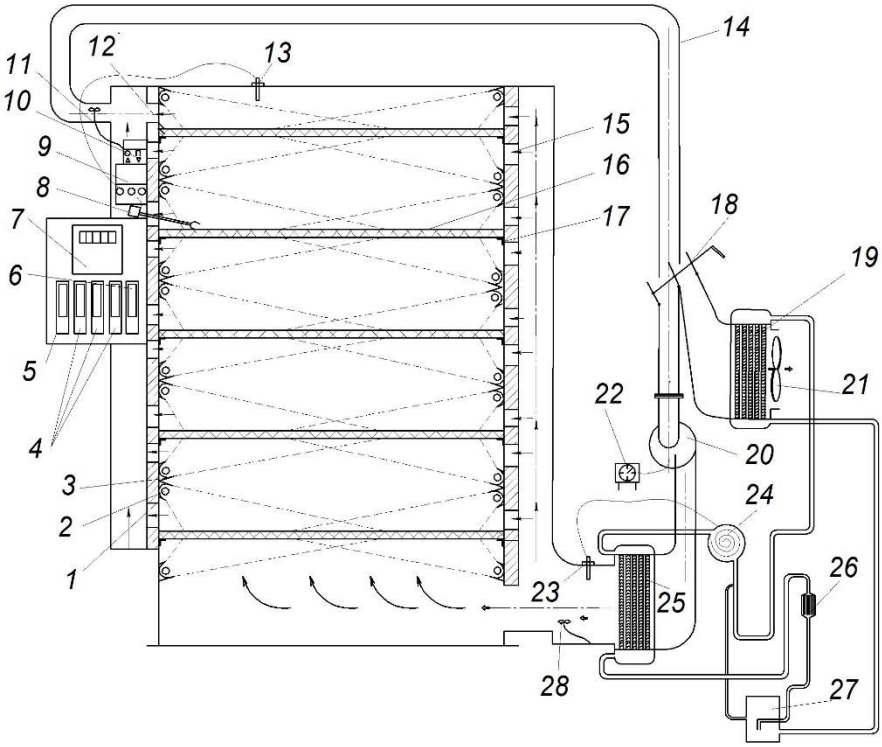

Figure 2. Scheme of thermoradiative-convective drying device with heat pump:

1 – drying chamber;
2 – infrared radiation emitter;
3 – reflector;
4 – automatic dryer switch;
5 – relay;
6 – automatic switch;
7 – energy consumption counter;
8 – thermocouples;
9 – automatic temperature control unit;
10 – regulator of relative moisture of air;
11 – sensor for measuring relative moisture at the exit from the drying chamber;
12 – technological channels for air removal;
13 – contact sensor at the exit from the drying chamber;
14 – circulation pipe;
15 – technological channels for air supply;
16 – dryer trays;
17 – shelves for trays;
18 – sliding door;
19 – heat pump evaporator;
20 – centrifugal fan;
21 – axial fan;
22 – block of automatic adjustment of the speed of movement of the coolant;
23 – contact sensor at the entrance to the drying chamber;
24 – compressor;
25 – heat pump condenser;
26 – throttle;
27 – separator;
28 – sensor for measuring relative moisture at the entrance to the drying chamber.

Contact sensors 13 and 23 were placed in the cabinet of the drying chamber, which sent a signal to turn on the thermoradiative generators and the heat pump together or separately according to the set air temperature at the entrance to the dryer in pulse mode "heating – cooling". The sensor 13 sent a signal to the relay 5 and turned on and off the radiation-infrared emitters 2. When the set temperature was reached, the contacts of the thermostat 23 opened and the electric motor of the heat pump compressor stopped. When the heat pump was turned off, the heated refrigerant (Freon) from the compressor 24 stopped being supplied to the condenser 25. As soon as the drying temperature reached the required value, which was fixed by the sensor 13, the infrared emitters 2 were turned off and the product in the dryer began to cool. When the product was cooled to the limit temperature, the infrared emitters 2 automatically turned on and the drying process was repeated in the same way until the material reached the specified moisture content.

Research process procedure

The prepared raw were dried by thermoradiative-convective method. The drying parameters were set experimentally: the temperature of the coolant in the drying chamber was 60 °C, the speed of air movement in the chamber was 5.5 m/s, specific load was 8.8 kg/m^2. The amount of radiation by thermoradiative generators was 8 kW/m^2, the wavelength of tubular "dark" thermoradiative generators was in the range of 2.0–4.0 μm. Air heating was carried out from an external heating element of 2.5 kW/m^2, the distance between thermoradiative heaters and the product was 14 cm.

Steps of the procedure:

1. Warm up the installation for 10–15 minutes. To do this, it was set the temperature on the controller of the control panel 9 (Figure 2), turn on the fans 20 and 21, the compressor of the heat pump 24 and the radioactive-infrared emitters 2 in sequence.
2. It was chopped the material to be dried (mushrooms, hawthorn, apples and apple snacks, etc.) into thin shavings 2–5 mm thick and place them evenly on the trays of the dryer 16.
3. It was opened the shutter 18 to the specified degree of air suction. When passing through the distribution mechanism, part of the spent coolant from the circulation pipe 14 is sucked by the centrifugal fan and cools the condenser of the heat pump 25, and the other part is sucked into the evaporator of the heat pump 19 by the axial fan 21.
4. It was controlled the specified pulse switching mode of the heat pump capacitor 25 and infrared radiation emitters 2 to ensure rational energy consumption by meter 7.
5. It was controlled control the overheating of the product with the help of installed temperature sensors 8 (thermocouples) immersed in the product, which send a signal to the temperature controller 9 and through the relay turn on the heat capacitor according to the temperature of the product in the pulse mode "heating-cooling" pumps 25 and radioactive-infrared emitters 2.
6. It was controlled the change in the amount of moisture in the heat carrier with the help of installed relative humidity sensors 11, which send signals to the relative humidity regulator 10, and through the relay, the supply to the condenser is switched on and off in pulse mode "heating-cooling" heat pump heated refrigerant and infrared emitters.
7. It was sequentially turned off the power supply of the heat pump compressor 24 and radioactive infrared emitters 2, and after 10 minutes the fans 20 and 21.
8. Let the product rest for 30 minutes, familiarize yourself with the state of the dried material, and unload it from trays 16 of the dryer into a packaging container.

Processing of research results

Determination of experimental data was carried out according to the algorithm (Akter F., et al., 2022), where we first determine the current mass of moisture in the material at the beginning and during drying, g:

$$M_{\text{m}} = M_i - M_{d.m}, \quad (1)$$

where M_{m} is the mass of moisture in the material at the i-th time of the experiment, g;

M_i is the mass of the material at the i-th time of the experiment, g;

$M_{d.m}$ is the mass of dry matter in the material for the entire experiment, g:

$$M_{d.m} = M_0 \cdot X_{d.m} / 100, \quad (2)$$

where M_0 is the initial weight of the material before drying, g; $X_{d.m}$ is the mass fraction of dry matter.

It was determined the moisture content of the material at the i-th drying time, %:

$$W = (M_{\text{m}} / M_{d.m}) \, 100 \quad (3)$$

During the drying process, the change in the temperature of the heat carrier, the density of the products, the specific heat capacity of the dry material, the specific heat of vaporization were recorded, and the coefficients of moisture diffusion, heat transfer, and moisture transfer were calculated and entered in Table 1.

Calculation data were determined by building a physical model and compiling a generalizing equation of the influence of molecular diffusion, thermodiffusion, and internal gas pressure on moisture transfer during the interaction of thermoradiation and convection. The complex system of equations was solved by integral Laplace transformations. A software module for calculating the process of drying high initial moisture content materials with thermoradiative-convective energy supply has been developed. The result of the approximation of experimental and calculated data of drying particles of cultivated mushrooms, hawthorn and apples is shown in Figure 4.

Results and discussion

In case of the thermoradiative-convective method of drying products of plant origin, the following stages of the process took place in sequence:

- Heating, which was accompanied by partial evaporation of moisture;
- Drying, accompanied by evaporation of moisture from the surface and deepening of the evaporation zone.

Options for setting thermoradiative-convective drying modes

1. According to air temperature. When setting the temperature of the air in the chamber and the range of inclusion and exclusion of radiation-infrared emitters 2, the duration of irradiation of the semi-finished product was controlled by the automatic temperature control unit 9, and the control of the supply of heated refrigerant (Freon) from the compressor 24 to the condenser 25 of the heat pump. Consumption of electrical energy was measured using a counter 7 (per kilogram of evaporated moisture or kilograms of finished products). The sensor with a thermostat 13 controlled the temperature at the outlet of the dryer depending on the properties and characteristics of the product, while the infrared radiation emitters 2 were turned on and off. The temperature at the inlet of the dryer and switching the heat pump on and off was controlled with the help of sensor 23. The heat pump and radiation-infrared emitters can be de-energized together or separately with automatic switches 4.

2. According to air humidity. You can set the drying mode according to the relative humidity of the air in the dryer chamber. The change in the relative humidity of the air at the entrance and exit from the drying chamber is recorded by sensors 28 and 11, which sent signals to the regulator of relative moisture 10. By setting the relative moisture range on the regulator 10 and through relay 5 switching on and off supply of the heated refrigerant (freon) occurs in pulse mode "heating – cooling" to the condenser 25 of the heat pump from the compressor 24 and infrared emitters 2 together or separately with different relative moisture of the air.

3. According to product temperature. Installed temperature sensors 8 (thermocouples), thanks to immersion in the product, allow you to carry out drying modes according to the temperature of the product, and not the temperature of the coolant, which prevents overheating of the raw material and improves the quality of the final product. Thermocouples send a signal to the temperature regulator 9 and through relay 5 turn on the heat pump capacitor 25 and infrared emitters 2 according to the product temperature in pulse mode "heating – cooling".

The measurement of the temperature of the product in the cross section was carried out by thermocouples 8, which sent a signal to the temperature controller 9. Through the relay 5 they supplied of heated refrigerant (Freon) to the condenser 25 of the heat pump from the compressor 24 according to the temperature of the product in the pulsed "heating – cooling" mode, and infrared emitters 2 (with the help of which the irradiation time of the semi-finished product changed) together or separately with different temperature regimes of the product. The drying process can be carried out according to the temperature of the semi-finished product, which was carried out by setting the automatic temperature control regulator 9 and thermocouples 8. The thermocouples were immersed in the drying products, then the product temperature and the range of turning on and off the infrared radiation emitters 2 and putting heated refrigerant (Freon) into the condenser 25 of the heat pump from compressor 24.

Drying was carried out in pulsed heating-cooling mode, while heating was carried out by a heat pump and infrared rays to a set temperature with a wavelength in the range of 1.2-4 μm with a flux density of 8 kW/m^2. After reaching the maximum set temperature of air or product during drying or relative Humidity of air, the heat pump and radiation-infrared emitters were turned off and switched to pulse switching mode. The duration of pulse switching on and pauses were correlated as 1:1, 1:2, 1:3, etc., depending on the type of semi-finished product. The duration of pulse activation and pause were correlated as 1:2 and depended on the semi-finished product and the maximum temperature at the exit from the drying chamber, the temperature of the semi-finished product, the temperature at the entrance to the drying chamber or relative moisture installed by the sensors 13, 8, 23 and 11, respectively.

In order to avoid stagnant zones and uniform distribution of air, technological channels for additional supply and removal of air, located in the side walls of the dryer, were provided. In addition to longitudinal movement (from bottom to top), the channels allowed to provide transverse movement. Placing air channels from bottom and top of the nodes of thermoradiative emitters with the simultaneous supply of air from the bottom to the top led to turbulence of air flows at low velocities. The formation of turbulent flows over the surface of the dried product led to more intense removal of moisture from the boundary layer of the product. At the same time, the drying process was accelerated and energy consumption was reduced.

The interaction of the energy of infrared radiation and an additionally installed heat pump, made it possible to reduce energy costs during using the dryer and the drying process, using alternative sources of heat (air, soil, water). The operation of the heat pump was based

on obtaining heat from an alternative source, increasing its temperature and using this heat in the dryer. The air passing through the condenser of the heat pump was heated, which led to a decrease in the relative moisture of the air supplied to the chamber. At the same time, the driving force of the process increased and, as a result, the drying time decreased.

Since high-moisture materials were crushed to intensify the drying process, the material particles can be represented in the form of a straight parallelepiped with sides *a, b* and height *h*, which were in a ratio close to one to each other (Figure 3).

Mathematical model of the drying process

The mathematical model of the drying process was formulated on the basis of the generalized law of moisture movement, which took into account the flow of moisture, both in the form of vapour and liquid, caused by the presence of a moisture gradient and a temperature gradient in the wet material.

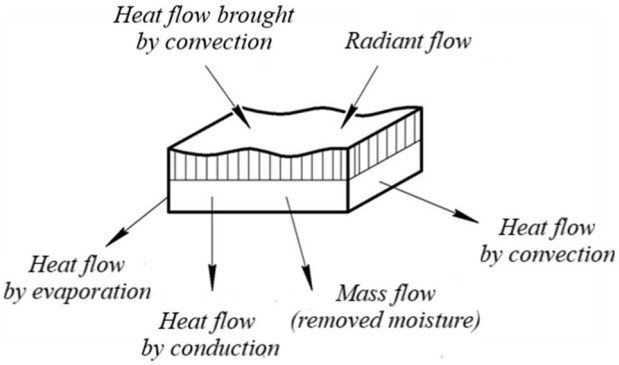

Figure 3. Model of drying particles of high-moisture materials by the thermoradiative-convective method

Total moisture flow in the middle of the material (Hayvas 2010):

$$j = -a_m \rho_0 \nabla W - a_m^T \rho_0 \nabla T - a_m^P \rho_0 c_p^a \nabla P \quad (4)$$

where ρ_0 is moisture density, kg/m^3; a_m is diffusion coefficient, m^2/s; a_m^T is thermodiffusion coefficient, m^2/s 1/K; a_m^P is barodiffusion coefficient, m^2/s 1/Pa; ∇W is moisture gradient, 1/m; ∇T – temperature gradient, K/m; ∇P – pressure gradient, Pa/m.

In this equation, each term describes the contribution to the resulting mass flow of separate physical phenomena: molecular diffusion, thermal diffusion (Sharma et al., 2005), convection mass transfer due to internal gas pressure, and convection moisture transfer (Bennamoun et al., 2015; Pal et al., 1997) caused by a change in the shape and volume of the sample due to deformation caused by shrinkage or swelling. A system of Lykov and Lutsik (Sorokova et al., 2022) equations was obtained that described the dynamics of mass, energy, and momentum transfer processes during the drying process:

$$\frac{\partial T}{\partial \tau} = a_m^T \nabla^2 T + \frac{\varepsilon r}{c}\frac{\partial W}{\partial \tau} - \frac{E_0\left(\gamma_T T_0 + \gamma_W W_0\right)}{c\rho_0} div\frac{\partial \vec{U}}{\partial \tau}$$

$$\frac{\partial W}{\partial \tau} = a_m \nabla^2 W + a_m^T \nabla^2 T + a_m^p c_p^a \nabla^2 P - div\frac{\partial \vec{U}}{\partial \tau}; \quad (5)$$

Since the temperature of the coolant in real conditions was less than 80°C (Giri et al., 2007), the phenomena of barodiffusion and thermal moisture conductivity were neglected.

The coefficients of absorption, reflection and transmission of the radiant flow were considered constant. In general, all heat and moisture transfer coefficients, as well as thermodynamic characteristics, depended on the moisture content and temperature. For simplicity, there was assumed that over time τ_k coefficients $a_m, \delta, \lambda, c, r, \varepsilon$ were considered constant. Then, after substitution, the equation was:

$$\begin{cases} \dfrac{\partial T}{\partial \tau} = a\nabla^2 T + \dfrac{\varepsilon r}{c}\dfrac{\partial W}{\partial \tau} \\ \dfrac{\partial W}{\partial \tau} = a_m \nabla^2 W + a_m^T \nabla T \end{cases} \tag{6}$$

In the heat transfer equation, it was necessary to add a term responsible for infrared heating. Absorption coefficient was denoted as A. The density of the radiant flow incident on the particle was marked $q(\tau)$

$$q(\tau) = Aq(\tau)\exp(k(R-r)) \tag{7}$$

where r is current radius, m; q_0 is density of the heat flow, which was directed to the surface (perceived by surface), J/(m^2×s); μ is attenuation coefficient, ω is reflection coefficient.

Combination of two radiant flows from lamps located on different sides gave heating that did not depend on the X coordinate.

Thus, the heat transfer equation was:

$$\frac{\partial T}{\partial \tau} = a\nabla^2 T + \frac{\varepsilon r}{c}\frac{\partial W}{\partial \tau} + \frac{Aq}{c\rho_0} \tag{8}$$

Under these conditions, the drying process was described by a system of differential equations in partial derivatives in spherical coordinates, consisting of differential equations of heat and mass transfer for the particle of the product.

$$\begin{cases} \dfrac{\partial T(r,\tau)}{\partial \tau} = a\left(\dfrac{d^2T(r,\tau)}{dr^2} + \dfrac{2}{r}\dfrac{dT(r,\tau)}{dr}\right) + \dfrac{\varepsilon r}{c}\dfrac{\partial W(r,\tau)}{\partial \tau} + \dfrac{Aq}{c\rho_0} \\ \dfrac{\partial W(r,\tau)}{\partial \tau} = a_m\left(\dfrac{d^2W(r,\tau)}{dr^2} + \dfrac{2}{r}\dfrac{dW(r,\tau)}{dr}\right) + a_m^T\left(\dfrac{d^2T(r,\tau)}{dr^2} + \dfrac{2}{r}\dfrac{dT(r,\tau)}{dr}\right) \end{cases} \tag{9}$$

With initial conditions

$$T(0,r) = T_n = \text{const}\ W(0,r) = W_n = \text{const}$$

All mass and heat transfer coefficients (a_m, δ, λ) as well as thermodynamic characteristics c, r, ε depended on moisture content and temperature. Boundary conditions of the third order, reflecting heat exchange, were:

$$-\lambda\left(\frac{\partial T}{\partial r}\right)_{r=R} + \alpha\left(T_c - T_n(\tau)\right) - r_c(1-\varepsilon)\beta\rho_0\left(W_n(\tau) - W_p\right) + A = 0 \tag{10}$$

where A is absorbed radiation flow density.

Mass exchange between the body surface and the environment:

$$-\lambda\left(\frac{\partial W}{\partial r}\right)_{r=R} + a_m\delta\left(\frac{\partial T}{\partial r}\right)_{r=R} + \beta\left(W_n(\tau) - W_p\right) = 0 \tag{11}$$

Symmetry conditions:

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0 \quad \left.\frac{\partial W}{\partial r}\right|_{r=0} = 0$$

The task was completed under the condition that the boundary was movable and its movement was described by a function *R(τ)*:

$$0 \le r \le R(\tau), \ \left[R(0) = R_0\right], \ \tau > 0$$

The task was the problem of heat and mass conduction with a moving boundary. Due to the dependence of the characteristic size of the area of heat and mass transfer on time, classical methods of separation of variables and integral Fourier transforms were generally not applied to this type of problem, because within the framework of mathematical physics, it was not possible to reconcile the solutions of heat and mass conduction equations with a moving boundary. One of the methods that can be applied to this class of problems was the method of functional transformations or, as it is called, the method of translating a boundary value problem of a generalized type into a classical task.

The resulting system of equations was a mathematical model of the process of drying high-moisture materials. Based on the fact that the heat and mass transfer coefficients, as well as the thermodynamic characteristics, were assumed to be constant, the possible options for applying the model were:

1. Solution of the system of equations of the drying process in a moving coordinate system. In this case, the system of equations was transformed into a moving system of coordinates, and then transformed into a classical system of differential equations, which can be solved by classical methods (separation of variables and integral Fourier transformations, etc.).
2. Zonal method of calculating moisture content and temperature fields. In this case, non-stationary heat and mass exchange was divided into zones. For each zone, the coefficients can be considered constant.

To carry out a zonal calculation, in general case, a zone was understood as a certain time interval $\Delta\tau_j = \tau_j - \tau_{j-1}$ ($\tau_{j-1} < \tau_j$, $j = \overline{0,k}$, $\tau_0 = 0$, τ_k - drying time), during which the heat and mass exchange process took place. At the same time, the following was accepted for each zone:

- The process was described by differential equations in time derivatives;
- The geometric shape of the dried product was constant;
- Thermophysical and mass exchange parameters were averaged;
- The initial distribution of temperature and moisture content by volume of the dried product was constant;
- Heat and mass flow density were constant;
- Division into zones allowed to achieve the necessary accuracy of calculating the temperature and moisture of the product.

3. Application of effective heat and mass transfer coefficients ($a_{hef}, \delta_{ef}, \lambda_{ef}$). In the presence of molar vapour transfer during drying of capillary-porous and colloidal materials containing macropores (at the temperature of the material above 100˚C), the influence of concentration and temperature components of molar vapour transfer was taken into account.

The calculation can also be carried out based on the averaged characteristics, which are sometimes called “effective”. However, such a way can be applied only in rare cases, since the issue of parameter averaging usually turns out to be extremely difficult.

Based on the boundary conditions, as well as introducing dimensionless quantities: temperature – T, moisture – W, coordinate – $X = \frac{r}{R}$, time – $Fo = \frac{\alpha \cdot \tau}{R^2}$ the following equation and boundary conditions for temperature change were obtained:

$$\frac{\partial T(X,Fo)}{\partial Fo} = \frac{d^2T(X,Fo)}{dX^2} + \frac{2}{X}\frac{dT(X,Fo)}{dX} - \varepsilon \mathrm{Ko}\frac{\partial W(X,Fo)}{\partial Fo} \quad (12)$$

$$\frac{\partial W(X,Fo)}{\partial Fo} = Lu\left(\frac{d^2W(X,Fo)}{dX^2} + \frac{2}{X}\frac{dW(X,Fo)}{dX}\right) - LuPn\left(\frac{d^2T(X,Fo)}{dX^2} + \frac{2}{X}\frac{dT(X,Fo)}{dX}\right) \quad (13)$$

The tasks were considered to be symmetric:

$$\frac{\partial T(0,Fo)}{\partial X} = \frac{\partial T(0,Fo)}{\partial X} = 0 \quad \begin{cases} T(0,Fo) \neq \infty \\ U(0,Fo) \neq \infty \end{cases}$$

Boundary conditions were:

$$\frac{\partial T(1,Fo)}{\partial X} - \mathrm{Bi}_q\left[1 - T(1,\mathrm{Fo})\right] + (1-\varepsilon)\mathrm{Ko}\cdot\mathrm{Lu}\cdot\mathrm{Ki}_m = 0 \quad (14)$$

$$-\frac{\partial U(1,\mathrm{Fo})}{\partial X} + \mathrm{Pn}\frac{\partial T(1,\mathrm{Fo})}{\partial X} + \mathrm{Ki}_m(\mathrm{Fo}) = 0 \quad (15)$$

where $\mathrm{Fo} = \frac{a\tau}{R^2}$ - Fourier criterion (homochromicity number of transfer potential fields); $\mathrm{Ko} = \frac{r\Delta W}{c_m \Delta T}$ – the Kosovych criterion (dependence between the amount of heat spent on the evaporation of a liquid and on the heating of a wet sample; $\mathrm{Pn} = \frac{\delta \Delta T}{\Delta W}$ Posnov criterion for diffusion transfer (equal to the ratio of the intensity of thermal diffusion transfer of moisture to diffusion transfer of moisture); $\mathrm{Lu} = \frac{a_m}{a}$ – the Lykov criterion (equal to the ratio of moisture mass diffusion coefficients to heat diffusion coefficients); $\mathrm{Bi}_q = \frac{aR}{\lambda}$, $\mathrm{Bi}_m = \frac{a_m R}{a_m}$ - heat exchange and mass exchange criterion of Bio; $\mathrm{Ki} = \frac{qR}{\lambda T_c}$ – Kirpichev criterion, (Sorochinsky, 2019).

Calculation of the parameters of the thermoradiative-convective drying process

When calculating the criteria the values $\Delta T = T_c - T_n$; $\Delta W = W_n - W_p$ were taken, where T_c, T_n the temperature of the environment and the initial temperature of the product; W_n, W_p – the initial and equilibrium moisture content of the product.

The obtained data are shown in Table 1.

Table 1

Process parameters

Parameter	Symbol	Unit	Value for			
			Mushrooms	Hawthorn	Apples	Apple snacks
Initial moisture content	W_n	%	810	330	715	520
Final moisture content	W_k	%	32	38	35	40
Equilibrium moisture content	W_p	kg/kg	0.0	0.0	0.0	0.0
The initial temperature of the product	T_n	K	297	297	297	297
Coolant temperature	T_c	K	333	333	333	333
Particle density	ρ	kg/m^3	750	1173.4	880	965
Specific heat capacity of dry material	c	kJ/kg×K	1.420	1.59	3.801	3.768
Thermal conductivity	λ	W/m×K	0.028	0.112	0.49	0.49
Thermal conductivity coefficient	a	m^2/s	76×10^{-7}	6.3×10^{-6}	14.6×10^{-8}	13.3×10^{-8}
Moisture diffusion coefficient	a_m	m^2/s	9.58×10^{-7}	6.8×10^{-7}	$8{,}48\times10^{-5}$	$8{,}28\times10^{-6}$
Thermal diffusion coefficient	δ	1/K	1.011×10^{-3}	0.51×10^{-2}	$3{,}096\times10^{-5}$	$4{,,}06\times10^{-2}$
Phase transformation coefficient	ε		0.5	0.5	0.5	0.5
Heat transfer coefficient	α	W/m^2×K	14	10.417	617.28	396.253
Moisture transfer coefficient	β	m/s	0.165	0.107	0.086	0.501
Specific heat of vaporization	r	kJ/kg	2443	2356.9	2356.9	2356.9

The moisture diffusivity is the highest among the studied products for cultivated mushrooms and is 9.58×10^{-4} m^2/s, due to the lowest density of 750 kg/m^3 and the highest porosity of the mushroom, which leads to deeper penetration of infrared radiation with a thermal diffusion coefficient of 1.011×10^{-3} 1/K. The moisture diffusion coefficient for hawthorn is 6.8×10^{-7} m^2/s, with a density of 1173.4 kg/m^3 and a thermal diffusion coefficient of 0.51×10^{-2} 1/K, due to the fact that the hawthorn fruits are spherical and were placed in the

dryer in a heap. Apples and apple snacks when placed in the dryer were cut into slices of 4–6 mm, for which the moisture diffusion coefficient for apples is 8.48×10^{-5} m^2/s, with the density of apples 880 kg/m^3 and the thermal diffusion coefficient 3.096×10^{-5} 1/K. Apple snacks were made by blanching apple cores in sugar syrup before drying, which led to a decrease in the moisture diffusion coefficient to 8.28×10^{-6} m^2/s, an increase in density to 965 kg/m^3, and a thermal diffusion coefficient of 4.06×10^{-2} 1/K compared to apple slices.

The solution of the task was obtained in the following form:

$$T\left(X,Fo\right)=1-\sum_{n=1}^{\infty}\sum_{i=1}^{2}c_{ni}\Phi_{\Gamma}\left(\nu_i\mu_n X\right)\exp\left(-\mu_n^2 Fo\right) \tag{16}$$

$$U\left(X,Fo\right)=1+\frac{1}{\varepsilon Ko}\sum_{n=1}^{\infty}\sum_{i=1}^{2}c_{ni}\left(1-\nu_i^2\right)\Phi_{\Gamma}\left(\nu_i\mu_n X\right)\exp\left(-\mu_n^2 Fo\right) \tag{17}$$

where

$$\nu_i^2=\frac{1}{2}\left[\left(1+KoPn+\frac{1}{Lu}\right)+\left(-1\right)^i\sqrt{\left(1+KoPn+\frac{1}{Lu}\right)^2-\frac{4}{Lu}}\right] \tag{18}$$

$$\nu_1^2=\frac{1}{2}\left(80.366-\sqrt{80.366^2-\frac{4}{Lu}}\right)=1\left(80.366+\sqrt{80.366^2-\frac{4}{Lu}}\right)=8.909$$

$$c_{n1}=\frac{2}{\mu_n\psi_n}\left|\left(1-\varepsilon KoK1\right)P_{n2}+\varepsilon KoQ_{n2}\right|\ c_{n2}=-\frac{2}{\mu_n\psi_n}\left|\left(1-\varepsilon KoK1\right)P_{n1}+\varepsilon KoQ_{n1}\right| \tag{19}$$

$$\psi_n=\nu_1A_{n1}P_{n2}+\nu_2B_{n2}Q_{n1}-\nu_2A_{n2}P_{n1}-\nu_1B_{n2}Q_{n2} \tag{20}$$

The separation of variables by the Fourier method allowed to advance much further than in the general case.

$$Q_{n1}=\left(1-\frac{1}{Bi_q}+\left(1-\nu_1^2\right)K1\right)\sin\left(\nu_i\mu_n\right)+\frac{1}{Bi_q}\nu_i\mu_n\cos\left(\nu_i\mu_n\right) \tag{21}$$

$$P_{ni}=\left(1-\nu_i^2\right)\sin\left(\nu_i\mu_n\right)+\frac{\left(1-\nu_i^2\right)+\varepsilon KoPn}{Bi_m}\left(\nu_i\mu_n\cos\left(\nu_i\mu_n\right)-\sin\left(\nu_i\mu_n\right)\right) \tag{22}$$

$$A_{ni}=\left[1+\left(1-\nu_i^2\right)K_1\right]\cos\left(\nu_i\mu_n\right)-\frac{1}{Bi_q}\nu_i\mu_n\sin\left(\nu_i\mu_n\right) \tag{23}$$

$$B_{ni}=\left(1-\nu_i^2\right)\cos\left(\nu_i\mu_n\right)-\frac{\left(1-\nu_i^2\right)+\varepsilon KoPn}{Bi_m}\nu_i\mu_n\sin\left(\nu_i\mu_n\right) \tag{24}$$

where μ_n is roots of the characteristic equation

$$P_{n1}Q_{n2}-P_{n2}Q_{n1}=0 \tag{25}$$

$$K_1-\text{value: }K1=\frac{1-\varepsilon}{\varepsilon}Lu\frac{Ki_m}{Bi_q} \tag{26}$$

The averaged heat and mass transfer potentials were calculated according to the following dependencies:

$$\overline{T}(Fo) = 1 + \sum_{n=1}^{\infty}\sum_{i=1}^{2} D_{ni} \exp\left(-\mu_n^2 Fo\right) \tag{27}$$

$$\overline{U}(Fo) = 1 - \frac{1}{\varepsilon Ko}\sum_{n=1}^{\infty}\sum_{i=1}^{2} D_{ni}\left(1-\nu_i^2\right)\exp\left(-\mu_n^2 Fo\right) \tag{28}$$

$$D_{ni} = 3C_{ni}\frac{\sin\left(\nu_i\mu_n\right) - \nu_i\mu_n\cos\left(\nu_i\mu_n\right)}{\left(\nu_i\mu_n\right)^2} \tag{29}$$

The obtained system of differential transport equations together with the initial and boundary conditions reflects in an analytical form the main features of the studied process of thermoradiative-convective drying of high-moisture materials, that is, it is its mathematical model. The solution of the model makes it possible to obtain a complete picture of the distribution of transfer potentials in a body or a system of bodies, to trace the change of potential fields over time, and on this basis to provide a detailed analysis of the kinetics and dynamics of the process of drying high-moisture materials.

Comparative analysis of analytical and calculation data of thermoradiative-convective drying

A software module for calculating the drying process of high-moisture materials during thermoradiative-convective dehydration has been developed. The result of the approximation of experimental data regarding the drying of particles of cultivated mushrooms, hawthorn, apples, and apple snacks is shown in Figure 3. Comparative analysis of calculated and experimental data showed good convergence: the deviation of calculated data from experimental data did not exceed 9.6%.

The obtained data are shown in Table 2.

When processing the data of Figure 4, for the dehydration of cultivated mushrooms, which is traced by a decrease in moisture content from 809 to 30%, it is necessary to spend 80 minutes, and to reduce the moisture content of hawthorn from 330 to 38%, the duration of the thermoradiative-convective drying process is 60 minutes.

The duration of drying of apple snacks increases by 10 minutes compared to apples, which is due to the sugar content in the snacks and the osmotic properties of sugar to retain moisture, which is characterized by the viscosity of colloids (Strelchenko et al., 2019). When drying, it is necessary to give the snacks more heat to loosen the colloid bonds and remove moisture from the product.

Comparative analysis of calculated and experimental data shows a satisfactory convergence: the deviation of calculated data from experimental data did not exceed 9.6% during thermoradiative-convective drying and is due to the fact that the model does not take into account all factors that affect the process, as well as simplifications, allowed in the model itself.

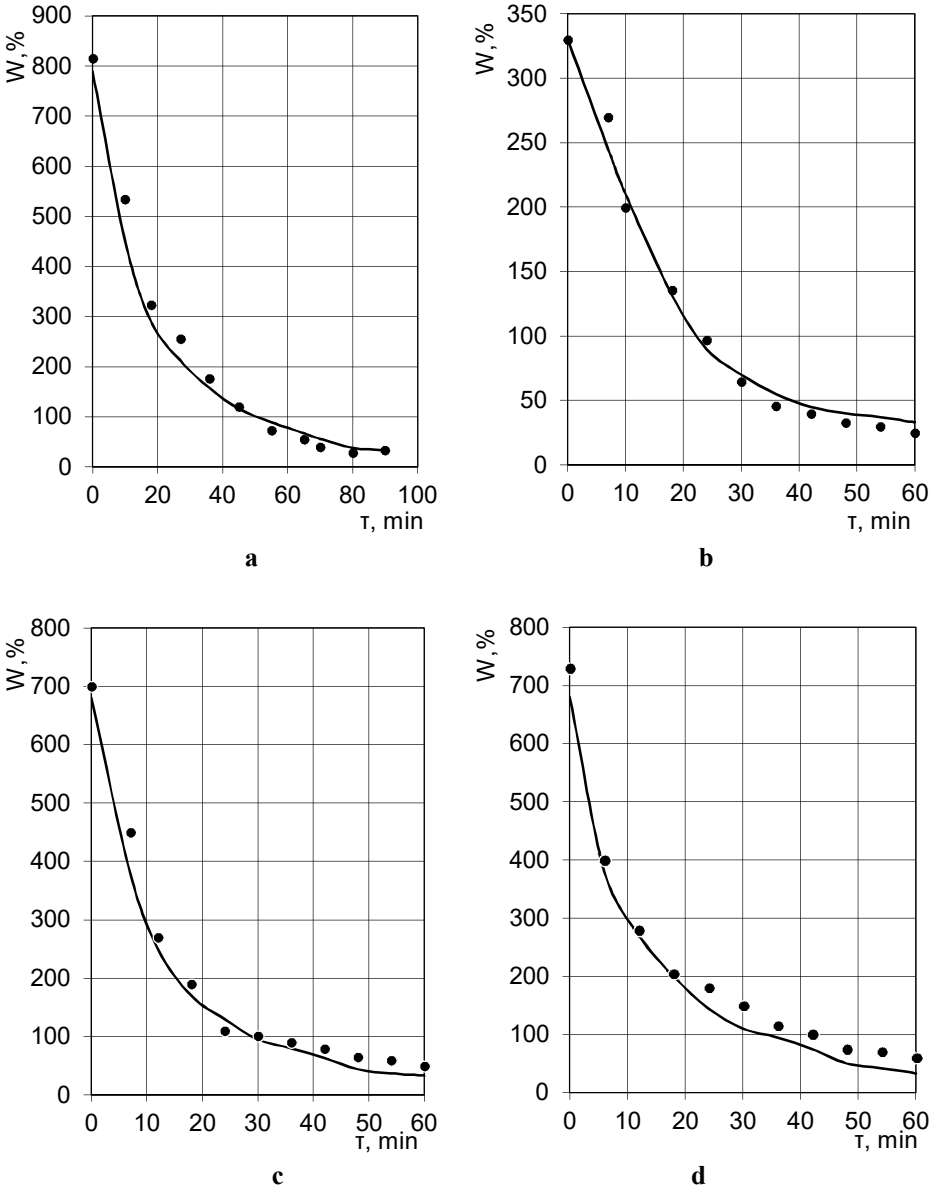

Figure 3. Change in moisture content of high-moisture materials over time
W is moisture content, %; τ is drying time, min.
a is cultivated mushrooms; b is hawthorn; c is apples; d is apple snacks.
● – experimental data
▬ – calculated data

Table 2

Comparative analysis of experimental and calculated data of thermoradiative-convective drying of products of plant origin

Duration, min	Wm (model), %		We (experimental), %		Relative difference, %	
	Cultivated mushrooms	Hawthorn	Cultivated mushrooms	Hawthorn	Cultivated mushrooms	Hawthorn
0	789	324	809	330	7.991	1.8
9	450	238	534	247	4.753	9.0
18	296	177	312	174	5.1	1.7
27	212	132	233	134	9.0	1.5
36	157	98.5	177	95	1.671	0.96
45	118	71.4	116	66	1.169	7.6
54	89	52.7	81	48	8.9	8.9
63	77	40.7	71	38	7.8	6.6
81	38	-	35	-	7.9	-
90	33	-	32	-	3.0	-
Duration, min	Apples	Apple snacks	Apples	Apple snacks	Apples	Apple snacks
0	680	487	713	517	7.056	5.8
7	380	360	450	380	4.733	5.2
12	251	270	270	279	3.116	3.3
18	170	200	190	205	2.206	2.4
24	130	145	110	158	1.493	8.2
30	95	120	102	130	1.185	7.7
36	80	92	87	100	0.917	8.0
42	64	75	82	83	0.731	9.6
48	44	55	65	64	0.593	9.0
54	37	42	60	50	0.508	8.0
60	33	40	50	48	0.366	8.0

Conclusions

1. The developed energy-efficient chamber thermoradiative-convective dryer with the combined interaction of infrared radiation and an additionally installed heat pump will make it possible to reduce energy costs for the drying process by up to 30%. The developed design of the technological channels of the dryer due to the additional supply and removal of air in the side walls of the dryer allows avoiding stagnant zones and uniform distribution of air.
2. For the first time, a comparison of the kinetics of thermoradiative-convective drying of the drying process of cultivated mushrooms, hawthorn, apples, and apple snacks was investigated, which showed a decrease in duration compared to convective drying and an improvement in the quality of products compared to thermoradiative drying.
3. Calculated moisture diffusion coefficients of thermoradiative-convective drying in the middle of products, which are for cultivated mushrooms – $9{,}58\times10^{-4}$ m^2/s, hawthorn – 6.8×10^{-7} m^2/s, apples – 8.48×10^{-5} m^2/s and apple snacks – 8.28×10^{-6} m^2/s.

4. A system of differential transport equations was obtained, which allows to display in an analytical form the main features of the simultaneous influence of convective and thermoradiative energy supply during drying of high-moisture materials with a discrepancy between experimental and calculated data of up to 9.6%.

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Changes in the chemical composition of extracts of wild berries growing in the Republic of Azerbaijan due to enzimatic pretreatment of their pulp

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Abstract

Introduction. The objective of this research was to study the influence of the enzymatic processing of the pulp of dogwood, elderberry, hawthorn, barberry, and raspberry berries on the content of ascorbic acid, sugars, polyphenols and heavy metals in their extracts.

Materials and methods. The berries were processed using enzyme preparations with pectolytic and glycolytic action. The identification of biologically active components in the extracts was carried out using high-performance liquid chromatography with ultraviolet and mass spectrometric detection.

Results and discussion. The use of enzyme preparations increased the yield of juices from berry pulp. The optimal juice extraction was attained after a 120-minute fermentation period for barberry and dogwood berries. For elderberry and raspberry, the optimal periods were 75 and 90 min, respectively. A processing temperature of 45 °C turned out to be the most suitable for most berries, except for barberry, which showed better results at a temperature of 60 °C. The use of both individual enzyme preparations and their complexes had a positive effect on the juice yield for all tested berries. For dogwood and hawthorn, the most effective was the combination of "Pectinex BE XXL" and "Fructosym P", and for elderberry, barberry and raspberry – "Amylase AG 300L" and "Sellolyuks-A".

An increase in the concentration of ascorbic acid and sugars in the juices obtained from berries after enzymatic treatment was observed. Enzymatic treatment led to a significant increase of the total concentration of polyphenols, as well as the content of some individual components. Thus, a significant increase in gallic acid content after enzymatic treatment was observed in all samples where it was detected. The exception was coumarins, the concentration of which decreased after enzymatic treatment. It was found that enzyme preparations generally have a positive effect on the content of biologically active substances in the juices of wild berries. However, no significant increase in the concentration of heavy metals was observed. In most cases, the use of multienzyme complexes demonstrated the greatest positive effect.

Conclusions. The results obtained are of high importance for the processing technology of the studied berries showing the promise of the enzymatic maceration for increasing the content of biologically active substances in their juices.

Introduction

Wild berries are actively used in the food industry, including for the production of soft drinks and energy drinks. These raw materials have a high content of biologically active substances, such as polyphenols, vitamins and sugars, which are responsible for the organoleptic and nutritional characteristics of berries (Dhalaria et al., 2020; Nile and Park, 2014; Stabnikova et al., 2024). Several wild berries have a high content of pectin substances, which are used as thickeners and stabilizers to impart the desired consistency and texture to products (Surolia and Singh, 2022). In addition, the use of natural berries has a positive effect on the taste of the product, making it more attractive to consumers. Wild berries are also actively used in the production of natural fruit juices and soft drinks such as lemonades, and other fruit beverages. Due to their high content of natural sugars, vitamins, minerals and antioxidants, wild berries have become popular ingredients in the energy drink industry in recent years.

Wild berries such as dogwood, elderberry, hawthorn, barberry and raspberry are abundant in Azerbaijan and are of interest for commercial juice, as well as puree production due to their high content of beneficial compounds like polyphenols, vitamins and sugars. However, issues like low juice yields and variability in phytochemical content have limited their utilization. Enzymatic pretreatments may help overcome these barriers, but research is lacking on their effects on the composition and properties of juices from these underutilized berries native to Azerbaijan.

To enhance juice yield using enzymatic methods, it is crucial to select enzymes that effectively break down cell walls, facilitating the release of juice. Common choices include pectinases, cellulases, and hemicellulases. These enzymes can be used individually or in combinations, and their selection often depends on the type of fruit and desired characteristics of the juice. Factors like enzyme concentration, temperature, and duration of treatment also play a vital role in maximizing juice yield. Optimizing these parameters through experimental trials and error analysis is essential for achieving the highest possible yield.

In recent years, increasing attention has been paid to the use of enzyme preparations to improve different processes in food technologies. The use of enzymes in the pretreatment of berry pulp can contribute to better extraction of biologically active substances from berry raw materials. Enzymes are capable of destroying cell walls, breaking down complex compounds and increasing the yield of valuable components. M. Kaveh et al. (2020) showed that enzymatic treatment of berries can increase the yield of several biologically active substances by breaking down cell walls. Polyphenols, vitamins, and sugars are of significant value to the food industry, which means increasing the availability of these compounds, which can lead to their increased concentration in the pulp. Polyphenols are biologically active phenolic compounds, widely present in wild berries. According to A.M. Zeynalova et al. (2019) polyphenols isolated from berries growing in Azerbaijan demonstrate antioxidant properties. Meanwhile, it was found that polyphenols exhibit a protective effect on body cells, reducing the risk of developing cardiovascular, oncological and neurodegenerative diseases (Rudrapal et al., 2022). In addition, it was shown that polyphenols have anti-inflammatory and antiviral properties (El-Missiry et al., 2021) and food rich in polyphenols demonstrated anti-obesity effects (Stabnikova and Paredes-Lopez, 2023). The sugar content affects the balance between the sweetness and acidity of the berries, which is important for ensuring a harmonious taste of the drinks, and sugar, found in raw berries, can influence fermentation during the beverage production process (Peighambardoust et al., 2021). Besides that, berries contain a significant amount of vitamins, including ascorbic acid, which exhibit significant antioxidant activity (Davronovich et al., 2022). It is worth noting that wild berries can be contaminated with

various environmental pollutants including heavy metals. Such pollution can occur due to industrial emissions, the use of pesticides, soil, and water pollution and several other anthropogenic factors. However, heavy metals such as lead, cadmium, nickel and arsenic are highly toxic to humans, even in trace amounts (Zaynab et al., 2022). Chronic consumption of foods containinghigh amounts of heavy metals can lead to serious problems such as organ damage and nervous system dysfunction. Enzymatic processing of berries can have an impact on the level of heavy metal contamination in theor extracts, so studies such as these will help determine optimal processing conditions that do not increase the content of heavy metals while increasing the concentration of beneficial biologically active substances in the product.

Studying the effect of enzymatic treatment on the content of ascorbic acid, polyphenols, sugars, and heavy metals in berry extracts allows gaining a deeper understanding of the mechanisms and influence of fermentation on the quality, as well as the properties of biologically active components of berries. This may have practical applications for the development of optimal technologies and processes for the production of berry drinks with improved properties, as well as high nutritional value and safety for the consumer.

Thus, the aim of this work was to obtain extracts of wild berries of dogwood, elderberry, hawthorn, barberry and raspberry, to process them with enzymatic preparations with pectolytic and glycolytic effects, as well as to analyse them to study the effect of the enzymatic treatment on the content of ascorbic acid, polyphenols, and sugars in them, as well as heavy metals in berries extracts.

Materials and methods

Samples of wild berries of dogwood (*Cornus mas* L.), elderberry (*Sambucus nigra* L.), hawthorn (*Crataegus monogyna subsp.*), barberry (*Berberis L.*) and raspberries (*Rubus L.*) were collected in various regions of the Republic of Azerbaijan during the period October 2021 to October 2022. Only fully ripe, undamaged berries were selected. Frozen berries were thawed and homogenized. Samples of the resulting pulp weighing 1 kg were heated to a temperature of 50 °C for 8 minutes. After this, enzyme preparations “Pectinex BE XXL”, “Pectinex Yieldash Extra”, “Amylase AG 300 L”, “Fructosym P”, “Rapidaza CR”, “Bryuzaym BGX”, “Laminex super”, “Selloviridin Q20X” were added to the samples. “Sellokyuks-A” and “Enzerzim XT” in amounts of 50, 75, 100 and 150 mg per 1000 g of pulp, as well as their compositions in the following combinations: “Pectinex BE XX” – “Fructosym P” (Multienzyme complex-I), “Amylase AG 300 L” – “Sellokyuks-A” (Multienzyme complex-II) and “Pectinex Yieldash Extra” – “Bryuzaym BGX” (Multienzyme complex-II) in amounts of 50, 75 and 100 mg of each drug per 1000 g of pulp. The maceration process in different experiments lasted 60, 75, 90, 105 and 120 minutes, at temperatures of 30, 45, 60 and 75 °C. Then juices were made from the samples using a Para-press laboratory press (Arauner Kitzingen, Germany) at a pressure of 0.28 MPa for 10 minutes. The results were compared with control samples that were subjected to similar processing but without the step of enzymatic treatment. The most effective enzyme preparation for each type of berry was determined.

To determine the ascorbic acid content, 10 g of raw material was weighed and homogenized using 25 ml of metaphosphoric acid solution with a concentration of 10 g/l. The samples were actively mixed for 15 minutes; after which they were centrifuged at 3800 g for 15 min at 4 °C. The extraction was carried out in duplicate. The resulting supernatants were combined, after which 10 g/l metaphosphoric acid was added, resulting in a volume of 50 ml. A mixture of 1 ml of dithiothreitol with a concentration of 50 g/l and 10 ml of sample

was prepared. Metaphosphoric acid was used to bring the volume of solutions to 25 ml. During chromatographic separation, the mobile phases consisted of methanol (phase A) and 0.005 mol/l of KH_2PO_4 solution (pH 2.6, phase B). The gradient method was used as follows: the percentage of phase A was increased from 5% to 22% over 6 minutes, followed by a return to baseline conditions over 9 minutes. Detection was performed at 245 nm and the flow rate 0.7 ml/min. The results were expressed in mg of ascorbic acid per 100 g fresh berry's weight.

To analyse polyphenol content, 10 g of samples were mixed with 50 ml of 70% methanol. The resulting mixture was processed for 15 minutes on a heated shaker and then centrifuged at 3000 g for 20 min. The extraction was repeated twice to ensure full extraction. The collected phenolic extracts were pooled and vacuum evaporated at 40 °C to concentrate them. Distilled water was used to bring the concentrated extracts to a final volume of 25 ml. The mobile phase used for analysis consisted of two components: solvent A, which was prepared by dissolving 60 g of acetic acid in 0.002 mol/l sodium acetate, and solvent B, which was acetonitrile. The entire analysis was carried out for 35 min at a constant flow rate of 1 ml/min. Compound separation was achieved using a gradient program starting with 0-15% B over 15 min, then 15-30% B over 25 min, then 30-50% B over 5 min and finally 50-100% B for 5 min. To quantify phenolic compounds, measurements were carried out at three different wavelengths: 280 nm, 320 nm and 360 nm. An external standard method was used utilizing gallic acid, chlorogenic acid and quercetin as reference standards. Mass spectrometric detection was used to identify polyphenols. Detection was carried out in positive ion mode (Mildner-Szkudlarz et al., 2015).

For sugar analysis, 20 ml of samples were hydrolysed with 1 ml of 1 M sulphuric acid by heating the mixture at 100 °C for 3 hours. After hydrolysis, the resulting hydrolyses were diluted 20-fold with distilled water and then treated with 1-phenyl-3-methyl-5-pyrazolone (PMP) for derivatization. As an internal standard, 10 µl of 0.5 mM 2-deoxyglucose was added to each sample. Sugar separation was achieved at a flow rate of 0.6 ml/min and was carried out at 30 °C. The mobile phases used for separation consisted of two components: (A) a mixture of 10% acetonitrile and 40 mM ammonium acetate at pH approximately 6.8 and (B) 70% acetonitrile. The separation process followed a gradient elution starting with 8% phase B, which increased to 16% phase over 12 min. Detection was performed at 250 nm. To determine the sugar content, the areas under the peaks observed in the chromatograms were compared with standard samples of glucose, fructose, galactose, and sucrose. All chromatographic studies were carried out using an Agilent Technologies 1200 LC system (Agilent Technologies, USA) equipped with a UV detector and a mass spectrometer. Separation was carried out on a Poroshell 120, SBC18 column (4.6 x150 mm, 2.7 µm). The concentration of a number of heavy metals was also measured in the resulting juices. Ni, Cu, Co, Pb, Cd and As were determined by atomic absorption spectrometry on a Perkin-Elmer 3030B flame spectrometer. Cr and Sr were analysed using an ISP AtomScan 25 emission spectrometer.

Results and discussion

When conducting preliminary experiments to measure the yield of juice from dogwood, elderberry, hawthorn, barberry and raspberry berries, the most effective enzyme preparations and optimal processing modes were established. The highest juice yield for barberry and dogwood berries was observed during fermentation for 120 minutes. For elderberry and raspberry, the optimal period was 75 and 90 minutes, respectively. With longer processing

for these berries, no significant increase in juice yield was observed. For most of the berries tested, the optimal processing temperature was 45 °C. The exception was barberry berries, for which this parameter was 60 °C.

The results obtained indicate that the most effective of the studied preparations for dogwood berries was the enzyme "Fructosym P" when treated, with which the juice yield increased from 50.2±1.34% to 58.5±0.78%. For elderberry and barberry, the enzyme preparation "Pectinex BE XXL" turned out to be optimal; when used, the juice yield increased from 54.5±0.87% and 52.6±2.24% to 61.3±1.74% and 60.4±3.08%, respectively. When processing hawthorn, the most effective enzyme was "Amylase AG300L"; compared to control samples, the juice yield increased from 48.4±1.06% to 57.8±1.56%. For raspberries, the enzyme preparation "Pectinex Yieldash Extra" was the most effective; after treatment, the juice yield increased compared to control samples from 58.4±1.46% to 67.2±3.23%. When processing dogwood and hawthorn, the most effective was the multienzyme complex consisting of the preparations "Pectinex BE XXL" and "Fructosym P", the juice yield increased from 50.2±1.34% and 48.4±1.06% to 64.6±3.04% and 60.5±2.54% respectively. For elderberry, barberry and raspberry, the combination of drugs "Amylase AG 300L" and "Sellolyuks-A" demonstrated the greatest efficiency, while the juice yield increased from 54.5±0.87%, 52.6±2.24% and 58.4±1.46% to 66.3±1.73%, 65.8 ±3.18% and 69.4±1.35%, respectively.

It was found that preliminary enzymatic treatment of crushed dogwood, elderberry, hawthorn, barberry, and raspberry berries with various enzyme preparations helps to increase the yield of unclarified juices by an average of 6.8-9.4% compared to control samples. The most effective drugs are "Fructosym P", "Pectinex BE XXL" and "Amylase AG 300L". When using the most effective multienzyme complexes, the juice yield increased by an average of 11-14.4% compared to control samples and by 2.2-6.1% compared to the use of effective enzymes. It was shown that the use of a complex of preparations "Pectinex BE XXL" and "Fructosym P" was more effective when processing dogwood, with an increase in juice yield from which was 6.1%. When processing elderberry and barberry, the best result was demonstrated by the mixture of Amylase AG 300L and Sellolyuks-A: the increase in juice yield was 5 and 5.4%, respectively. The use of multienzyme complexes turned out to be relatively less effective for hawthorn and raspberry, as juice yield increased by only 2.7% and 2.2%, respectively.

The concentration of ascorbic acid was measured in dogwood, elderberry, hawthorn, barberry, and raspberry berries subjected to preliminary enzymatic treatment, as well as without such treatment. The obtained data are presented in Table 1.

The yield of vitamin C in the juice fraction after treating the berries with the most effective enzyme preparations increased for dogwood berries by 1.18 times, elderberries by 1.23 times, hawthorn by 1.22 times, barberries by 1.38 times, and raspberries by 1.2 times. An increase in the content of ascorbic acid in the juices of these berries using multienzyme complexes was observed on average by 1.35-1.52 times. The most likely reason for the increase in the yield of ascorbic acid is the hydrolytic breakdown of the structural components of the cell wall, and above all, cellulose and hemicellulose, as a result of which bound forms of vitamin C are released into juices. In the analysed juices, the presence of glucose, fructose, galactose, and sucrose were identified and the concentrations were quantified. The results are shown in Table 2.

Table 1

Content of ascorbic acid in berry juices subjected to various types of preliminary enzymatic maceration

Berry	Ascorbic acid concentration (mg/100 g)				
	No treatment	Best drug	Multienzyme complex	"No treatment" vs. "Best drug" (paired t-test) (Not statistically significant at α = 0.05)	"No treatment" vs. "Multienzyme complex" (paired t-test) (Not statistically significant at α = 0.05)
Dogwood	75	88.7	101.2	p-value = 0.057	p-value = 0.004
Elderberry	38.2	47.2	52.4	p-value = 0.086	p-value = 0.001
Hawthorn	39.8	48.6	57	p-value = 0.095	p-value = 0.0002
Barberry	84.5	116.8	128.3	p-value = 0.001	p-value = 0.00005
Raspberry	57.6	69.1	81.3	p-value = 0.002	p-value = 0.00002

Source: compiled by the author

Table 2

Sugar concentration in berry juices subjected to various types of preliminary enzymatic maceration

Berry	Processing method	Content (g/100g)			
		glucose	fructose	galactose	sucrose
Dogwood	No treatment	4.2	3.8	0.7	0.5
	Best drug	5.2	4.1	0.8	0.6
	Multienzyme complex	6.5	5.7	1.3	0.8
Elderberry	No treatment	5.7	4.6	0.5	0.3
	Best drug	6.7	4.5	0.6	0.4
	Multienzyme complex	6.9	7.1	0.6	0.7
Hawthorn	No treatment	8.5	3.4	0.2	1.5
	Best drug	8.7	4.8	0.3	1.4
	Multienzyme complex	9.4	7.8	0.3	1.7
Barberry	No treatment	7.3	6.5	0.1	0.1
	Best drug	8.1	7.8	0.1	0.2
	Multienzyme complex	9.7	8.9	0.2	0.4
Raspberry	No treatment	7.6	6.8	0.2	0.4
	Best drug	8.2	6.9	0.5	0.5
	Multienzyme complex	8.3	7.4	0.5	0.6

Source: compiled by the author

Because of treating the pulp with enzyme preparations, a significant increase in glucose concentration was observed in all studied samples, which was directly related to the breakdown of polysaccharides. In addition, increases of the amounts of other sugars were also observed. This effect was most significant when using multienzyme complexes. When using the enzyme preparation "Fructosym P", the increase in sucrose content in the samples was on average no more than 12%, and when using the complex of preparations "Pectinex

BE XXL" and "Fructosym P", an increase in the concentration of this component was observed by 1.58 times. In general, the increase in the concentration of sugars in the samples is associated with the destruction of the cell wall, and s a result of what their extractability increases. The total concentration of polyphenols in berry juices is given in Table 3.

Table 3

Total content of phenolic compounds in berry juices subjected to various types of preliminary enzymatic maceration

Berry	Ascorbic acid concentration (mg/100 g)		
	No treatment	Best drug	Multienzyme complex
Dogwood	645.1	657.5	705.3
Elderberry	575.8	596.8	613.6
Hawthorn	458.9	499.3	511.1
Barberry	589.2	610.1	610.9
Raspberry	35.8	46.2	56.5

Source: compiled by the author

The total content of phenolic compounds was highest in the juices of dogwood berries. A significant increase in the total concentration of polyphenols in pulp samples was observed after their treatment with enzymatic preparations. The data obtained indicate that the destruction of polysaccharides during enzymatic maceration leads to the release of some polyphenols. During the study, 10 phenolic compounds were identified in the analysed pulp extracts. However, only coumarins, quercetin, gallic and chlorogenic acids were measured quantitatively.

The largest amount of phenolic compounds was found in dogwood berries. Its juices, pre-treated with enzyme preparations, contained chlorogenic acid, 257 mg/100 g, and quercetin, 65 mg/100 g. It was found that the content of the latter in dogwood and elderberry juices prepared from pulp subjected to pectinolysis was higher than in untreated samples by 15% and 17%, respectively. In all samples where gallic acid was detected, a significant increase in its content was observed after enzymatic treatment. Compared to untreated samples, hawthorn juices prepared from pulp subjected to pectinolysis showed the most significant increase by 16%. Several samples showed the appearance of peaks of certain compounds after enzymatic hydrolysis. The only exception was hawthorn juice, the peak of quercetin in which disappeared after treating the samples with enzymatic preparations. Among the hydroxybenzoic acids, two compounds have been identified: 4-hydroxybenzoate and formyl salicylic acid. It is worth noting that the content of 4-hydroxybenzoate increased significantly in samples subjected to enzymatic maceration. 4-Hydroxybenzoate is a phenolic compound associated with plant cell walls, which may explain its higher content in pre-treated extracts. The data obtained indicate that the use of enzymatic treatment of pulp may increase the extractability of 4-hydroxybenzoate. However, the biosynthetic pathway and degradation of 4-hydroxybenzoate in plants are not yet fully understood.

The evaluation of juices' organoleptic properties entails the assessment of sensory attributes such as flavour, fragrance, visual appeal, and consistency. To assess the sensory properties of dogwood, elderberry, hawthorn, barberry, and raspberry juices produced through enzymatic treatment, a descriptive approach was used for organoleptic evaluation (Table 4).

Table 4

Organoleptic evaluation of juices

Berry	Appearance	Aroma	Taste
Dogwood	The juice has a vibrant reddish hue with excellent clarity, making it visually appealing.	The juice offers a delicate and fruity aroma with hints of berry notes and a subtle floral undertone.	The taste profile is pleasantly sweet, mildly tart, and features distinct berry-like flavors.
Elderberry	The juice exhibits a deep purple color with good clarity, which is visually striking.	The juice releases a strong and distinctive berry fragrance, displaying the characteristic aroma of elderberries.	The juice offers a well-balanced sweetness with a noticeable tartness and a rich, bold berry flavor.
Hawthorn	The juice is slightly cloudy with a pleasant, pale red color.	The juice has a mild, fruity aroma with faint floral hints that contribute to its overall appeal.	The juice has a mildly sweet and slightly tart taste with subtle fruity notes.
Barberry	The juice is clear and possesses an inviting golden color.	The juice has a fresh and slightly tangy aroma with subtle citrus notes, reflecting its unique character.	The juice is characterized by its refreshing tartness, mild sweetness, and a unique citrus-like tang.
Raspberry	The juice is notably vivid, displaying a rich red hue that is visually enticing.	The juice presents a bold and fruity aroma dominated by the sweet and tangy scent of ripe raspberries.	The juice is notably sweet, tangy, and bursting with the authentic flavor of ripe raspberries.

Note: This organoleptic evaluation is subjective and reflects one individual's assessment.
Source: compiled by the author.

Furthermore, an examination of the overall characteristics of these wild berries is included: (a) the consistency of all the juices is velvety and devoid of any discernible pulp, ensuring a delightful drinking sensation; (b) elderberry and raspberry juices stand out for their rich and distinctive flavors, with elderberry offering a berry profile, and raspberry providing an authentic raspberry experience. Dogwood juice also deserves recognition for its balanced sweetness and fruity appeal.

Among the derivatives of hydroxycinnamic acid, two compounds have been identified: chlorogenic acid and coumarin. Chlorogenic acid content showed no significant differences between fermented samples and extracts obtained from untreated pulp. Elderberry juices subjected to enzymatic treatment had the highest content of chlorogenic acid. The content of coumarins was significantly lower in juices prepared from unprocessed pulp. However, overall, the results of the study indicate that enzymatic treatment of berry pulp led to better retention of phenolic compounds in juices compared to untreated samples.

Data regarding the content of heavy metals in the analysed juices are presented in Table 5.

Table 5

Concentration of heavy metals in juices of berries subjected to various types of preliminary enzymatic maceration

Berry	Processing method	Content, mg/100 g							
		Ni	Cu	As	Cd	Co	Cr	Pb	Sr
Dogwood	No treatment	1.71	1.33	0.04	-	0.01	0.05	0.24	0.2
	Best drug	1.74	1.34	0.04	-	0.01	0.05	0.24	0.2
	Multienzyme complex	1.73	1.4	0.04	-	0.01	0.05	0.25	0.21
Elderberry	No treatment	0.62	0.81	0.03	-	-	0.04	0.15	0.09
	Best drug	0.64	0.82	0.03	-	-	0.04	0.15	0.09
	Multienzyme complex	0.66	0.85	0.03	-	-	0.04	0.16	0.09
Hawthorn	No treatment	1.23	1.2	-	-	0.01	0.05	0.16	0.1
	Best drug	1.24	1.21	-	-	0.01	0.05	0.16	0.1
	Multienzyme complex	1.29	1.26	-	-	0.01	0.05	0.17	0.11
Barberry	No treatment	1.47	1.13	0.10	-	0.07	0.03	0.05	0.07
	Best drug	1.48	1.14	0.10	-	0.07	0.03	0.05	0.07
	Multienzyme complex	1.54	1.19	0.11	0.01	0.07	0.03	0.05	0.07
Raspberry	No treatment	0.35	0.54	0.01	-	0.02	0.03	0.1	0.03
	Best drug	0.35	0.55	0.01	-	0.02	0.03	0.1	0.03
	Multienzyme complex	0.37	0.57	0.01	-	0.02	0.03	0.11	0.03

Source: compiled by the author

The results demonstrate that the methods of preliminary enzymatic maceration used do not lead to a significant (more than 5%) increase in the concentration of heavy metals in the juices of the tested berries. It is worth noting that cadmium, Cd, was not found in any of the unprocessed juices. A low concentration of this metal (0.01 mg/100 g) was recorded only in barberry juices treated with a multienzyme complex. Cobalt, Co, was not found in elderberry juices, and arsenic, As, was not found in hawthorn juices.

Discussion

The obtained results showed a notable enhancement in the juice yield from berries following their pre-treatment with enzyme preparations. The used pectolytic preparations are capable of destroying pectins, which are the main component of cell walls, which makes them more susceptible to mechanical destruction. L.R. Larsen et al. (2021) showed that this process facilitates the release of juice during further processing of berries. Also, it was demonstrated that preliminary enzymatic maceration promotes better drainage of juice from berries. This is due to their ability to break down cellular structures and facilitate fluid flow. Thanks to this, the process of juice extraction becomes more complete and efficient. Enzyme preparations with glycolytic action can soften the cells and tissues of berries (Streimikyte et al., 2022). They affect glycosidic bonds in carbohydrate molecules, which leads to the

destruction of cell structure. Softening the tissue makes it easier to release the juice by pressure or centrifugation.

Enzyme preparations may affect oxidases that are present in the samples, which may promote the oxidation of ascorbic acid. C. Bender et al. (2017) reported a similar effect in their study, where they found that heating blackcurrant pulp before pectinolysis resulted in higher ascorbic acid content in juices compared to pectinolysis without heating. However, this effect was species-dependent, since, for example, it was not observed in raspberries. Similarly, a decrease in ascorbic acid content in goldenrod berry extract prepared from enzymatically treated pulp was not observed in the study of M.F. Ramadan and H.T. Moersel (2006). Long-term ageing of barberry pulp with preliminary enzymatic and thermal treatment led to a decrease in the content of ascorbic acid in the extracts and juices prepared from enzymatically treated raw materials had significantly lower ascorbic acid content compared to untreated samples (Radziejewska-Kubzdela et al., 2020). It was suggested that the retention of ascorbic acid during pretreatment without prior inactivation of ascorbic acid oxidase might depend on the specific profile of phenolic compounds present in the raw material (Clegg and Morton, 1968). In this study, no reduction in vitamin C content was observed in the samples due to enzymatic treatment. On the contrary, there was a noticeable increase in the concentration of ascorbic acid in juices treated with multienzyme complexes.

As with other biologically active substances, one of the main mechanisms for increasing polyphenol concentrations is likely due to breakdown by cell wall enzymes. Enzymatic pre-treatment helps release polyphenols, making them easier to extract and increasing their concentration in the extract. In addition, introduced enzymes that can activate internal enzymatic systems such as polyphenoloxidases present in berries (Nicolescu et al., 2022). These enzymes catalyse the oxidative reactions of polyphenols, which can lead to the formation of polymeric and oxidized forms. In addition, enzymes can promote the hydrolysis of glycosidic bonds that link polyphenols to other molecules such as sugars or organic acids. This may result in the release of polyphenols from complexes and increase their availability for extraction. The use of various enzymes (Cellubrix, Neutrase and Viscozyme) on grape pomace from Cabernet (red) and Garnatxa (white) varieties increased the yield of antioxidant compounds during extraction (Costoya et al., 2010). Enzymatic treatment, especially when a mixture of three enzymes was used, significantly increased extractable phenolics by 21% for Garnatxa and 46% for Cabernet compared to untreated samples. At the same time, enzymatic treatment also increased the solubility of several compounds in water. This suggests that administering enzymatic drugs prior to treatment may enhance the ability of compounds to dissolve, thereby potentially improving their availability for biological processes and the efficiency of their extraction.

It was found that because of the pre-treatment of berries with enzyme preparations, a more effective extraction of polyphenols and an increase in their concentration in the extract is achieved. The findings are consistent with previous studies that also reported similar effects. The study conducted by L.N. Lieu and B.B. Le (2010) compared the effects of enzymatic treatment and sonication on grape must. An increase in the overall concentration of phenolic compounds in the berry extracts, even after enzymatic treatment was observed. However, in a study of E. Radziejewska-Kubzdela et al. (2020), no such relationship was found. On the contrary, they observed a decrease in the total amount of polyphenols in berry extracts because of pre-enzymatic treatment. They suggested that the effect might be due to the activity of a by-product esterase present in the enzyme used, or to partial degradation of phenolic compounds during processing. In addition, residual polyphenol oxidases present in grape pomace may also contribute to the reduction of phenolic and antioxidant content. Researchers demonstrated that the use of enzymatic or thermal pretreatment improved the

extractability of 4-hydroxybenzoate compared to sonication or untreated samples. The specific mechanisms underlying this improvement may vary and include factors such as increased enzymatic activity, cell wall disruption, or increased solubility of 4-hydroxybenzoate during enzymatic pretreatment processes. A. Chaovanalikit and R.E. Wrolstad (2008) suggest that enzyme preparations may promote the activation of endoglycosidases, which hydrolyse glycosidic bonds connecting phenolic compounds to other molecules, in particular sugars. As a result, this causes the anthocyanins to be released more and become more extractable. In addition, according to E. Radziejewska-Kubzdela et al. (2020), the activity of pectolytic enzymes can affect the activity of polyphenol oxidase, which oxidizes several polyphenols.

During the study, it was shown that pre-treatment of berries with enzyme preparations of pectinase and cellulose leads to an increase in the concentration of sugars in their extracts. One of the main mechanisms for increasing the concentration of sugars is associated with the destruction of cell wall polysaccharides. Pre-treatment with pectolytic enzymes promotes the breakdown of these polysaccharides into mono and disaccharides, mainly glucose and fructose. According to K.R. Corbin et al. (2015), this process also increases the availability of sugars for extraction and leads to their increased concentration in the extract. Researchers claim that pectolytic enzymes can activate glycosidases, which hydrolyse the glycosidic bonds connecting carbohydrates to glycoproteins, which also contributes to the release of monosaccharides and their increased concentration in the extract. In addition, they suggested that pretreatment with enzyme preparations may also promote the activation of endogenous amylases, which break down oligosaccharides into mono and disaccharides. In a study by the researchers, the decrease in soluble and insoluble dietary fibre and the increase in free monosaccharides following enzymatic hydrolysis of fruit peels is consistent with the breakdown of complex polysaccharides into simpler sugars. This study demonstrated that after pre-treatment of berries with enzyme preparations, the concentration of sugars in the extracts increases. Thus, the results obtained are mainly consistent with those obtained from the literature.

The obtained values of concentrations of heavy metals in the juices of wild berries correlate with the results obtained by L.F. Steingräber et al. (2021). The researchers' data indicate that drugs used in the enzymatic processing process can potentially activate the processes of mobilization of heavy metals from berry tissues. If the berries have been contaminated with heavy metals from the environment, enzymes can help release those metals from the cells, making them more available for extraction in the juice. However, in this study, no significant increase in the content of heavy metals was observed after enzymatic treatment, which may be due to the initially low content of these components in the analysed berries.

Conclusions

1. This study examined the impact of treating wild berry pulp with enzyme preparations on the concentration of biologically active compounds in their juices. The optimal juice extraction was attained after a 120-minute fermentation period for barberry and dogwood berries. For elderberry and raspberry, the optimal periods were 75 and 90 min, respectively. A processing temperature of 45 °C turned out to be the most suitable for most berries, except for barberry, which showed better results at a temperature of 60 °C.

2. The use of both individual enzyme preparations and their complexes had a positive effect on the juice yield for all tested berries. For dogwood and hawthorn, the most effective was the combination of "Pectinex BE XXL" and "Fructosym P", and for elderberry, barberry and raspberry – "Amylase AG 300L" and "Sellolyuks-A". The yield of vitamin C increased for dogwood berries – 1.18 times, for elderberries – 1.23 times, for hawthorn – 1.22 times, for barberry – 1.38 times, and raspberries – 1.2 times. In most cases, the use of multienzyme complexes demonstrated the greatest positive effect.
3. The use of multienzyme complexes additionally increased the vitamin C content in the juices of these berries by an average of 1.35-1.52 times.
4. Juices after treatment with enzymes showed a significant increase in sugar content; the greatest effect was achieved when using multienzyme complexes. The complex "Pectinex BE XXL" and "Fructosym P" increased the concentration of sucrose in the samples by an average of 1.58 times.
5. It was found that enzyme preparations generally have a positive effect on the content of biologically active substances in the juices of wild berries. Dogwood berry juices showed the highest amount of phenolic compounds among the tested samples. After treatment with enzyme preparations, they contained a predominant amount of chlorogenic acid (257 mg/100 g) and quercetin (65 mg/100 g). The quercetin content in pre-treated dogwood and elderberry juices was higher by 15% and 17%, respectively, compared to untreated samples. A significant increase in gallic acid content after enzymatic treatment was observed in all samples where it was detected. Hawthorn juices showed the most significant increase in the content of this component (16%).
6. No significant influence of enzymatic pretreatment on the concentration of heavy metals in berries extracts was found.
7. The results of the study indicate the promise of enzymatic maceration of wild berries for their further use in the food industry. Further research is needed to establish in more detail the mechanisms of such effects for different classes of compounds.

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Bioactive compounds and potential applications of *Aloe vera* (L.) in the food industry

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Abstract

Introduction. The aim of the review is to characterize the bioactive compounds present in *Aloe vera* and to consider the possibilities of its application in the food industry.

Materials and methods. Data collection involved searching multiple databases, including Google Scholar, ScienceDirect, PubMed, SpringerLink, and Wiley Online Library. The search queries encompassed a wide range of terms, such as bioactive compound; *Aloe vera*; potential application of *Aloe vera* in the food industry; anti-inflammatory, antioxidant, anti-bacterial, anti-fungal, antiviral, and antiseptic properties of *Aloe vera*'s bioactive compounds.

Results and discussion. The discussion outlines the chemical composition, bioactive compounds of *Aloe vera* plant, and potential applications of *Aloe vera* in the food industry. *Aloe vera* is rich in various components, including polysaccharides (55%), sugars (17%), minerals (16%), proteins (7%), lipids (4%), and phenolic compounds (1%). This plant contains numerous bioactive compounds such as flavonoids, phenolic acids, tannins, mono- and polysaccharides (mannose-6-phosphate, acemannan and glucomannan), polyphenols, coumarin, proanthocyanidin, alkaloids, anthraquinone derivatives, aloe-emodin, aloin, aloesin, saponin, chromones, β- carotene, vitamin C, vitamin E, enzyme bradykinase, and steroids, making it a valuable pharmaceutical and cosmetic raw material. Aloe vera demonstrates diverse health benefits having emollient, purgative, anti-inflammatory, antioxidant, antimicrobial, anti-helmenthic, antifungal, and antiseptic properties. Depending on the purpose of using, leaves of *Aloe vera* could be processed by whole-leaf processing, mechanically filleted or manual filleted processing to obtain *Aloe vera* gel. After that, the gel could be used for production of juice, concentrate and powder products. The products of *Aloe vera* are natural functional ingredients or additives for the fortification of food products from vegetable sources to improve food quality, prolong the shelf life of vegetables and fruits, improve acceptability of food, enhance the growth of probiotics cultures, and could be also used in the pharmaceutical and cosmetic industries. The main areas of *Aloe vera* applications in the food industry include edible coatings production, fruits preservation, and beverages, dairy, confectionary, and sport nutrition products processing.

Conclusion. The products from *Aloe vera* plant and its bioactive compounds can act as a promising human health, prolong the shelf life of vegetable and fruits, and enhance the growth of probiotics cultures. Safety should be considered when using *Aloe vera* products.

Introduction

Plants produce a wide array of chemical compounds to support their growth and development. These compounds can be broadly categorized into primary and secondary metabolites. Primary metabolites are directly involved in essential processes like photosynthesis, translocation, and respiration. On the other hand, secondary metabolites are smaller organic molecules derived from primary metabolites and are typically around 3000 daltons in molecular weight (Twaij and Hasan, 2022). Secondary metabolites can be classified into four major classes: terpenoids, phenolic compounds, alkaloids, and sulphur-containing compounds (Guerriero et al., 2018). These secondary metabolites play a crucial role in plants and have various beneficial properties for humans. They are known for their antioxidant, anti-inflammatory, antimicrobial, anticoagulant, antidiabetic and lipid-lowering properties (Teoh, 2015). Specific compounds found in plants, such as flavonoids including chalcones, flavones, flavanols, flavanones, anthocyanins, and isoflavones; phenylpropanoids, which are involved in the production of essential aromatic amino acids such as phenylalanine and tyrosine; terpenes with antitubercular and anticancer activities; and N-containing compounds (caffeine, nicotine, cocaine and morphine), could be used in the anxiolytic, analgesic, and hallucinogenic treatments (Twaij and Hasan, 2022). Bioactive compounds refer to secondary metabolites extracted from plants. It has been found that they have pharmacological or toxicological effects on living organisms. They also found a widespread application in the food and pharmaceutical, as well as in cosmetic industries (Pai et al., 2022). The bioactive compounds of plants have many important benefits for current and future use in medicine (Wawrosch and Zotchev, 2021).

Bioactive constituents presented in vegetables, fruits, and whole grains are essential for the human body (Pai et al., 2022). These bioactive compounds include carotenoids, flavonoids, carnitine, choline, coenzyme Q, dithiolethiones, phytosterols, phytoestrogens, glucosinolates, polyphenols, vitamins, and minerals (Hamzalıoğlu Gökmen, 2016). Currently, they are intensively studied to evaluate their physiological, behavioral, and immunological properties for potential practical applications (Huang and Chen, 2022).

Aloe vera is a perennial green herb with bright yellow tubular flowers that is extensively distributed in hot and dry areas of North Africa, the Middle East of Asia, the Southern Mediterranean, and the Canary Islands. The colorless mucilaginous gel from *Aloe vera* leaves has been extensively used for pharmacological and cosmetic applications (Sánchez et al., 2020). *Aloe vera* contains polysaccharides (55%), sugars (17%), minerals (16%), proteins (7%), lipids (4%), phenolics (1%) (Kumar et al., 2019) and numerous bioactive compounds that have benefits for human health (Gangadharan et al., 2019). *Aloe vera* is one of the oldest and most traditional medicinal plants with biological activity that is why it is applied for medicinal purposes, food, and is used in food processing (Martínez-Burgos et al., 2022). *Aloe vera'* leaves contain numerous vitamins, minerals, natural sugars, enzymes, amino acids, and as well rich in various bioactive compounds that exhibit a wide spectrum of beneficial properties including emollient, purgative, anti-inflammatory, antioxidant, antimicrobial, anthelmintic, antifungal, aphrodisiac, and antiseptic actions (Hong et al., 2018; Lanka, 2018; Sánchez et al., 2020). In addition, *Aloe vera'* gel and extracts have been scientifically confirmed to be effectiveness in treating gastrointestinal disorders, lowering low density lipoprotein, increasing high density lipoprotein, and decreasing blood glucose level (Martínez-Burgos et al., 2022). Application of plant additives, which have pharmacological properties, in the manufacturing of traditional products to increase their health value, is a new trend in food production (Stabnikova et al., 2021). The present review explores new information related to *Aloe vera's* the bioactive compounds and potential applications of *Aloe*

vera in the food industry. The new information was searched from the publications (original papers) published in English in peer-reviewed scientific journals of the Web of Science, Scopus, Pubmed, Google Scholar database. The major objective of this review is to summarize the most research on the bioactive compounds present in *Aloe vera* and its potential application in the food industry.

Materials and methods

Data collection involved searching multiple databases, including Google Scholar, ScienceDirect, PubMed, SpringerLink, and Wiley Online Library. The search queries encompassed a wide range of terms, such as bioactive compound; *Aloe vera*; potential applications of *Aloe vera* and its bioactive compounds in the food industry; anti-inflammatory, antioxidant, anti-bacterial, anti-fungal, antiviral, and antiseptic properties. The study was not subject to any restrictions regarding research methodology of the study, sample size, or outcome measurement.

Results and discussion

General characteristic of *Aloe vera*

Worldwide, *Aloe vera* is a popular herbal medicine that has antibacterial and antioxidant properties, maintains cholesterol and blood sugar levels, and body weight. Therefore, it has a wide field of applications that include pharmaceuticals, cosmetics, and food.

According to the taxonomic classification, *Aloe vera* is representative of Kingdom, *Plantae*; Class, *Magnoliophyta*; Order, *Asparagales*; Family, *Asphodelaceae/Xanthorrhoeaceae*; Genus, *Aloe* L.; Species, *Aloe vera* (L.) Burm. f.

Aloe plants contain important chemical constituents in their swollen and succulent leaves because of their surviving ability in hot and dry conditions (Yadeta, 2022). *Aloe vera* is an arborescent, perennial, xerophytic, succulent, thick and short-stemmed plant; is green in color and about 12 – 19 inches (30 –50 cm) in length, and is commonly grown in arid regions of India, Africa, Asia, Europe and the Americas (Mitra et al., 2023).

The genus *Aloe* includes approximately 600 species. The natural components isolated from various species of the genus *Aloe*, including anthraquinones and their glycosides, anthrols, chromones and their glycosides, pyrones, steroids, triterpenes, vitamins, coumarin, flavonoids, lignin, proteins, alkaloids, glycoproteins, and naphthalene (Rehman et al., 2017). The leaf of *Aloe vera* has 3 layers: (1) the first layer is called the gel with the characteristics of viscous, colorless, and clear, which contains water (99%), amino acids, glucomannans, vitamins, and lipids and sterols; (2) the second central layer contains holding latex with the characteristics of bitter, yellow and red aloin; glycosides and anthraquinones; and (3) the outermost thick layer has a protective function that synthesize carbohydrates and proteins (Mitra et al., 2023). The *Aloe vera* fresh leaf contains fibers, proteins, organic acids, minerals, monosaccharides, and polysaccharides (Liu et al., 2019; Zhang et al., 2018). Generally, *Aloe* leaf contains more than 200 nutritional substances, including vitamins, minerals, amino acids, and active enzymes (Yadeta, 2022). Image of *Aloe vera* leaves is shown in Figure 1.

Aloe flesh has jelly-like consistency and contains water (96%) and dry matter (4%), which contains protein (6.86%), fat (2.91%), dietary fibre (73.35%), ascorbic acid (0.004%), and ash (16.88%) (Hęś et al., 2019). It could serve as an ingredient that is used in some food

and beverage products, functional and nutraceutical foods, edible coatings/films due to benefits of its bioactive phytochemicals. Some *Aloe* species are used as cooked vegetables and raw eating; as ingredients in food and beverage products such as soft drink: Aloe sports drink with electrolyte, Aloe vera lemon juice, diet drink with soluble fiber, health drink, hangover drink with B vitamin, amino acids and acetaminophen, healthy vegetable juice mix, tropical fruit juice with *Aloe vera*, and Aloe vera yogurts (Yadeta, 2022).

Figure 1. *Aloe vera* leaves

Chemical composition of *Aloe vera*

Chemical composition of *Aloe vera* depends on the geographical location, type of soil, harvest time, conditions of cultivation, and variety (Hęś et al., 2019; Quispe et al., 2018). Approximate chemical composition of *Aloe vera* gel is shown in Table 1.
Besides compounds shown in Table 2*, Aloe vera* contains 20 of the 22 human required amino acids and 7 of the 8 essential amino acids, vitamin E, vitamin B12, provitamin A – β-carotene, folic acid and choline. It contains a wide spectrum of enzymes including aliiase, amylase, alkaline phosphatase, oxidase, catalase, bradykinase, carboxypeptidase, cellulase, lipase, peroxidase and cylooxygenase, and carboxypeptidase. Carbohydrates of *Aloe vera* include monosaccharides (glucose and fructose) and polysaccharides (glucomannans/polymannose). Hormones auxins and gibberellins present in *Aloe vera* have anti-inflammatory action and help in wound healing. It also contain steroids (cholesterol, campesterol, β-sisosterol, and lupeol), γ-linolenic and arachidonic fatty acids, lignin, saponin, terpenes, and phenolic compounds (Arshad et al., 2015; Lanka, 2018; Mitra et al., 2023; Narsih and Agato. 2016; Rehman et al., 2017; Sánchez et al., 2020; Surjushe et al., 2008).

Table 1

Chemical composition of *Aloe vera* gel

Compounds	Values	References	Compounds	Values	References
Macronutrients, mg/100 g			**Phenolic compounds, mg/100 g**		
Moisture	96 300	Elbandy et al., 2014	Pyrogallol	18.518	Elbandy et al., 2014
Protein	44	Añibarro-Ortega et al., 2019	Gallic acid	0.339	
Ash	150		Catechin	0.457	
Fat	17		Chlorogenic acid	0.160	
Carbohydrates	630		Catechol	1.105	
Dietary fibre	840		Caffeic acid	0.153	
Crude fibre	120		Vanillic acid	0.069	
Organic acids	111		Caffeine	0.117	
Minerals, , mg/100 g			Ferulic acid	1.509	
Potassium,	127.46	Elbandy et al., 2014	p-Coumaric acid	0.532	
Calcium	71.46		Benzoic acid	3.322	
Sodium	49.65		Ellagic acid	2.535	
Magnesium	20.74		Salicylic acid	2.204	
Zinc	0.114		Cinnamic acid	0.658	
Copper	0.034		Chrysin	0.195	
Flavonoids, mg/100 g					
Hesperidin	2.271	Elbandy et al., 2014	Narengenin	37.521	Elbandy et al., 2014
Rosmarinic acid	1.382		esperetin	1.014	
Rutin	1.138		Kaempferol	0.205	
Quercitrin	0.572		Apigenin	0.322	

Bioactive compounds present in *Aloe* species

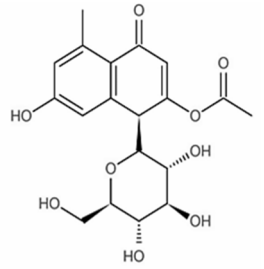
Bioactive compounds of *Aloe vera* have an anti-inflammatory effect. The biological activities of compounds from *Aloe vera* such as aloe-emodin, aloin, aloesin, emodin, acemannan have been studied (Sánchez et al., 2020). Rehman et al. (2017) showed that C-glucosyl chromones (named aloeverasides A and B) isolated from the resin of *Aloe* species is a bioactive compound. It has a glucose moiety at the C-8 position. The C-glucosyl chromones was also detected in many *Aloe* species such as *Aloe angelica*, *Aloe arenicola*, *Aloe comptonii*, *Aloe dabenorisana*, *Aloe distans*, *Aloe erinacea*, *Aloe melanacantha*, *Aloe meyeri*, *Aloe mitriformis*, *Aloe pearsonii*, *Aloe peglerae*, and *Aloe yavellana* (Rehman et al., 2017).

Aloe vera contains antioxidants, which may increase the shelf-life and nutritional value of food. Antioxidant activity has been demonstrated in *Aloe vera* leaf's skin, flowers, and gel (Hęś et al., 2019).

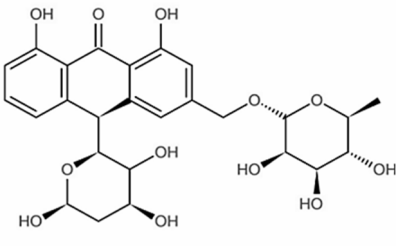
Table 2 presents the chemical structure of some bioactive compounds present in *Aloe vera*.

Table 2

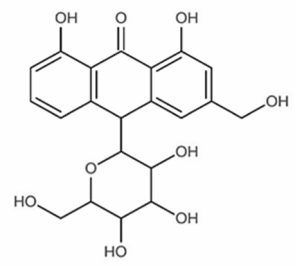
Chemical structure of some bioactive compounds present in *Aloe vera*



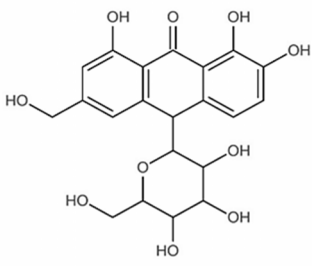
Aloisin



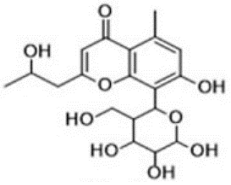
Aloinoside



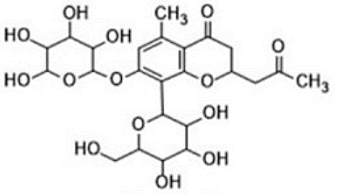
Aloin



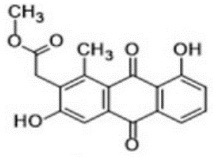
Hydroxyaloin



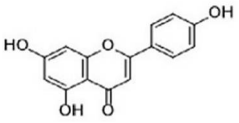
Aloesinol



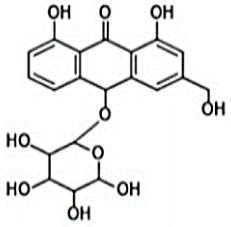
Aloeresin B



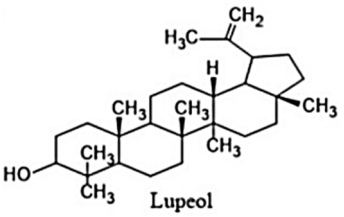
Aloesaponarin



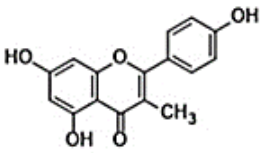
Apigenin



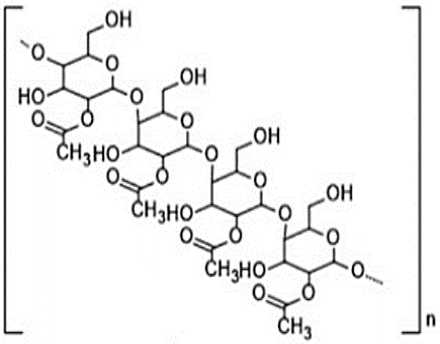
Barbaloin



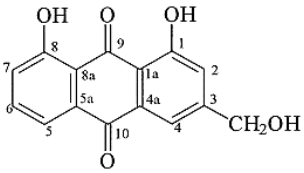
Lupeol



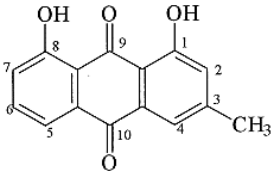
Naringenin



Acemannan



Aloe-emodin



Chrysophanol

Properties of bioactive compounds from *Aloe vera*

Function properties of several bioactive compounds present in *Aloe vera* are shown in Table 3.

Table 3

Functions of several bioactive compounds present in *Aloe vera*

Bioactive compound	Function/Properties	Reference
Polysaccharides	Anti-inflammatory	Cock I. E., 2015 Lawrence et al., 2009 Massoud et al., 2022
Acemannan (Acetylated mannan)	Immune-stimulating	Sierra-Garcíaa et al., 2014
Mannose-6-phosphate Glucomannans	Anti-inflammatory	Lanka, 2018 Mitra et al., 2023
Polyphenols	Antioxidant, anti-inflammatory	Babu and Noor, 2020 Olubunmi and Anthony, 2011
Flavonoids	Antioxidant activity by radical scavenging and prevention of oxidative cell damage	Olubunmi and Anthony, 2011 Semerel et al., 2022

Proanthocyanidins (polyphenolic bioflavonoids)	Antioxidant activity by eliminating hydroxyl radicals	Olubunmi and Anthony, 2011
Phenolic acids	Antioxidant property	Semerel et al., 2022
Tannins	Antioxidant property	Olubunmi and Anthony, 2011
Alkaloids	Antiseptic and bactericidal activities	
Anthraquinones (aloin, anthranol, barbaloin, isobarbaloin, aloetic acid, aloe-emodin and ester of resistannol, cinnamic acid, chrysophannic acid and emodin)	Antioxidant, antimicrobial, antifungal, antiviral, and laxative properties	Lawrence et al., 2009 Mitra et al., 2023 Rehman et al., 2017 Sadiq et al., 2022 Syed et al., 2022 Zeng et al., 2020
Aloe-emodin	Anticancer, antivirus, anti-inflammatory, antibacterial	Semerel et al., 2022 Zeng et al., 2020
Aloin	Anti-inflammatory	
Aloesin	Anticancer, anti-inflammatory, immunomodulatory	Semerel et al., 2022 Zeng et al., 2020
Saponin	Antimicrobial and anti-inflammatory	Lawrence et al., 2009 Olubunmi and Anthony, 2011
Chromones	Antioxidant	Semerel et al., 2022
Vitamins A (beta-carotene), C and E Vitamins B1, B2, B6, B12, folic acid, and choline	Antioxidant	Lanka, 2018 Grune et al., 2010 Higashi-Okai et al., 2006 Massoud et al., 2022
Enzymes: Aliiase, alkaline phosphatase, amylase, oxidase, carboxypeptidase, catalase, cellulase, lipase, cylooxygenase, and peroxidase	To break down sugars, proteins and fats	Lanka, 2018 Mitra et al., 2023 Arshad et al., 2015 Massoud et al., 2022
Enzyme: Bradykinase	Helps to reduce excessive inflammation	Lanka, 2018
Minerals: Calcium, chromium, copper, selenium, magnesium, manganese, potassium, sodium, and zinc	Essential minerals of various enzyme systems and antioxidant action	Mitra et al., 2023 Arshad et al., 2015 Massoud et al., 2022
Organic acids: Sorbate, salicylic acid, uric acid	Antiseptic	Lanka, 2018 Mitra et al., 2023
Hormones: Auxins and gibberellins	Wound healing; anti-inflammatory	Lanka, 2018 Mitra et al., 2023
Steroids (Campesterol, β-sisosterol, lupeol, and fatty acids (γ-linolenic acid andarachidonic acid)	Anti-inflammatory and antiseptic	Mitra et al., 2023

Aloe vera is a medicinal plant. Several bioactive constituents from *Aloe vera* have been identified and used in therapeutic applications for disease prevention and treatment through the modification of biological and genetic activities. *Aloe vera* displays function as an antioxidant through free radical- and superoxide radical-scavenging activities; anti-inflammatory activities *via* inhibition of prostaglandin E2 production from arachidonic acid; and also inhibition of various transcription factors and the activities of enzymes including lypoxygenase and cyclooxygenase. *Aloe vera* exhibits antimicrobial effects due to the ability to destroy bacterial cell walls (Arshad et al., 2015). Aloe vera' extract possesses anti-inflammatory and vasodilatory properties *via* cyclooxygenase inhibition by salicylic acid (a COX inhibitor). Emodin and emolin, anthraquinone derivatives, demonstrate anti-inflammatory properties because they are competitive inhibitors of thromboxane synthase (Zeng et al., 2020).

Anti-inflammatory properties of *Aloe vera*

Wound healing in the human body is going through the four stages, including hemostasis, inflammation, proliferation, and remodeling (Guo et al., 2010; Landén et al., 2016). The healing process of wounds or burns can be accelerated through medical intervention, including the use of *Aloe vera* (Arbab et al., 2021). The anti-inflammatory activity of extracts of *Aloe vera* adventitious root displayed through the modification of elementary and secondary metabolites *via* salicylic acid elicitation (Lanka, 2018). *Aloe vera* gel also helps to enhance the amount of collagen in wounds and collagen cross-linking leads to promote wound healing (Hekmatpou et al., 2019). Due to the action of glucomannan, a polysaccharide rich in mannose, together with gibberellin, which is a growth hormone, fibroblasts are stimulated, promoting proliferation and wound healing. (Massoudi et al., 2022). Aloesin enhances the wound healing process by reducing wound inflammation, stimulating fibroblast proliferation, collagen synthesis and activating of the Smad and MAPK signaling proteins in the process such as cell migration, angiogenesis, and tissue development (Wahedi et al., 2017).

The anti-ulcer effect of the bioactive compounds of *Aloe vera* in anti-inflammatory drugs without non-steroids induced peptic ulcers in rats was proven. The bioactive compounds inhibiting the cyclooxygenase pathway led to reduced production of prostaglandin E2 from arachidonic acid. The anti-inflammatory activity of extracts of *Aloe vera* adventitious root displayed through the modification of elementary and secondary metabolites *via* salicylic acid elicitation (Lanka, 2018)

Anti-bacterial, anti-fungal, antiviral, and antiseptic properties of *Aloe vera*

Antimicrobial resistance is one of the major public health problems that lead to reduction of the synthetic drugs effectiveness (Leitgeb et al., 2021). Meanwhile, the growth of bacteria, fungi, and viruses could be inhibited by action of some bioactive compounds. Antimicrobial action of bioactive compounds from medicinal plants have been known for a long time. Applications of such substances, having antioxidant and anti-inflammatory activities, for the development of new therapeutic drugs to suppress microbial infections could reduce oxidative damage and inhibit inflammatory pathways. Bioactive compounds can directly scavenge free radicals, protect against oxidative damage, prevent the generation of pro-inflammatory cytokines, and reduce the activity of inflammatory enzymes (Dar et al., 2023).

Aloe species have been used in traditional medicine for treating skin and digestive problems, wound healing, anti-inflammatory, and antimicrobial properties (Leitgeb et al., 2021). Bioactive compound of *Aloe vera* inhibited the growth of *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Salmonella typhi*, *Actinobacillus*

actinomycetemcomitans, and *Porphyromonas gingivalis* (Arshad et al., 2015). Anthraquinone derivatives emodin, Aloe-emodin, aloin, and chrysophanic acid from *Aloe vera* have both antimicrobial and anti-inflammatory activities. Anthraquinones perform the antimicrobial activity by altering solute transport through membranes, cell walls, and fatty acid elongation (Zeng et al., 2020). Several antiseptic agents present in *Aloe vera* such as triterpenoid lupeol, salicylic acid, urea nitrogen, cinnamic acid, phenols, and sulfur display actions against fungi, bacteria, and viruses (Lanka, 2018).

Each ingredient of the *Aloe* gel has its own mechanism of action, acting synergistically or individually (Lawrence et al., 2009). The antimicrobial and inhibitory activities of *Aloe vera* gel against oral pathogenic bacteria have been proven at the concentrations of 100% and 50%. At lower concentration, there was no antibacterial effect (Jain et al., 2016). The ethanol extracts of *Aloe vera* from leaves and roots have been used against skin infections alongside conventional antibiotics (Arbab et al., 2021). The antiviral activity of Aloe extracts was carried out indirectly by stimulating the immune system and directly by anthraquinones. For example, the anthraquinone aloin inactivates various enveloped viruses including *Herpes simplex*, *Varicella zoster*, and *Influenza* (Lanka, 2018).

Potentially bioactive compounds include salicylates, magnesium lactate, acemannan, lupeol, campesterol, β-sitosterol, aloin A, and anthraquinones. The *Aloe vera* is an antibacterial agent, effectively kills or greatly reduces or eliminates the growth of *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Streptococcus pyogenes*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Propionibacterium acne*, *Helicobacter pylori*, *Bacillus subtilis*, *Bacillus cereus*, and *Salmonella typhi* (Lawrence et al., 2009). The *Aloe vera* based hydrogels demonstrated antibacterial effects for Gram-positive bacteria *Staphylococcus aureus* and Gram-negative bacteria *Pseudomonas aeruginosa* (Chelu et al., 2023).

Antioxidant properties of *Aloe vera*

Oxidative stress has been identified as a factor contributing to various diseases, such as atherosclerosis, arthritis, cardiovascular disorders, Alzheimer's disease, and cancer. Therefore, antioxidants play a crucial role, and there is a growing inclination to substitute synthetic antioxidants with natural alternatives (Lourenço et al., 2019). The antioxidants are used as an adjunct to initial intervention aimed at inhibiting systemic effects of oxidant species. The antioxidant effect of *Aloe vera* depends on the activity of glutathione peroxidase, superoxide dismutase enzymes, and phenolic antioxidants (Zeng et al., 2020). Some *Aloe* species have medicinal characteristics and high economic values, such as *Aloe djiboutiensis*, originating from Djibouti, East Africa and used as a medicinal plant in Djibouti. *Aloe djiboutiensis* contained some bioactive compounds such as aloin A, aloin B, and isoaloeresin D (Hinokidani et al., 2022). *Aloe* extracts have antioxidant effects. Many constituents, such as vitamins, amino acids, carbohydrates, and phenolic compounds are active in controlling or neutralizing reactive oxygen species. Free radical production is balanced through the antioxidative defense system of human body, and any alteration occurring between the generation of reactive oxygen species and its neutralization by antioxidant defenses causes oxidative stress, which plays a role in the pathogenesis of diseases (Arshad et al., 2015).

Phenolic compounds as the most important secondary metabolites in many medicinal plants have antioxidant activities allowing them to act as reducing agents, hydrogen donors, and radical scavengers (Leitgeb et al., 2021). APS-1, a polysaccharide from *Aloe vera,* has the antioxidant function and the protection of heart tissue. APS-1 contains a high content of rhamnose and arabinose in polysaccharide fraction. Aloe emodin displays anti-cancer potential against hepatoma cells. Aloin displays anti-cancer activity by inhibiting the tumor angiogenesis

by inactivating the signal transduction and activators of transcription 3 pathway. Aloe polysaccharides were proven to have the effects for antitumor activity against sarcoma 180 cells (Babu and Noor, 2020).

Methods for screening, extracting, identifying, and isolation of bioactive compounds from *Aloe vera*

Collecting bioactive chemicals from medicinal plants is an initial step in the discovery and development of new drugs. Many methods for screening, extracting, identifying, and isolation of bioactive metabolites from medicinal plants have been performed. Table 4 shows the methods applied in therapeutic applications (Dar et al., 2023).

New methods for isolation of bioactive substances from *Aloe vera* are proposed. Thus, ultrasound-assisted extraction (UAE) is known as method used for the extraction of thermo-labile compounds (Ivanov et al., 2021). The advantages of UAE are decreasing extraction time and temperature, low consumption of energy, and increasing the rate of extraction. Ultrasonic-assisted extraction was proposed to be used to obtain of aloin and aloe-emodin compounds from *Aloe vera* (Gansukh et al., 2018; Kamble et al., 2021).

Potential applications of *Aloe vera* in the food industry

The global *Aloe vera* hydrogel market is expected to reach USD 712.3 million by 2032, at a compound annual growth rate of 7.8% from 2022 to 2032 (Chelu et al., 2023). *Aloe vera* has antibacterial, antioxidant, anti-inflammatory and other functional properties. So, it has been popular for applications in various fields including food preservation, sustainable packaging, cosmetics and pharmaceutical industries. *Aloe vera* has functional bioactive compounds and has been used in health drinks and other beverages in the form of powder. As a natural food preservative, *Aloe vera* can protect food products from oxidative and microbial deteriorations, extend the shelf life of food products, improve their texture, and enhance nutritional/health-promoting values (Kumar et al., 2022; Yadeta, 2022). For example, *Aloe arborescens* and *Aloe vera* are frequently usedd in the production of dairy products like yogurt and ice cream, acting as a food preservative, while *Aloe ferox* finds application in the processing of fruit juices and confectionery products (Yadeta, 2022).

Aloe vera is a popular plant having many functional compounds that are beneficial for human health. The U.S. Food and Drug Administration approved *Aloe vera* as a food flavoring agent in accordance with good manufacturing practices. The study on the processing of therapeutic and high nutritional mango nectar by supplementation of mango pulp with *Aloe vera* gel showed that the supplementation with 20–25% *Aloe vera* gel allowed producing high quality functional mango nectar containing natural preservative ingredients. This resulted in a fall in the total bacterial counts: decreased from $\log_{10}$ 3.9 ± 0.06 CFU/ml to $\log_{10}$ 2.05 CFU/ml (Elbandy et al., 2014).

The main areas of *Aloe vera* applications in the food industry include edible coatings production, fruits preservation, and beverages, dairy, confectionary, and sport nutrition products processing (Figure 2).

Table 4

Identification of bioactive compounds in *Aloe vera*

Step	Identification of bioactive compounds in *Aloe vera*	Reference
Initial screening of phytochemicals from *Aloe vera*	This is an initial step for the identifying bioactive compounds present in medicinal plants based on certain types of chemicals, including alkaloids, flavonoids, terpenoids, phenolics, and glycosides. Common phytochemical screening techniques: color reactions, thin-layer chromatography (TLC), and spot tests	Dar et al., 2023
Collection of *Aloe vera* gel	Leaves of *Aloe vera* were cut, washed with distilled water, surfaces were sterilized by 70% ethyl alcohol followed by 0.1% $HgCl_2$, peeled, and gel was collected	Lawrence et al., 2009
Extract preparation	Extraction of bioactive substances is performed by ethanol or methanol from *Aloe vera* gel. The *Aloe vera* powder was obtained from the fresh leaf gel by drying in the oven at 80°C for 48 h and then powdered. The obtained powder was soaked in 200 ml of the solvents (ethanol or methanol) for 24 h to collect an extract. The extract was filtered, evaporated, and the dried extract was used in powder form	Lawrence et al., 2009
Extraction of bioactive compounds	Techniques: Maceration, percolation, supercritical fluid extraction (SFE), ultrasonic extraction, and Soxhlet extraction	Dar et al., 2023
Separation, purification, and analysis of bioactive compound	Based on bioactive compound characteristics: for the separation and quantification of substances, Gas chromatography (GC) and High-performance liquid chromatography (HPLC) techniques are used. For the separation and purification of specific compounds, Column chromatography, flash chromatography, and thin-layer chromatography (TLC) are also used	Dar et al., 2023
Antibacterial activity of *Aloe vera* gel or extract	Bioactive compound destroys cell membranes and inhibits enzymes. Agar Well Diffusion Technique: About 0.1ml of Aloe vera gel extracts was poured into each well (5 mm in diameter, contained sterile nutrient agar) swabbed with an overnight bacterial broth culture, and then incubated at 37°C ± 0.2°C. Antibacterial activity in terms of zones of inhibition (mm) was recorded after 24 h of incubation	Dar et al., 2023 Lawrence et al., 2009
Antiviral activity	Bioactive compounds can be antiviral agents by inhibiting the replication of toxic virus	Dar et al., 2023
Bioassays and bioactivity Screening	Bioassays: the biological activities evaluation of isolated compounds, such as antimicrobial, antioxidant, anti-inflammatory, anticancer, and other pharmacological properties. Bioassays techniques: disk diffusion method, broth microdilution method, antioxidant assays, enzyme inhibition assays, and cell-based assays	Dar et al., 2023

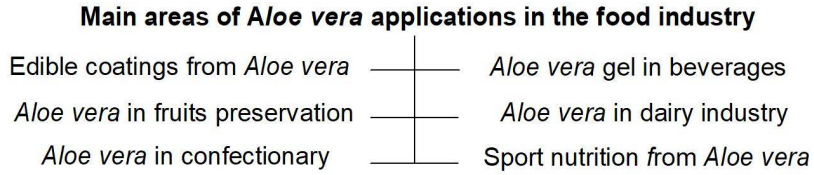


Figure 2. Main areas of *Aloe vera* applications in the food industry

The processing of *Aloe vera* leaves to obtain *Aloe vera* gel could include whole-leaf processing, mechanical filleting, or manual filleting, depending on the intended use (Hęś et al., 2019). *Aloe vera* gel is a natural hydrocolloid consisting mainly of polysaccharides. The approximal composition of *Aloe vera* gel consists water (96 %), and dry matter (4 %), which contains organic acids (22.8 %), dietary fiber (18.8 %), polysaccharides (8.8 %), protein (4.7%), lipids (2.7 %), and ash (16.0 %) (w/w). *Aloe vera*'s bioactive compounds are aloin, aloe emodin, anthraquinones, and acemannan. The gel has antioxidant and antimicrobial effects and can increase the shelf life of fruits and vegetables by acting as a semipermeable barrier for gases and water vapor, decreasing the respiration and ripening processes of the fruit, thus maintaining weight, firmness and content of valuable compounds (Nicolau-Lapeña et al., 2021).

Figure 3 presents products from *Aloe vera* plant used in the food industry, including gel, juice, concentrate, and powder (Ahlawat and Khatka, 2011).

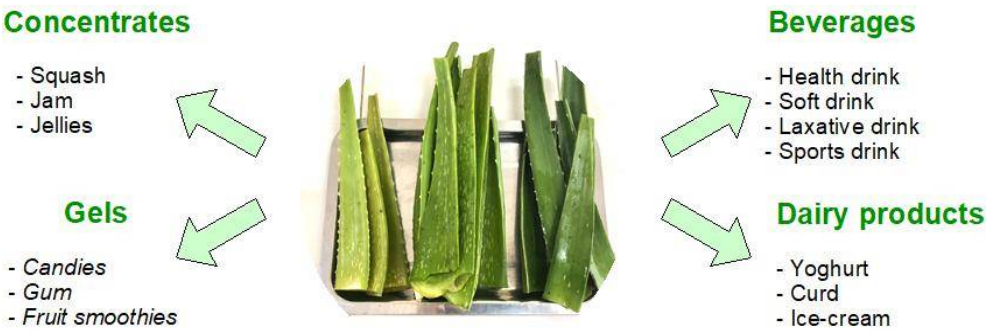


Figure 3. Food products from *Aloe vera*

Aloe vera gel could be usedf as a natural functional ingredient or additive to fortify food products of plant origin. This application aims to enhance food quality, extend the shell life of vegetables and fruits, reduce microbial pathogens, preserve the antioxidant activity of bioactive compounds, improve product acceptability and promote the growth of probiotic cultures (Hęś et al., 2019). Nagpal et al. (2012) showed that the addition of *Aloe vera* juice at a concentration of 5% (v/v) into the growth media of Lactobacilli promoted the growth of *Lactobacillus acidophilus*, *Lactobacillus plantarum*, and *Lactobacillus casei*, as was evident from the fall in pH and increased acidity, as well as from the diminishing of generation time. At concentrations of 15 to 25% (v/v), the growth was not affected compared to control. However, at concentrations higher than 25% (v/v), the growth was inhibited (Nagpal et al., 2012).

Edible coatings with *Aloe vera*

The edible coating is an environmentally friendly technology, often applied to fresh-cut fruit products. Among them, *Aloe vera* gel is potentially applicable because of containing several functional components. The main advantage of *Aloe vera* coating is that additives can be incorporated into the polymer matrix to enhance its properties to improve the safety, nutritional, and sensory attributes of fresh fruits (Suriati, 2022). Utilizing edible and biosafe coatings derived from the *Aloe vera* plant in fruit preservation aims to establish a barrier that restricts the exchange of moisture and oxygen, as well as the movement of solutes in the products (Yadeta, 2022). In a study conducted by Mahajan and colleagues (2021), an edible film made from *Aloe vera* (15%), glycerol (14%), and carrageenan (15%), enhanced the microbial and lipid oxidative stability of frozen dairy products. This edible film exhibited antibacterial properties, stabilized lipid oxidation in frozen dairy products, and showed potential commercial application for improving the storage stability of such products (Mahajan et al., 2021).

Aloe vera gel coating is quite effective in extending the shelf life of various perishable food items depending on the dosage of gel used (Maan et al., 2021). The study of Benítez et al. (2015) indicated that *Aloe vera* edible coating could extend the postharvest shelf life and maintain the sensory properties of minimally processed kiwifruit through the storage period. *Aloe vera* edible coating extended the shelf life and maintained the quality of kiwifruit slices by 11 days at 4±1 °C (Benítezet al., 2015). In addition, the study Farooq et al. (2022) has proved that aloe vera-based coating in combination with chitosan is a successful and effective way to prolong the shelf life and sustain the quality attributes of tomatoes during storage of 12 days at 8 °C.

***Aloe vera* gel in beverages**

The use of *Aloe vera* gel in the food industry is mainly to provide functional ingredients, especially used to prepare health food drinks and other beverages (Alvarado-Morales et al., 2019). It can be added to juices for better digestion and health benefits. In the production of *Aloe vera* juice, the shelf life of the product will vary depending on the type of *Aloe vera* used (Hasan et al., 2023). A study performed by Kausar (2020) showed that the addition of *Aloe vera* had little effect on the physicochemical characteristics, reduced microbial load, increased total phenolic content, antioxidant activity and reducing capacity. The sensory evaluation of orange juice with 5% *Aloe vera* gel showed its acceptability even after 90 days of storage.

***Aloe vera* in fruit preservation**

Prolongation of shelf life of fresh fruits and vegetables is a matter of great importance because the losses of them estimated by Food and Agriculture Organization of the United Nations consists about 50% (Pirog et al., 2022a). Edible coatings are traditionally used to improve food appearance and preservation. Natural biopolymers such as plant or microbial polysaccharides, plant gums, peptides, and lipid-based materials are proposed for development of edible coating (Pirog et al., 2022b). The diluted aqueous extract of *Aloe vera* edible coating could maintain the quality of the tomatoes during storage period in ambient conditions and slow down ripening. The pure extract of *Aloe vera* could inhibit the growth of fungi *Rhizoctonia solani* and *Alternaria alternata* (García et al., 2014).

In the study of Das et al. (2022), the *Aloe vera* gel and sodium benzoate were used to increase the shelf life and quality of three tomato varieties. The results showed that the total phenolic content and antioxidant activity were higher than in control for all varieties. The application of the mixture of 3% sodium benzoate and 10% *Aloe vera* gel allowed extending the shelf life of the tomato up to 21 days and providing a way to diminish the cost in their preservation (Das et al., 2022).

Aloe vera gel was used as an edible coating in the storage period for the Pisang Awak bananas. Application of the gel in optimal concentration has a positive effect on the ripening process, prevents softening and discoloration, and improves the quality of bananas (Quoc, 2021).

Aloe vera in dairy industry

Aloe vera in gel form is considered as a health-promoting ingredient in food (Bahrami et al., 2019). In the dairy industry, *Aloe vera* gel or *Aloe vera* juice are used for incorporation in various dairy products such as flavored milk, ice cream, and yogurt (Srikanth et al., 2016). The adding 3% *Aloe vera* gel to replace milk fat in yogurt formulations showed that *Aloe vera* gel improved the texture of yogurt containing buffalo milk as well as the sensory properties of the product (Ikram et al., 2020). The addition of *Aloe vera* with high aloin content to yogurt helps to stimulate and increase the content of bifidobacterium (Hussain et al., 2017).

Aloe vera contains several ingredients that interact with probiotics, and serve as a source of prebiotics and antioxidants. The addition of 1% *Aloe vera* oil to both non-dairy and dairy products resulted in favourable sensory quality compared to the control samples (Kim et al., 2022). Incorporation of *Aloe vera* gel into non-dairy vegetable cream helped to reduce the melting rate and affected the texture of the cream. The final cream product had a soft, fluffy structure, did not melt quickly when exposed to air, and had a mild, attractive sweet taste (Nguyen and Do, 2023).

Aloe vera in confectionary products

Aloe vera gel is used to produce some products such as candies, bars, chewing gums, gums for sore or bleeding gums, candy type *Aloe* vitamins, and *Aloe vera* fruit smoothies. *Aloe vera* concentrate was collected from the *Aloe vera* juice processing under vacuum (125 mm Hg vacuum, at temperature below 50 °C, and concentration time was less than 2 minutes) to prevent the loss of biological activity. The *Aloe vera* concentrate was used to process various foods such as squash, jam, and jellies. In addition, the concentrate of *Aloe vera* can also be mixed with tea, water or juice. *Aloe vera* powder can be used in curd, lassi, ice cream, and yoghurt productions (Ahlawat and Khatka, 2011).

Aloe vera in sport nutrition products

Aloe vera contains valuable nutrients needed to provide good nutrition for health and can be used to create functional products to support the body's immunity (Haristy et al., 2021). *Aloe vera* has been used to produce several products such as drinks (health drinks, soft drinks, laxatives), sports drinks (with electrolytes), diet drinks (with soluble fiber), hangover drink (with B vitamins), vegetable juice mix (Natalia, 2018).

Safety aspects of *Aloe vera*

According to Kumar et al. (2022), scientific reports have agreed that *Aloe vera* is safe for use on external wounds, burns, inflammations, but the safety for use in humans, especially for immunocompromised consumers such as pregnant women, children and patients with gastrointestinal diseases, depends on the usability, dosage and concentration of *Aloe vera* in the food. Determining the safety of *Aloe vera* is quite rigorous due to the lack of standardization in the commercial manufacturing of *Aloe vera* products. The ingestion of *Aloe vera* preparations is associated with diarrhea, hypokalemia, and kidney failure (Guo and Mei, 2016).

Conclusions

1. *Aloe vera* is rich in various valuable components, including polysaccharides (55%), sugars (17%), minerals (16%), proteins (7%), lipids (4%), and phenolic compounds (1%). This plant also contains numerous biologically active compounds, providing diverse health benefits such as emollient, purgative, anti-inflammatory, antioxidant, antimicrobial, anti-helminthic, antifungal, antiseptic, and pharmaceutical and cosmetic values.
2. Depending on the purpose of using, leaves of *Aloe vera* could be processed by whole-leaf processing, mechanically filleted or manual filleted processing to obtain *Aloe vera* gel. After that, the gel was used to produce juice, concentrate and powder products.
3. The products of *Aloe vera* are natural functional ingredients or additives for the fortification of food products from vegetable sources to improve food quality, prolong the shelf life of vegetable and fruits, reduce microbial load, increase antioxidant activity, improve acceptability of products, enhance the growth of probiotics cultures, and are also used in the pharmaceutical and cosmetic industries.
4. The main areas of *Aloe vera* applications in the food industry include production of edible coatings, fruits preservation, and beverages, dairy, confectionary, and sport nutrition products processing.
5. Further research into *Aloe vera*'s bioactive compounds will help unlock their health benefits, thereby minimizing and preventing numerous diseases. Safety should be considered when using *Aloe vera* products.

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Potential benefits of functional antianemic energy bars

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Abstract

Introduction. A multicomponent formulation of antianemic energy bars with improved nutritional and sensory properties has been developed.

Materials and methods. Model systems based on grains and nuts, dried fruits, honey and dietary iron supplements were used in the study. The chemical composition of the energy bars was analysed by colorimetric methods, liquid chromatography, and gas chromatography–mass spectrometry. Microbiological analysis was done according to generally accepted methods. Sensory analysis was carried out using a developed 10-point scale.

Results and discussion. Addition of dietary iron supplement in the amount 1.0 and 3.0 % to the recipe mixture increases the content of ash by 1.35 and 1.37 times; iron content by 1.27 and 1.29 times; the content of other minerals by 1.52±0.75%; vitamins by 1.36±0.41%; protein by 1.16 and 1.18 times; carbohydrates by 0.53±0.02%; and fat by 3.40±0.02%. At the same time, incorporation of dietary iron supplement in the amount 1.0 and 3.0 % improves the structure of bars by 1.06 and 1.08 times, the surface by 1.10 and 1.12 times, and consistency by 1.15 and 1.17 times; decreased the moisture content by 1.12–1.14 times, water activity by 1.13–1.15 times and the level of illumination, L* by 1.11 and 1.28 times, respectively; increases the index a* (degree of redness) by 6.78 and 8.56 times; index b* (degree of yellowness) by 2.14 and 3.16 times, respectively.

Texture profile analysis has proven that the addition of dietary iron supplement in the amount 1.0 and 3.0% increases the stiffness by 5.6 and 6.0%; adhesiveness by 1.86 and 2.76%; cohesiveness by 2.89 and 3.71%; elasticity (stability) by 1.54 and 2.30%; chewing rate by 1.76 and 2.62%; reduces elasticity by 1.86±0.21%, respectively.

The optimal mass fraction of dietary iron supplement was determined as 3.0%. Microscopic observations have proven the suppression of microbial contamination of the surface of prototypes of energy bars with the introduction of dietary iron supplement, 3.0%.

Conclusions. The multicomponent formulation of energy bars using dietary iron supplement has been developed. High functional and technological potential of the dietary iron supplement was shown, which gives opportunity to recommend it as a stabilizer, structure former, and improver of confectionery products.

Introduction

Food is a source of energy, the required amount of nutrients and biologically active substances: complete proteins, essential amino and fatty acids, vitamins, micro- and macroelements necessary for the normal functioning of the body. Currently, the main trend in the food industry is the creation of high-quality and safe products, so preservatives, synthetic additives and dyes are becoming increasingly unacceptable for consumers. In particular, the energy bars provide health benefits and also contain no traces of fertilizers and pesticides, which are often found in conventional foods (Iuliano et al., 2019).

In today's busy society, consumers are often looking for healthy and ready-to-eat food. Energy bars is a food in bar form designed to increase physical energy. This multi-component food system is a popular nutritional supplement due to its availability, compactness, convenience and ready-to-use, as well as a diverse, balanced composition of nutrients, high energy, biological and nutritional value (Fanari et al., 2023). There are a lot of energy bars types: high-carbohydrate (carbohydrate content more than 70%); high-protein (protein content from 5 to 20%); whole grains (oats, muesli, wheat, corn, rice), chocolate and multifruit bars (Boukid et al., 2022). Energetic bars supply the body with useful substances: proteins, fats, and carbohydrates to replenish energy, and in some cases with vitamins, minerals and antioxidants (Jabeen et al., 2020). It was foreseeable that the production and consumption of food products formulated for specific sporting activities would continually increase (Ivanov et al., 2021). Energy bars are recommended as food products for the nutrition of athletes, as they help strengthen the body and increase the effectiveness of training (Boukid et al., 2022; Fanari et al., 2023).

To produce multi-component energy bars with increased biological and nutritional value, mechanical grinding and mechanical activation of various raw materials are used. Raw ingredients of plant origin undergo technological, physicochemical and thermodynamic changes. Due to this, they acquire a light (crushed) structure and become more digestible by the body while maintaining their therapeutic and preventive properties.

In recent years, the trend towards consuming natural products has increased worldwide. Thus, sales of energy bars on the Great Britain market tripled for the period from 2017 to 2022, reaching 167 million euros, and in the US market it doubled, reaching 2919 million euros (Fanari et al., 2023). Numerous energy bar formulations have been developed to meet the energy and nutrient needs of different age groups and people with varying physical activity levels.

There are many studies aimed at enriching energy bars with various functional ingredients, such as soy products (Aramouni et al., 2011; Lobato et al., 2012), banana peel flour (Carvalho and Conti-Silva, 2018), pear, apple, and date fibres (Bchir et al., 2018), tempeh (Melo et al., 2020), bean flour (Maia et al., 2021), brewer's grain (Stelick et al., 2021), fish protein concentrate (Vitorino et al., 2020), fish oil (Nielsen and Jacobsen, 2009), milk proteins (Hogan et al., 2012), whey protein concentrate and bioactive ingredients (Szydłowska et al., 2017), and wine fermentation biomass (Borges et al., 2021). So, energy bar recipes consist primarily of cereals, legumes, fruits and nuts with the addition of natural enhancers, chocolate pieces or chocolate coating. To meet consumer demands for taste, texture and natural ingredients, innovative companies are using alternative protein sources, reviewing initial formulations, enriching them with essential and biologically active substances; adding unusual ingredients to create new functional products (Munir et al., 2019). However, there is practically no information on the production of energy bars with antianemic properties.

Iron deficiency is believed to be the leading cause of anemia, which affects more than 2,000 million people (World Health Organization, 2008). Recently, dietary iron supplements are considered to be appropriate food ingredients for the target population, fortifying the diet with the micronutrient iron (Banu and Mageswari, 2015; Evlash et al., 2021; Jarzębski et al., 2023; Hou et al., 2019; Riabchykov et al., 2022; Tang et al., 2015; Tsykhanovska et al., 2021; Tsykhanovska et al., 2022a, b; Xing et al., 2022). Therefore, creating new health products enriched with iron is relevant.

Dietary iron supplement (DIS) is a brown fine powder with a particle size of 50 microns having neutral taste and without smell. It is made from dietary blood of animal origin and contains heme iron in a reduced, easily digestible form Fe^{2+}. Iron supplement contains, %: protein, 75.0; fat, 2.5; carbohydrate, 20.0; organic acids, 0.4; cholesterol, 0.1; minerals, 1.5; and heme iron, 0.1 (Evlash et al., 2021). Hemovital contains all essential amino acids, as well as vitamins: A (retinol), E (α-tocopherol), C (ascorbic acid), B1 (thiamine), B2 (riboflavin), B3 (PP, niacin), B6 (pyridoxine), B9 (folic acid), B12 (cyanocobalamin) and minerals: Ca, K, Na, P, Mg, Cl, Cu, Se, Co, Zn, Mn, and I. Dietary iron supplement enriches the human body with complete protein and the trace element iron; it can be used as a natural dye; it improves the functional and technological properties, biological, nutritional value and quality indicators of finished food products.

The aim of the present research was to propose a multicomponent formulation of antianemic energy bar containing dietary iron supplement and study nutritional and sensory properties of enriched products.

Materials and methods

Materials

Sweet almond seeds, oat flakes, white flaxseeds, sunflower seeds, chia seeds, natural honey, nut butter, raisins, dried cherries, dried cranberries, and dietary iron supplement were used as raw materials for the production of energy bars.

Dietary iron supplement was introduced into the recipe mixture without changing the mass ratio of other recipe components of the product, at a dosage of 1.0 and 3.0%, respectively, 5.5 and 16.5 g per 550.0 g of the raw material mixture or 5.5 and 16.5 mg heme iron in mixture.

Since dietary iron supplement has color-forming properties, the use of a higher than 3.0% mass fraction of DIS by weight of the recipe mixture can adversely affect the color of the product, and in addition impart a pronounced off-flavor to the product. It should be noted that energy bar from 550.0 g of recipe mixture with addition of 3.0% DIS (or 16.5 mg of heme iron) covers the daily requirement of the human body for iron (on average 15–17 mg/day of total iron) (Latunde-Dada, 2024). That is, the product can be considered as an additional source of easily digestible iron in reduced form (Fe^{2+}) in the human diet, which is important in the modern nutritional structure of the population. Formulations for energy bars are shown in Table 1.

Production of energy bars

The traditional flow chart for the production of energy bars is shown in Figure 1.

Table 1

Formulations for energy bars with dietary iron supplement (DIS), g

Raw material	Control without DIS	Sample 1 with DIS, 1.0%	Sample 2 with DIS, 3.0%
Almond seeds	74.25±0.55	74.25±0.55	74.25±0.55
Oat flakes	148.50±5.50	148.50±5.50	148.50±5.50
White flaxseeds	19.80±1.10	19.80±1.10	19.80±1.10
Sunflower seeds	19.80±1.10	19.80±1.10	19.80±1.10
Chia seeds	19.80±1.10	19.80±1.10	19.80±1.10
Natural honey	79.75±5.50	79.75±5.50	79.75±5.50
Nut butter	56.10±5.50	56.10±5.50	56.10±5.50
Raisins	56.10±5.50	56.10±5.50	56.10±5.50
Dried cherries	56.10±5.50	56.10±5.50	56.10±5.50
Dried cranberries	56.10±5.50	56.10±5.50	56.10±5.50
Dietary iron supplement	–	5.50±0.02	16.50±0.02
The finished product output	586.30 ±36.30	591.80±36.32	602.80±36.32

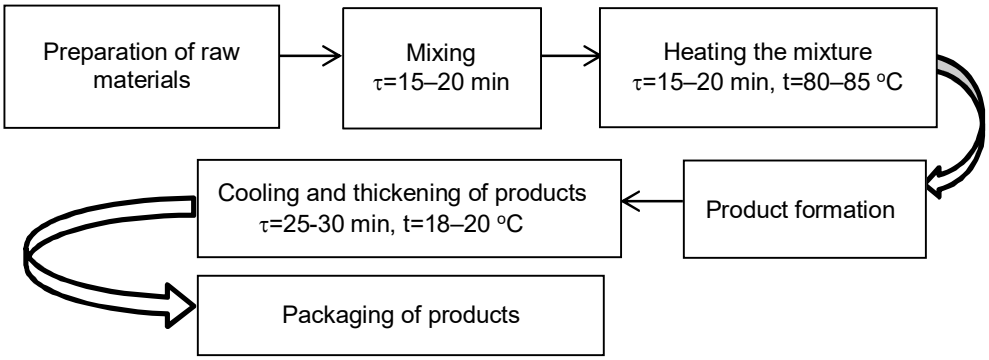

Figure 1. Flow chart for the production of energy bars

Oatmeal is crushed; almond, white flax, sunflower and chia seeds are sorted, cleaned of mechanical impurities, and crushed; dried fruits (raisins, cherries, cranberries) are washed, dried and cut into pieces; honey is heated to a temperature of t=45–50 ºC and mixed with nut butter; the dietary iron supplement is sifted, mixed with water GM=1:1 and kept for swelling at a temperature of 15–18 ºC for 35–40 min; combine the prepared components and mix thoroughly for 5–10 min. The mixture is heated to a temperature 80–85 ºC for 15–20 min; bars are formed by pouring the mass into a mold, cooled and kept for thickening at a temperature of 18–20 ºC for 20–25 min.

Methods

Physico-chemical analysis

Moisture content (W,%) was determined by the gravimetric method at a temperature of 105°C until the sample weight remained constant for 24 hours (Fanari et al., 2023).

Water activity (a_w) was measured at 25 °C using Aqualab 4TE (Decagon Devices Inc., Pullman, WA, USA) (ISO 18787, 2017).

Color was assessed using a CR-600d D65 colorimeter (Minolta Co., Osaka, Japan) by measuring CIE L*a*b parameters (Luo, 2015) at three points, ten strokes for each sample. The total color difference (ΔE) was calculated using CIE76 by formula (1), based on the Euclidean distances between colours in CIELab space:

$$\Delta E = \sqrt{(L_o - L)^2 + (a_o - a)^2 + (b_o - b)^2}\ , \quad (1)$$

where L, a and b are parameters CIELab of sample, L_0, a_0 and b_0 are parameters CIELab of control.

Texture analysis. Texture was assessed using a TA.HDplusC Texture Analyser (Stable Microsystems, Surrey, UK) equipped with a 250 kg load cell; at a speed of 2 mm/s and a sample deformation of 75%. The samples were cut into 2x2 cm squares and kept for 2 hours at 20±2ºC and 45–50% relative humidity to standardize water absorption before testing. Next, 10 different parts were selected for 3 different batches, which were used to analyze the textural characteristics: hardness, adhesiveness, cohesiveness, elasticity, chewiness, and springiness according to the method (Szczesniak, 2002). PTA is a double compression test known as the “two bite test”, which simulates chewing with the mouth. The test results are displayed as a graph of force (compression or tension) as a function of time or distance: Hardness, F1(g) is maximum value of force (tension); adhesiveness, A3 (g/s) is negative area of the graph; cohesiveness, A2/A1 (g) is ratio of areas under two peaks; elasticity, A5/A4 (g) is ratio of areas under the first erysipelas; elasticity, T2/T1 (g) is ratio of the time of formation of two peaks; chewing, F1× (A2/A1)2 (%) is stickiness × cohesiveness.

Nutrient analysis. The mass fraction of fat was determined using an automatic installation for solid-hour extraction SOXTHERM SOX414 (Gerhardt, Germany) and using a Minispec MQ-20 NMR relaxometer (Bruker BioSpin GmbH, Germany) in accordance to the method (Gianferri et al., 20).

The biological value of the fatty acid complex was studied by experimental determination of the fatty acid composition by gas chromatography-mass spectrometry (GC-MS) using a Clarus 600 T GC-MS device (PerkinElmer, USA) and the methodology given in (Dulf, 2012; Petraru et al., 2021). The protein mass fraction was determined using the N2/DKL8 protein quantitative identification system (Velp Scientifica, Italy) according to the method (Krasina and Tarasenko, 2016).

The biological value of the protein complex was studied by experimental determination of the amino acid composition using the capillary electrophoresis system "Carel-105M" with a spectrophotometric detector (Lumex, Ukraine) according to the method given in (Krasina and Tarasenko, 2016), and using liquid chromatography (Dionex ICS-3000, USA) with an

electrochemical detector (Electrochemical Detector Cell) according to the method given in (Oseyko et al., 2020; Petraru et al., 2021; Rosa et al., 2009).

The mass fraction of fiber was determined using a FIBRETHERM FT12 fiber analysis unit (Gerhardt, Germany) according to the user instructions and methods given in (Krasina and Tarasenko, 2016).

Organic acids were determined by high-performance liquid chromatography of an HPLC system on an LC-20AD instrument (Schimadzu, Kyoto, Japan) with a SIL-20A sampler, a CTO-20AC column oven, a Phenomenex Luna® Omega 3 μm SUGAR 1 column and a RID-10A diode detector according to methodology (Pauliuc et al., 2021).

Content of vitamins sis was determined using an Agilent 1100 high-performance four-channel liquid chromatograph (Agilent Technologies, USA) combined with a diode array detector and mass spectrometry according to the method (Katsa et al., 2021; Sim et al., 2016).

The mineral composition was determined by mass spectroscopic studies (mass spectrometer Agilent 7500 S, USA) in accordance with the methodology given in (Sinkovic and Kolmanic, 2021).

Sensory analysis

Sensory analysis of energy bars was carried out in accordance with the methodology (Fanari et al., 2023; Jabeen et al., 2020).

A tasting commission of 15 tasters who had experience in sensory analysis of various food products for more than 2 years, based on the hedonic scale, determined the following indicators: color: 3, max score, weight coefficient, 0.3; smell: 1, max score, weight coefficient, 0.1; taste 1, max score, weight coefficient, 0.1; surface 1, max score, weight coefficient, 0.1; texture 1, max score, weight coefficient, 0.1; consistency 3, max score, weight factor, 0.3. Overall score, 10, weight coefficient, 1.0, with: 9.5–10.0, excellent; 9.4–9.0, very good; 8.5–8.9, good; 8.0–8.4, satisfactory; less than 8.4 is unsatisfactory. The sample size was 3-4 g for each test bar. Before each subsequent test, drinking water was offered as a mouth rinse.

Microbiological analysis

To conduct microbiological studies, the following media were used: nutrient agar was used for plate counting of the total number of microorganisms, namely the number of mesophilic aerobic and facultative anaerobic microorganisms (MAFAM); potato dextrose agar was used for counting yeasts and molds; Salmonella Shigella Agar was used for the determination of *Salmonella* spp.; Endo Agar was used for determination of the presence of *Escherichia coli* bacteria; Kessler medium was used for determining of colliter. Microbiological analysis was carried out according to the conventional methods for microbiological analysis of food products (Erkmen, 2022; Hasell et al., 2003; Olunlade et al., 2013).

Statistical analysis

Statistical analysis of the experiment results was carried out using Statistica 6.0, Microsoft Office Excel 2007 and Mathcad. Data were expressed as mean ± standard deviation to define three measurements.

Results and discussion

The chemical composition of the main raw ingredients was experimentally determined (Table 2).

Almond seeds contain, %: proteins, 18.6; carbohydrates, 21.6; fat, 49.9; as well as 8 water-soluble and 1 fat-soluble vitamins; 5 macroelements and 4 microelements. It is important to note that almond protein contains a high amount of arginine, 11.2%, and is highly digestible. Almonds contain a complex of unsaturated fatty acids, namely: oleic acid, 78.0%, linoleic acid, 21.5%, linolenic acid, 9.8%, and palmitoleic acid, 1.5%. Almond fat is highly resistant to oxidation due to the content of antioxidants (phytosterols, vitamin E), which is consistent with the data from other sources (Franklin et al., 2019; Tomishima et al., 2022; Zhu et al., 2015). The chemical composition of almond seeds provides it with natural biological and nutritional value, health benefits including lowering cholesterol, improving cardiovascular health and reducing blood pressure.

Oat flakes contain protein, carbohydrate, fatty acid and vitamin-mineral complexes, namely nine vitamins (B1, B2, B4, B5, B4, B6, B9, C, PP, E) and nine minerals (K, Na, Ca, Mg, P, Fe, Zn, Cu, Se). The absence of gluten makes all cereals friendly to people with celiac disease. The absence of gluten makes oat flakes friendly to people with celiac disease. Oat flakes is a source of many compounds having high antioxidant capacity, such as flavonoids, phenolic acids, and vitamin E (Hu, 2014; Zhang et al., 2021).

Flaxseeds contain a significant amount of fat (45%), which has a high content of linolenic acid, which provides the fat with the ability to dry quickly, forming a thin, smooth and shiny film. Flax seeds are a "source of protein", accounting for 22.5% of the total seed mass. It should be noted that there is a fairly high content of vitamins B4 (78.7 mg/100 g), B9 (87.0 μg/100 g), E (19.9 mg/100 g) and minerals such as potassium, magnesium, phosphorus, iron, selenium. Flaxseeds contain a high amount of α-linolenic acid (ω-3), and have low ratio ω-6/ω-3, 0.27, which makes them the perfect material to be used for creating functional products (Stabnikova and Paredes-Lopez, 2024). The presence of natural antioxidants (α-tocopherol, chlorogenic acid) helps combat oxidative stress, which contributes to improved overall health (Ayelign et al., 2016; Bernacchia et al., 2014).

Sunflower seeds have a very diverse chemical composition and include different classes of compounds that are beneficial to human health (Tsykhanovska et al., 2023). It has been determined that sunflower seeds contain 20.8% protein, rich in amino acids, including essential ones. The seeds contain 51.5% fat, which includes saturated fatty acids, 10.24%; monounsaturated fatty acids, 37.82%; polyunsaturated fatty acids, 51.94%. Vitamins found in sunflower seeds are: C, E, group B, but the largest amount is for B3, 8.3 mg/100 g; B9, 227.0 μg/100 g, and E, 35.2 mg/100 g; minerals, among which the following are potassium, 645.0 mg/100 g, magnesium, 325.0 mg/100 g, phosphorus, 660.0 mg/100 g, iron, 5.3 mg/100 g, and selenium, 53.0 μg/100 g (Table 2). This is consistent with the experimental data of other scientists (Bashir et al., 2015; González-Pérez et al., 2017; Petraru et al., 2021).

Chia seeds have a high protein content, 21.8%, carbohydrates, 41.0% and fat, 31.2%. The main components of chia seed fats are polyunsaturated fatty acids, in particular α-linolenic and linoleic acids. The ratio between ω-6 and ω-3 fatty acids is 0.33 (Stabnikova and Paredes-Lopez, 2024). In addition, chia seeds contain minerals such as calcium, phosphorus, potassium, magnesium, iron, selenium; vitamins B1, B2, B3, B6, B9; a large number of natural antioxidants such as tocopherols, phytosterols, carotenoids and polyphenolic compounds. The findings are consistent with the results of other researchers (Imran et al., 2016; Kulczyński et al., 2019).

Table 2

Chemical composition of raw materials

Compounds	Sweet almond	Oat flakes	White flaxseeds	Sunflower seeds	Chia seeds	Natural honey	Peanut butter	Raisins	Dried cherries	Dried cran-berries
Nutrients, g/100 g										
Protein	18.6 ±0.50	15.48 ±0.46	22.5 ±0.6	20.8 ±0.62	21.8 ±0.65	0.07 ±0.002	23.2 ±0.7	3.4 ±0.1	1.5 ±0.04	0.2 ±0.006
Carbo-hydrate	21.6 ±0.65	69.12 ±2.07	25.1 ±0.75	20.0 ±0.60	41.0 ±1.23	96.0 ±2.88	21.15 ±0.6	79.5 ±2.4	76.5 ±2.30	82.8 ±2.50
Fat	49.9 ±1.50	8.78 ±0.26	45 ±1.35	51.5 ±1.54	31.2 ±0.94	n.d	51.4 ±1.5	1.35 ±0.04	0.2 ±0.01	1.1 ±0.03
Vitamins, mg/100 g										
B_1	0.17 ±0.01	1.17 ±0.03	1.6 ±0.05	1.5 ±0.04	0.48 ±0.01	5.2 ±0.15	0.6 ±0.02	n.d	0.02 ±0.00	0.02 ±0.00
B_2	0.62 ±0.02	0.22 ±0.01	0.2 ±0.01	0.4 ±0.01	0.17 ±0.01	45 ±1.35	0.1 ±0.01	0.2 ±0.006	0.02 ±0.00	0.02 ±0.00
B_4	0.22 ±0.01	40.4 ±1.21	78.7 ±2.36	55.1 ±1.65	n.d*	2.2 ±0.06	63.0 ±1.89	11.1 ±0.33	4.8 ±0.14	8.3 ±0.25
B_5	0.78 ±0.02	1.49 ±0.04	1.0 ±0.03	1.1 ±0.03	n.d	0.1 ±0.01	1.1 ±0.03	0.1 ±0.003	0.06 ±0.00	0.01 ±0.00
B_6	0.82 ±0.02	0.17 ±0.01	0.5 ±0.01	1.3 ±0.04	0.180 ±0.005	128 ±3.80	0.3 ±0.01	0.3 ±0.01	0.04 ±0.00	0.02 ±0.001
PP(B_3)	4.8 ±0.14	0.934 ±0.03	3.1 ±0.09	8.3 ±0.25	6.95 ±0.21	76 ±2.28	13.1 ±0.40	1.1 ±0.03	0.4 ±0.01	0.5 ±0.015
C	8.5 ±0.25	0.01 ±0.00	0.6 ±0.02	1.4 ±0.04	1.60 ±0.05	0.5 ±0.01	n.d	3.2 ±0.10	12.4 ±0.40	0.2 ±0.001
E	23.5 ±0.70	1.01 ±0.03	19.9 ±0.6	35.2 ±1.05	1.48 ±0.04	n.d	9.1 ±0.30	0.1 ±0.00	0.24 ±0.01	2.1 ±0.06
B_9, µg /100 g	44.1 ±1.32	52 ±1.56	87.0 ±2.6	227.0 ±6.8	0.15 ±0.00	2.0 ±0.06	87.0 ±2.61	3.0 ±0.10	4.8 ±0.14	0.5 ±0.015
Minerals, mg/100 g										
K	733.1 ±21.9	566 ±17.00	800.1 ±24.0	645.0 ±19.3	420.8 ±12.6	410.0 ±12.3	558.0 ±16.7	746.0 ±22.4	204.8 ±6.14	49.0 ±1.47
Na	1.0 ±0.03	2.0 ±0.06	30.0 ±0.90	9.0 ±0.27	16.1 ±0.5	24.6 ±0.74	426.0 ±12.7	12.4 ±0.4	16.0 ±0.50	5.0 ±0.15
Ca	269.0 ±8.07	58 ±1.74	267.0 ±8.01	78.0 ±2.34	594.0 ±17.8	26.5 ±0.8	47.24 ±1.4	53.3 ±1.6	29.6 ±0.80	9.0 ±0.27
Mg	270.0 ±8.10	235 ±7.05	400.2 ±12.0	325.0 ±9.75	296.4 ±8.8	6.82 ±0.2	168.0 ±5.04	35.7 ±1.07	20.8 ±0.60	4.0 ±0.12
P	481.0 ±14.4	734 ±22.02	667.0 ±20.01	660.0 ±19.8	720.0 ±21.6	38.3 ±1.15	334.6 ±10.0	115.4 ±3.5	24.0 ±0.70	8.0 ±0.24
Fe	3.7 ±0.11	5.41 ±0.16	4.8 ±0.14	5.3 ±0.16	7.1 ±0.2	2.3 ±0.07	1.4 ±0.04	1.8 ±0.05	0.4 ±0.01	0.4 ±0.01
Zn	3.1 ±0.09	3.11 ±0.09	4.0 ±0.12	5.0 ±0.15	4.6 ±0.14	0.3 ±0.01	2.4 ±0.07	0.3 ±0.01	0.12 ±0.00	0.1 ±0.00
Cu, µg/100 g	1.0 ±0.03	403 ±12.09	1.2 ±0.04	1.8 ±0.05	1.09 ±0.03	0.01 ±0.0003	0.4 ±0.01	0.4 ±0.01	80.4 ±2.40	0.1 ±0.00
Se, µg/100 g	4.1 ±0.12	45.2 ±1.35	25.4 ±0.76	53.0 ±1.59	54.6 ±1.64	0.8 ±0.024	4.1 ±0.12	0.7 ±0.02	0.08 ±0.00	0.6 ±0.02

*n.d-non-detects

Nut (peanut) butter contains 23.2% highly digestible proteins, 51.4% fats and 21.15% carbohydrates. Nut butter is rich in vitamins, especially B vitamins, namely: B3, 13.1 mg/100 g, B4, 63.0 mg/100 g, B5, 1.1 mg/100 g. Nut butter contains a fairly high amount of tocopherols, 9.1 mg/100 g; minerals: potassium, sodium, phosphorus, zinc, selenium and bioactive compounds that can exhibit protective effects against cardiovascular diseases, cancer, diabetes, osteoporosis and other degenerative diseases (Bonku et al., 2020; Shibli et al., 2019).

Natural honey contains a significant amount, g/100 g, of: carbohydrates, 96.0, mainly fructose, 2.8, glucose, 27.7, and sucrose, 0.5. Honey contains vitamins, especially vitamins of B-group, among which B1, 5.2 mg/100 g, B2, 45 mg/100 g, B3, 76 mg/100 g, and B6, 128 mg/100 g, are predominate. Honey contains macroelements (potassium, calcium and sodium), and microelements (iron, copper, and zinc), which perform a fundamental function in biological systems: maintaining normal physiological reactions, inducing general metabolism, influencing the circulatory system and reproduction, as well as catalysts for various biochemical reactions. Honey contains only trace amounts of protein, which agrees with the data of others (Bogdanov et al., 2008; Tafere, 2021).

Raisins contain small amounts of protein, 3.4%, and fat, 1.35%. Carbohydrates, 79.5%, which are represented by fructose, 24.3 g/100 g, glucose, 18.2 g/100 g, and small amounts of sucrose, 0.85 g/100 g, are dominated compounds in the honey composition. Raisins contain vitamins of B-group, vitamins C and E; minerals (potassium, calcium, iron, magnesium, and phosphorus). Raisins contain valuable pectin, 2.4%, and dietary fiber, 0.91%. Pectin is practically not absorbed by the human digestive system. It plays a role of adsorbent capable of binding heavy metals, radionuclides and excess cholesterol and removing them from the body. It has antimicrobial and anti-inflammatory agents, helps reduce cholesterol and blood sugar levels, and improves digestive function (Ghrairi et al., 2013; Maki et al., 2023).

Cherry fruits contain a small amount of protein, 1.5%, and fat, 0.2%. Identified carbohydrates make up to 76.5%, represented by fructose, 22.3%, glucose, 14.4%, and sorbitol, 8.9%. They also contain dietary fiber, 0.86%; organic acids (malic, 8.0%, succinic, 1.2%, salicylic, 1.8%, citric acid, 6.0%); minerals, vitamins, namely thiamine, ascorbic acid, and nicotinic acid. Cherries also contain tannins, coloring substances and antioxidants. Consumption of cherry fruits improves appetite, regulates intestinal activity, and increases the digestibility of fats and proteins (Cairone et al., 2023; Serradilla et al., 2017; Sokół-Łętowska et al., 2020).

Cranberry fruits contain a small amount of proteins, 0.2%, and fats, 1.1%. The amount of carbohydrates is 82.8%, which includes fructose, 16.7%, glucose, 8.44%, sucrose, 1.6%, dietary fiber, 0.8%. Cranberry fruits contain vitamins B group, vitamins C and E, and antioxidants. There is a large amount of minerals present, namely potassium, phosphorus, magnesium, calcium, iron, zinc, copper, which is consistent with the data of other researchers (Jurikova et al., 2019; Nemzer et al., 2022).

Dietary iron supplement provides the human body with complete protein and can be used as a natural brown dye. DIS contains 75% of protein and 0.1% heme iron (Figure 2). The use of such a supplement allows to enrich diet with iron and protein, improves the functional and technological properties and quality indicators of finished confectionery products.

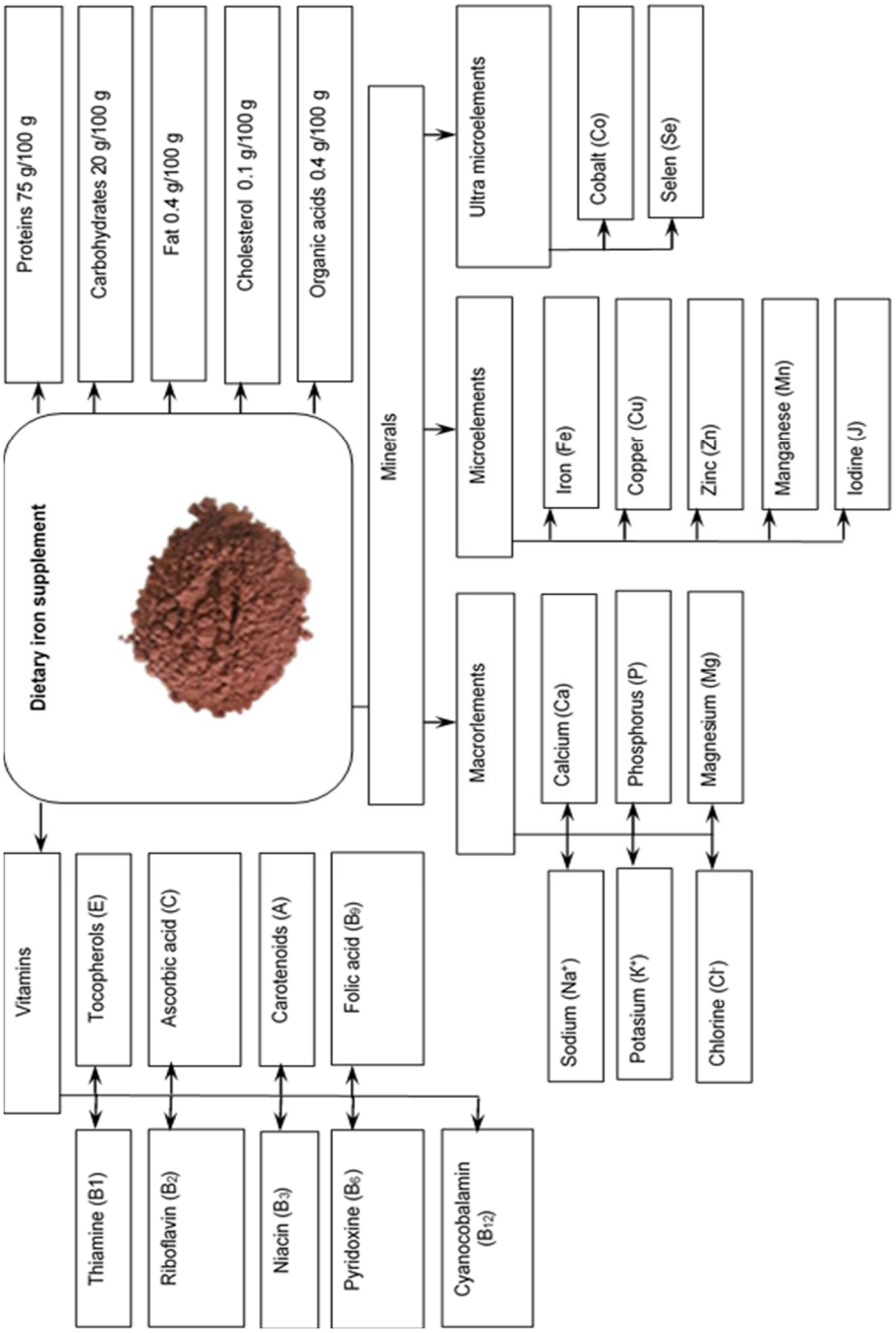

Figure 2. Nutrient profile of dietary iron supplement

To determine the rational amount of dietary iron supplement in the formulation of energy bars, a sensory analysis of samples was carried out. The results are shown in Table 3, Table 4, and Figure 3.

Table 3

Sensory analysis of energy bars with dietary iron supplement (DIS)

Sample	Structure	Consistency	Taste	Smell	Color	Surface
Control	Fine crystalline uniform mass, with barely noticeable small hard slices of components	Semi-solid, but not dense, with low viscosity	Pleasant, with pronounced taste of dried fruits	Pleasant, with pronounced dried fruit aroma	Brown, homogeneous in mass	Non-sticky, homogeneous mass with small, isolated cracks
Sample 1 with DIS, 1%	Fine crystalline, with even distribution components throughout the mass	Semi-solid, with uniform density	Pleasant, with pronounced taste of dried fruits	Pleasant, with pronounced dried fruit aroma	Brown, homogeneous in mass	Non-sticky, homogeneous mass without cracks
Sample 2 with DIS, 3%	Fine crystalline, with even distribution components throughout the mass	Semi-solid, with uniform density	Pleasant, with pronounced taste of dried fruits	Pleasant, with pronounced dried fruit aroma	Brown, homogeneous in mass	Non-sticky, homogeneous mass without cracks

Energy bars with dietary iron supplement added to the recipe mixture in amounts of 1.0% and 3.0% had the same organoleptic properties (surface, taste, smell and color) as control. However, the structure, surface and consistency of the bars with DIS were improved compared to control.

Addition of DIS, 3.0% (w/w), allowed to introduce 16.5 mg of heme iron in 550.0 g of the product that practically satisfies the daily need of the human body for iron (on average 15–17 mg/day of total iron). Thus, the most acceptable are energy bars with introduction of dietary iron supplement in the amount 3.0% by weight in the recipe mixture.

Results of sensory assessment of the energy bars in points are shown in Table 4 and Figure 3.

Energy bars prepared with addition of dietary iron supplement in the amounts 1.0% and 3.0% by weight of the recipe mixture had the highest score of 9.77 ± 0.22. The data obtained confirm the results of the sensory analysis indicated in Table 3. That is, compared to control, the following were improved: structure by 1.07 times, surface by 1.11 times and consistency by 1.16 times; the color becomes somewhat saturated; the total score increases by 1.07 times.

Table 4

Sensory assessment of the energy bars with dietary iron supplement (DIS) in points

Parameters	Control	Sample 1 with DIS, 1.0%	Sample 2 with DIS, 3.0%
Structure	0.92±0.02	0.98±0.02	0.98±0.02
Smell	0.95±0.03	0.95±0.03	0.95±0.03
Surface	0.88±0.02	0.98±0.02	0.98±0.02
Color	2.90±0.06	2.94±0.06	2.94±0.06
Consistency	2.55±0.05	2.97±0.07	2.97±0.07
Taste	0.95±0.03	0.95±0.03	0.95±0.03
Overall score	9.15±0.21	9.77±0.22	9.77±0.22

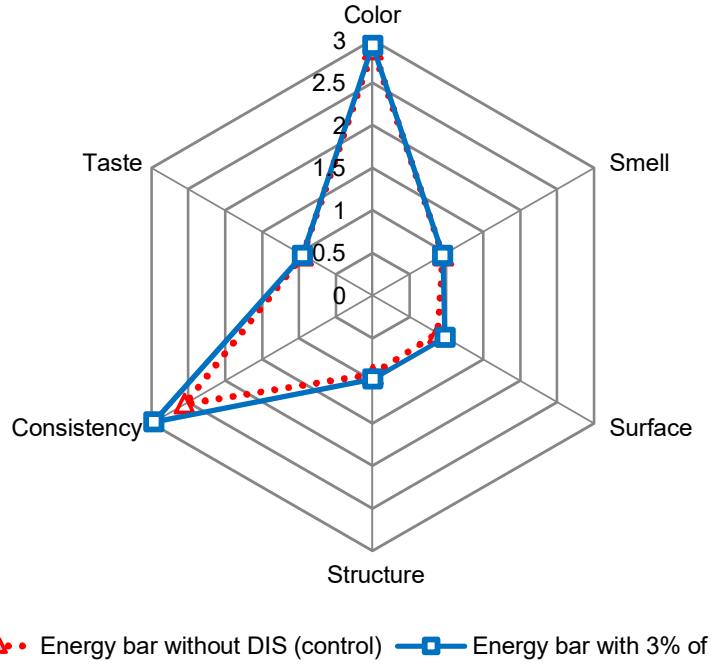

Figure 3. Sensory assessment of the energy bars with dietary iron supplement (DIS)

Thus, the recommended amount of dietary iron supplement is 3.0% by weight in the recipe mixture of energy bars.

Analysis of the chemical composition of energy bars shows an improvement in the biological value of the product added with DIS compared to control (Table 5).

Table 5

Chemical composition of energy bars with dietary iron supplement (DIS)

Compounds	Control	Sample 2 with DIS, 3,0%	Compounds	Control	Sample 2 with DIS, 3.0%
Macronutrients, g/100 g dry weight			P	191.08±3.73	191.66±3.74
Water	9.56±0.08	8.43±0.04	I	0.009±0.0	0.012±0.0
Proteins	9.61±0.28	11.28±0.31	Fe	59.08±1.69	75.78±1.89
Fat	8.30±0.24	8.58±0.24	**Vitamins, g/100 g dry weight**		
Carbohydrate	68.22±1.06	70.62±1.07	A	2.92±0.06	2.96±0.07
Fiber	3.97±0.09	3.97±0.09	E	1.51±0.04	1.54±0.04
Organic acids	0.42±0.01	0.46±0.01	C	0.82±0.02	0.85±0.02
Ash	2.14±0.05	2.96±0.06	B_1	0.41±0.01	0.44±0.01
Minerals, g/100 g dry weight			B_2	0.31±0.01	0.33±0.01
Na	55.04±1.68	56.26±1.71	B_3 (PP)	0.62±0.01	0.65±0.02
K	465.0±13.0	468.0±13.0	B_6	1.60±0.04	1.64±0.04
Ca	86.12±2.18	87.65±2.16	B_9	0.52±0.01	0.54±0.01
Mg	99.14±2.34	101.34±2.42	B_{12}	0.82±0.02	0.85±0.02

Addition of dietary iron supplement, 3.0% (w/w) improves the mineral-vitamin and protein-carbohydrate compositions compared to control, namely, the Fe content increases by 1.28 times; other micro- and macroelements by 1.52±0.75%; vitamins by 1.36±0.41%; ash by 1.38 times; protein by 1.17 times; carbohydrates by 0.55%; as well as fat by 3.42%. This is due to the rich chemical composition of dietary iron supplement. The water absorption capacity of highly dispersed powdered DIS reduces the moisture content by 1.13 times compared to control, which helps to improve the microbiological characteristics of the finished product.

It has been shown that the main supplier of energy in energy bars with DIS is carbohydrates (Table 6).

Table 6

Nutritional value of energy bars with dietary iron supplement (DIS)

Compounds	Control	Sample 2 with DIS, 3.0%
Protein, g/100 g energy bar	9.61±0.28	11.28±0.31
Fat, g/100 g energy bar	8.30±0.24	8.58±0.24
Carbohydrates, g/100 g energy bar	72.19±1.16	74.59±1.17
Approximate calorie content, Kcal/100 g	401.90	420.70
Calories from carbohydrates, %	288.76	298.36

Energy bar added with dietary iron supplement was enriched in comparison with control with complete proteins of animal origin containing a balanced composition of essential amino acids. Consequently, the addition of DIS in an amount of 3.0% by weight of the recipe mixture improves the nutritional value and consumer properties of the finished product.

Analysis of the physicochemical characteristics of energy bars shows that the introduction of 1.0% and 3.0% brown dietary iron supplements into the recipe compared to control reduces the lighting level L* by 1.11 and 1.28 times, respectively; significantly increases: index a* (degree of redness) by 6.78 and 8.56 times, respectively; indicator b* (degree of yellowness) 2.14 and 3.16 times, respectively (Table 7).

Table 7

Physicochemical characteristics of energy bars with dietary iron supplement (DIS)

Samples	L*	a*	b*	ΔE	M, %	a_w
Control	74.93±0.82	0.68±0.02	17.58±0.12	0.00	9.56±0.04	0.476±0.002
DIS, 1.0%	67.55±0.51	4.61±0.12	37.68±0.21	23.45±0.51	8.39±0.03	0.416±0.001
DIS, 3.0%	58.46±0.42	5.82±0.14	55.52±0.36	29.82±0.57	8.43±0.03	0.419±0.001

These color changes may be due to the high content of hemoglobin and myoglobin (red color) and bilirubin (yellow color pigment) in DIS (dietary blood product). The value of the "color difference", ΔE, in the samples with DIS was above 7.0, that is, the color of the bars is considered visible to the human eye, and DIS has color-forming ability. The color changes are more pronounced in the energy bar containing 3.0% of dietary iron supplements.

It has been found that the use of addition of dietary iron supplements, 1.0% and 3.0%, reduced moisture content by 1.13 times compared to control. It is related to the hydration capacity of the protein-carbohydrate complex of highly dispersed DIS powder. This effect on moisture content was also influenced by the values of water activity, a_w, which were lower in bars with DIS by approximately 1.14 times compared to control. Similar results for moisture content and water activity were observed by other authors for confectionery products with the addition of highly dispersed food additives (Batista et al., 2019; Fanari et al., 2023). The crispness of the product is highly dependent on the water content and/or a_w values. When they decrease, food products become harder and crispier. In any case, taking into account the influence of the mass fraction of DIS on the consumer properties of the finished product in this study, the rational mass fraction of DIS is 3.0% (w/w) of the mass of the recipe mixture. This amount of DIS is not capable of causing negative changes in the texture of the energy bars (Table 8).

Table 8

Texture profile of energy bars with dietary iron supplement (DIS)

Samples	Hardness, g	Adhesiveness, g/s	Cohesiveness, g	Elasticity, g	Chewing, %	Springiness, g
Control	792.3 ±2.1	-86.42 ±0.33	0.242 ±0.001	0.482 ±0.012	74.26 ±1.13	0.052 ±0.001
DIS, 1.0%	836.5 ±2.2	-88.03 ±0.33	0.249 ±0.001	0.473 ±0.012	76.12 ±1.13	0.060 ±0.001
DIS, 3.0%	843.8 ±2.2	-88.81 ±0.33	0.255 ±0.001	0.462 ±0.012	76.88 ±1.13	0.064 ±0.001

The texture of energy bars is an important factor for consumer acceptance beyond appearance and taste. Texture is inextricably linked to the structure of the product at the micro- and macro-levels, and is strongly influenced by the interaction of food biopolymers: proteins, polysaccharides and lipids. In addition, the components of the product must be released from the food matrix to reach the appropriate taste buds. This process is closely related to the way in which the food structure breaks down in the mouth, both in terms of the

initial texture of the food product and the change in its texture during chewing. The hardness of test samples with 1.0% and 3.0% of DIS increases compared to control by 5.6% and 6.0%, respectively, due to lower moisture content, increased protein content and the Maillard reaction, which induces polymerization and interaction of protein molecules and polysaccharides, helping to strengthen the structure. The added amounts of DIS ("protein source") was not sufficient to achieve an undesired hardening according to Regulation of the European Parliament and of the Council (EC) No. 1924/2006, taking into account also the high content of carbohydrates present in the dietary iron supplement. A decrease in hardness by 5.8±0.2% and an increase in elasticity by 1.86±0.21% of control bars is influenced by a higher moisture content and higher water activity, which promotes the action of H_2O as a retarder of cross-linking of sugars and proteins.

Addition of 1.0% and 3.0% DIS increases adhesiveness by 1.86% and 2.76%, respectively, due to the hydration, structure-forming and stabilizing ability of the increased amount of proteins and the migration of moisture from the outer layers to the inner layers , which helps strengthen the adhesion of the product to the surface; cohesiveness by 2.89% and 3.71%, respectively, due to cross-linking between biopolymer molecules: proteins, carbohydrates, lipids and the formation of a stable spatial food matrix.

Higher adhesiveness and cohesiveness of the energy bars added with 1.0% and 3.0% DIS compared to control resulted in an improvement in the chewing ability of the product and an increase in the chewing index by 1.76% and 2.62%, respectively.

Addition of 1.0% and 3.0% DIS increases elasticity (stability) by 1.54% and 2.30%, respectively. This is due to the strengthening and stabilization of the structure of the product through electrostatic intermolecular interactions of biopolymer ingredients: hydrophobic and polar sections of macromolecules, ionic and ionized groups.

Therefore, the results of physicochemical and structural-mechanical studies confirmed that the recommended mass fraction of DIS is 3.0% by weight of the recipe mixture.

The results of the influence of DIS on microbial contamination of the surface of energy bars initial after production and after storage for 75 days at relative air humidity 75±2% are shown in Table 9.

Table 9

Microbiological analysis of energy bars

Characteristics	Standard**	Energy bars	
		Control	with DIS, 3.0%
MAFAM, CFU*/g, initial / after 75 d	≤1.0×10^3	n.d.*** / 2.0×10^2	n.d. / 1.0×10^2
Yeasts, CFU/g, initial / after 75 d	≤50	n.d. / 6.0	n.d. / 4.0
Coliform bacteria, initial / after 75 d	n.a.**** in 0.1 g	n.d. / n.d.	n.d.
Pathogens (*Salmonella*), initial / after 75 d	n.a. in 25.0 g	n.d. / n.d.	n.d.
Molds, CFU/g, initial / after 75 d	≤ 50	n.d. / 6.0	n.d. / 3.0

*CFU, colony formed units;

**The standards are established by ISO 16140:2016 Microbiology of the food chain and European Food Safety Authority, 2021;

***n.d., not detected,

****n.a., not allowed

Microbiological analysis of energy bars with DIS, 3%, showed that they correspond to regulatory documentation. In addition, the introduction of 3.0% DIS suppresses contamination of the surface of energy bars: the number of mesophilic aerobic and facultative anaerobic microorganisms (MAFAM) was 2 times lower compared to control, yeasts by 1.5 times, molds by 2.0 times after storage at air humidity 75±2% for 75 days. This is due to the water-absorbing and structure-forming effect of the dietary iron supplement, which helps reduce the moisture content in the product.

Conclusions

The nutrient composition of the raw materials of multicomponent antianemic energy bars and the finished product has been studied. The results of a study of the influence of dietary iron supplements on the quality indicators of antianemic energy bars showed that the addition of 1.0 and 3.0 % (w/w) dietary iron supplements has a positive effect on the biological and nutritional value; sensory, physico-chemical, structural-mechanical and microbiological characteristics of the finished product, in particular:

1. Addition of 1.0 and 3.0% dietary iron supplement improved compared to control: biological and nutritional value of the finished product, namely the content increases: Fe by 1.27–1.29 times; other micro- and macroelements by 1.52±0.75%; vitamins by 1.36±0.41%; ash by 1.37–1.39 times; protein by 1.16–1.18 times; carbohydrates by 0.53±0.02%; fat by 3.40±0.02%; structure by 1.06–1.08 times, surface by 1.10–1.12 times and consistency by 1.15–1.17 times; the color becomes somewhat saturated; the total score increases by 1.07 times, respectively.
2. Physicochemical studies showed that the addition of 1.0–3.0% dietary iron supplement compared to control: reduces moisture content by 1.12–1.14 times and water activity by 1.13–1.15 times; reduces the lighting level, L*, by 1.11 and 1.28 times, respectively; significantly increases: index a* (degree of redness) by 6.78 and 8.56 times, respectively; indicator b* (degree of yellowness) by 2.14 and 3.16 times, respectively.
3. Texture profile analysis proved that the addition of 1.0% and 3.0% dietary iron supplement compared to control: increases hardness by 5.6% and 6.0%; adhesiveness by 1.86% and 2.76%; cohesiveness by 2.89% and 3.71%; elasticity (stability) by 1.54% and 2.30%; chewing rate by 1.76% and 2.62; reduces elasticity by 1.86±0.21%, respectively.
4. The recommended amount of dietary iron supplements was determined as 3.0% of the weight of the recipe mixture.
5. The decrease of microbial contamination of the surface of energy bars with the dietary iron supplement, 3.0%, has been proven.
6. The conducted studies showed a high functional and technological potential of the dietary iron supplement, which could be recommended as a stabilizer and improver of structure of food items, in particular confectionery products.

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Lactic acid bacteria for the synthesis of metals nanoparticles

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Abstract

Introduction. Metal nanoparticles (NPs) are widely used in various fields of scientific and practical activities. Biogenic metal nanoparticles attract attention with their unique properties and relative low cost of production, and lactic acid bacteria as biosafe producers.

Materials and methods. Morphological analysis of clusters of scientific knowledge about metal nanoparticles biosynthesis using lactic acid bacteria and antimicrobial properties of produced NPs.

Results and discussion. For biosynthesis of nanoparticles it is important the choice of: an ecofriendly biological agent; precursor metal salt; nontoxic material as a capping agent to stabilize the synthesized nanoparticles, and factors providing optimal conditions for the formation of nanoparticles, such as pH, temperature, pressure, time, agitation, biological reducing agent concentration, initial precursor salt concentration, and light. Lactic acid bacteria (LAB), which are belonging to the RG1 group of microorganisms (biologically safe) according to the European Union Directive, attract the attention as biosafe producers of various metal nanoparticles in a relatively inexpensive and accessible process of NPs biosynthesis. The last decade increasing interest in LAB use in the form of biomass, cell lysate, or cell-free supernatant (filtrate) has been observed. All metal nanoparticles exhibit high antimicrobial activity, and these properties against pathogenic bacterial strains are very important for NPS practical applications in treating bacterial infections, especially in conditions of widespread phenomenon of microorganism resistance to antibiotics. Especially important is the fact that metal nanoparticles have non-specific bacterial toxicity that makes it difficult to develop resistance by bacteria. NPs synthesized by lactic acid bacteria are effective against many antibiotic-resistant bacterial strains, including *Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus pyogenes, Klebsiella pneumoniae* and *Salmonella typhi*, as well as for different fungi and yeasts. The statistically proven absence of significant differences in the inhibitory effect of AgNPs synthesized by LABs on the growth of Gram-positive and Gram-negative bacteria was shown.

Conclusions. Lactic acid bacteria could serve as biosafe producers of different metal nanoparticles having strong antimicrobial abilities.

Introduction

Interest in nanotechnology, the branch of science and engineering devoted to the synthesis, manufacturing and application of tiny in size materials, has increased exponentially due to progress and technological innovation (Radulescu et al., 2023). Nanomaterials have special characteristics that differ from its bulk form with the same composition and thanks to them are found wide application in medicine, pharmaceutical, agriculture, food production, electronic devices, optical, catalysis, and environmental management. Nanoparticles (NPs) are the particles having size less than 1000 nm in at least one dimension (Gosh et al., 2021; Jeevanandam et al., 2018), meanwhile particles with size from 10 to 100 nm have even more valuable properties due to large surface-to-volume ratio and high surface energy, which make them more in demand. However, it should be noted that various physicochemical methods used for the synthesis of metal nanoparticles are expensive, need high thermal conditions, involve the use of toxic chemicals, generate excess by-products, and lead to pollution of the environment and the biosphere. Besides that, chemically produced nanoparticles have limited fields of application because of their toxicity (Singh and Singh, 2019). Thus, with modern advances in science and technology, an alternative method is biogenic synthesis, which has enormous potential as a sustainable, environmentally friendly and cost-effective method that does not require toxins, aggressive chemicals and the use of large amounts of energy, which is essential for physicochemical synthesis (Gupta and Seema, 2021). Different biological agents such as viruses, bacteria, actinomycetes, fungi, molds, microalgae, and plant extracts could be used for the biosynthesis of nanoparticles of a wide range of metals including silver, gold, platinum, palladium, copper, zinc, iron, titanium, magnesium, selenium, tellurium, cerium, and zirconium (Pandit et al., 2022). Microbial biosynthesis of nanoparticles involves metal capture, enzymatic reduction, and capping (Ghosh et al., 2021). Schematic for biological synthesis of nanoparticles, so called green nanotechnology, is shown in Figure 1 (adapted from Patra and Baek, 2014).

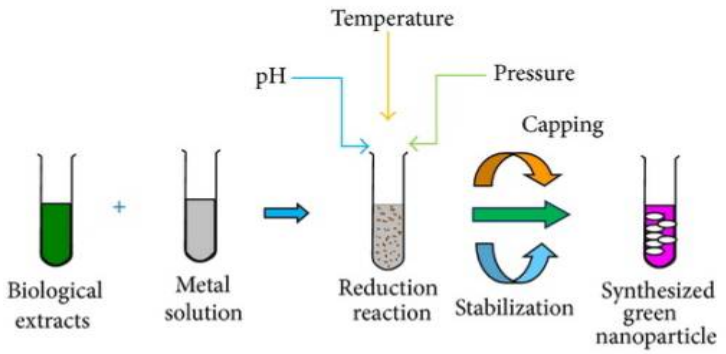

Figure 1. Biological synthesis of nanoparticles (Patra and Baek, 2014)

According to the given scheme, for biosynthesis of nanoparticles it is important: a) the choice of an ecofriendly biological agent; b) the choice of initial precursor metal salt; c) factors influenced on the process of biosynthesis (pH, temperature, pressure, time, agitation, biological reducing agent concentration, initial precursor salt concentration, light); and d) the choice of a nontoxic material as a capping agent to stabilize the synthesized nanoparticles (Javed et al., 2020; Miu and Dinischiotu, 2022; Patra and Baek, 2014).

When exploring the selection of biological agents capable of producing metal NPs, particular attention is drawn to lactic acid bacteria (LAB), which are belonging to the RG1

group of microorganisms (biologically safe) according to the European Union Directive (Directive 2000/54/EC, 2000) and considered Generally Recognized as Safe (GRAS) by the US Food and Drug Administration (Colautti et al., 2022; EFSA; 2016; Stabnikova et al., 2023).

Among lactic acid bacteria there are many representatives capable of synthesizing metal NPs; in particular, these bacterial strains belong to the genera *Lactobacillus*, *Lactococcus*, *Enterococcus, Streptococcus, Pediococcus* and *Leuconostoc.*

Biosynthesis of metal nanoparticles using lactic bacteria

Bacteria can synthesise metallic nanoparticles by either intracellular (endogenous) or extracellular (exogenous) mechanisms. Extracellular synthesis consists of enzyme secretion during bacteria cultivation and application of these reductase enzymes for metal bioreduction and formation of nanoparticles (Das et al., 2014; Singh and Singh, 2019). To obtain nanoparticles it is possible to use a cell-free supernatant containing microbial enzymes.

In turn, the intracellular biosynthesis of NPs is based on the origin of the living organisms to extract metals from the surrounding media, enzymatically convert the metallic ions into elemental form, and accumulate them (Li et al., 2011; Miu and Dinischiotu, 2022). Positively charged metal ions are adsorbed on the negatively charged microbial cells, bioreduced, and form nanoclusters inside the cell (Marooufpour et al., 2019). Accumulation of nanoparticles in cells is confirmed by the appearance of a specific color of microbial biomass, which could be pinkish for gold NPs, red for selenium NPs, brownish for silver nanoparticles, and so on.

Biosynthesis of silver nanoparticles by lactic acid bacteria

The majority of lactic acid bacteria used for biosynthesis of silver nanoparticles belong to the genus *Lactobacillus* that are gram-positive having in their cell wall teichoic acids which give it an overall negative charge (Chapot-Chartier and Kulakauskas, 2014). In formation of negative charge on the surface of gram-positive bacteria, anionic polymers of the cell walls, especially peptidoglycan, are also involved. It is assumed that electrostatic interaction that occurs between positive charged ions and negatively charged original cells resulted in biosorption of metal ions on the surface of microorganism cells. Silver ions being trapped on the surface or inside of the microbial cells are reduced to respective metal atom Ag^+ due to action of reductase enzymes using functional groups of the cell that serve as an electron donor, and subsequently developing Ag nanoparticles (Yusof et al., 2020a). Examples of the biosynthesis of AgNPs with lactic acid bacteria are given in Table 1.

Biosynthesis of AgNPs by lactic acid bacteria can be carried out using cell-free supernatant (Awadelkareem et al., 2023), biomass (Yusofet al., 2020a) or cell lysate (Mousavi et al., 2020). Bacterial biomass is used less frequently for this purpose, since most metal ions are toxic to bacteria. Silver nitrate, $AgNO_3$, is usually used as a biosynthesis precursor with different concentration ranges from 0.1 to 100 mM, among which the most used concentration is 0.1 mM $AgNO_3$ (Dybkova et al., 2020; Mousavi et al., 2020; Popoola and Adebayo-Tayo, 2017; Sharma et al., 2022; Syame et al., 2020). The biosynthesis of AgNPs is carried out at temperatures from 22 to 37 ºC (Matei, 2020; Naseer et al., 2020; Rajesh et al., 2015; Sharma et al., 2022; Vijayakumar, 2023) usually for 24 hours (Awadelkareem et al., 2023; Rajesh et al., 2015; Sani et al., 2018; Sharma et al., 2022; Syame et al., 2020; Yusof et al., 2020a). However, in some cases the biotransformation of the precursor into NPs was going for 72 hours (Mousavi et al., 2020), 12 hours (Naseer et al., 2020); 5 days (Matei et al., 2020), and even 7 days (Viorica et al., 2018). The formed NPs have a spherical shape and different sizes in the range from 0.2 nm to 233 nm.

Table 1

Biosynthesis of silver nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus rhamnosus GG	Spherical, average size 233 nm	1 mM cell lysate, pH 7.0, 1 mM $AgNO_3$, 25 °C, 72 h, 150 rpm, in a dark	Mousavi et al., 2020
Lactobacillus acidophilus	Spherical, 4–50 m, average size 33 nm	Supernatant, 1 mM $AgNO_3$, 35°C, 24 h, in a dark	Rajesh et al., 2015
Lactobacillus sp. LCM5	Spherical, 3–35 nm average size13.8± 4.6 nm	Cell-free supernatant, 1 мМ $AgNO_3$, 28 °C, 5 days, 200 rpm	Matei et al., 2020
Lactobacillus crustorum F11	Spherical, average size 10±2.9 nm	Supernatant, 0.1 мМ $AgNO_3$, 30 °C, 24 h, in a dark	Sharma et al., 2022
Lactobacillus pentosus S6	Spherical, average size 50±2.9 nm		
Lactobacillus plantarum F22	Spherical, average size 20±2.9 nm		
Lactobacillus paraplantarum KM1	Spherical, average size 50±2.9 nm		
Lactobacillus plantarum TA4	Spherical, average size 14.0±4.7 nm	Biomass, 2 мМ $AgNO_3$, 37 °C, 24 h, 150 rpm, in a dark	Yusof et al., 2020a
Lactobacillus bulgaricus	Spherical, ranged from 30 to 100 nm	Biomass, 1 мМ $AgNO_3$, over night at room temperature	Naseer et al., 2020
Lactobacillus plantarum	*, 4-6 nm	Biomass, 0.1 M (Ag:NH_3=1:2), room temperature, 24 h, 120 rpm	Dybkova et al., 2020
Lactobacillus plantarum	Spherical or polyhedral, poly-dispersed, 5 to 40 nm	Cell-free supernatant, 2 мМ $AgNO_3$, pH 8.3, 37 °C, 24 h, 150 rpm, in a dark	Syame et al., 2020
Lactobacillus brevis			
Lactococcus lactis 56 KY484989	Sperical, 5-50 nm, average size 19±2 nm	Supernatant, 1 мМ $AgNO_3$, 26 °C, 7 days, agitation	Viorica et al., 2018
Lactobacillus delbrueckii subsp. *bulgaricus*	Sperical, 1.4–8.9 nm	Supernatant, 1 мМ $AgNO_3$, room temperature, 24 h, exposed to direct sunlight for 10 min	Sani et al., 2018
Lactobacillus casei LPW2	*, 0.2–10 nm	Supernatant, 10 мМ $AgNO_3$, room temperature, 24 h	Popoola and Adebayo-Tayo, 2017
Bifidobacterium bifidum NCDC 229	Sperical, *	Supernatant, 1 мМ $AgNO_3$, 37 °C, 24 h, 160 rpm, pH 6,0	Kumar et al., 2016
Lactobacillus plantarum	Sperical, average size 14.0±4.7 nm	Supernatant, 1 мМ $AgNO_3$, 37 °C, 24 h	Vijayakumar et al., 2023

*There was no information.

Biosynthesis of selenium nanoparticles by lactic acid bacteria

Selenium nanoparticles have higher bioavailability, higher antioxidant activity, and scavenging effect on free radicals than sodium selenite (Deng et al., 2023). An analysis of the literature shows that to obtain selenium nanoparticles using lactic acid bacteria, biomass of LAB usually is applied (Hu et al., 2023; Laslo et al., 2022; Wang et al., 2023). Among the factors influencing selenium biotransformation, the source of Se and its concentration in the medium are the most significant (Liao and Wang 2022; Stabnikova et al., 2023). As a biosynthesis precursor, sodium selenite (Na_2SeO_3), sodium hydroselenite ($NaHSeO_3$) and, much less frequently, selenium oxide (SeO_2) were used (Kheradmand, 2014; Spyridopoulou et al., 2021; Vicas, 2021). Maximum concentration of Na_2SeO_3 in medium for lactic acid bacteria cultivation is considered to be 5 mg/l, but further increase may inhibit growth of nanoparticle producer and even can cause mass death of microbial culture cells (Pescuma et al., 2017; Spyridopoulou et al., 2021; Stabnikova et al., 2023).

The accumulation of selenium depends on the time of microbial cultivation. Thus, the amount of accumulated Se increased with the incubation period for *Lactobacillus acidophilus* CRL 636 and *Lactobacillus reuteri* CRL 1101 (Pescumav et al., 2017). The formation of SeNPs during LAB cultivation can be monitored by the appearance of a dark red color of cultural medium. It was found that the time of its appearance varied among different strains, and the color change could occur at different stages of bacterial growth. In case of strain *Lactobacillus casei* growth in nutrient medium with an initial $NaHSeO_3$ content of 20 μg/ml, colour became red only at 96 h of cultivation, which corresponded to the late logarithmic/early stationary phase of bacterial growth (Spyridopoulou et al., 2021). However, change of the bright yellow colour of medium for *Lactobacillus paracasei* cultivation to red was observed on 32 h in the exponential phase of bacterial growth (El-Saadony et al., 2021a).

It should be noted that the properties of selenium nanoparticles depend on their size: with the decrease of particle size, the ratio of surface area to volume increases, as well as the bioavailability and biological activity against hydroxyl radicals and the protective effect against DNA oxidation (Deng et al., 2023). The size of selenium NPs decreases in the presence of O_2 as it promotes the oxidation of Se, resulting in the redox process becoming slower and smaller SeNPs being formed (Martínez et al., 2020; Spyridopoulou et al., 2021). Particle size also depends on the strain (Martínez et al., 2020). The range of possible sizes of SeNPs should be limited to 20 to 500 nm. Most LABs produce spherical selenium NPs, but hexagonal SeNPs synthesized by *Lactobacillus paracasei* HM1 are also reported (El-Saadony et al., 2021a). SeNPs can be individual or form aggregated conglomerates (Spyridopoulou et al., 2021). Examples of the biosynthesis of SeNPs with lactic acid bacteria are given in Table 2.

Table 2

Biosynthesis of selenium nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus casei ATCC 393	*, 50-80 nm	Luria-Bertani broth, 200 mg/l Na_2SeO_3, 37 °C, 24 h	Xu et al., 2018
Lactobacillus acidophilus CRL 636	Sperical, average size 176 nm	Broth De Man, Rogosa and Sharpe (MRS), 25 mg/l Na_2SeO_3, 37 °C, 24 h	Moreno-Martin et al., 2017
Lactobacillus reuteri CRL 1101	Sperical, average size 160±24 nm		
Lactobacillus delbrueckii subsp. bulgaricus CRL 65	Sperical, average size 130±23 nm		
Lactobacillus rhamnosus	Sperical, 20-60 nm	Luria-Bertani broth, 4 mM Na_2SeO_3, 35 °C, 48 h, 170 rpm	Rajasree and Gayathri, 2015
Lactobacillus acidophilus	Sperical, 40-60 nm		
Lactobacillus plantarum	Sperical, 60-80 nm		
Enterococcus faecalis	Sperical, 29–195 nm	Luria-Bertani broth, 33–514 mg/l Na_2SeO_3, 37 °C or 42 °C, 24 h and 48 h, 150 rpm	Shoeibi and Mashreghi, 2017
Lactobacillus paracasei HM1	Hexagonal monodisperse, average size 91±1.8 nm	Luria-Bertani broth, 692 mg/l Na_2SeO_3, 35 °C, 32 h, 160 rpm, pH 6.0	El-Saadony, et al., 2021a
Lactobacillus casei ATCC 393	*, 170-550 nm	Broth MRS, 20 mg/l $NaHSeO_3$, 37 °C, 96 h	Spyridopoulou et al., 2021
Lactobacillus casei LC4P1	Sperical, ≤ 80 nm	Broth MRS, 200 мг/л Na_2SeO_3, 37 °C, 48 год	Vicas et al., 2021
Lactobacillus plantarum ATCC 8014	Sperical, 25 – 250 nm	Broth MRS, 200 мг/л SeO_2, 37 °C, 120 h, stirring	Kheradmand et al., 2014
Lactobacillus johnsonii			
Lactobacillus. acidophilus CRL636	*, 25–370 nm	Broth MRS, 5 mg/l Na_2SeO_3, 37 °C, 24 h	Pescuma et al., 2017
Lactobacillus reuteri CRL1101			
Lactobacillus brevis	*	Broth MRS, 254 mM SeO_2, 37 °C, 72 h	Yazdi et al., 2013

Table 2 (*Continue*)

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus pentosus ADET MW861694	Sperical, average size 106.1 nm	Broth MRS, 5 mM Na_2SeO_3, 37 °C, 72 h	Adebayo-Tayo et al., 2021
Lactobacillus casei IMB B-7280	Sperical, different in size: small (30–50 nm) and large (150–250) nm	Broth MRS, 5 ppm Na_2SeO_3, 30 °C, 24 h, 220 rpm	ok et al.,
Lactobacillus gasseri 55	*	Corn medium, 8 mg/l Na_2SeO_3, 37 °C, 24–48 h	Ohirchuk and Kovalenko, 2016
Pediococcus acidilactici DSM20284	Sperical, average size 239 nm	Broth MRS, 100 mg/l Na_2SeO_3, 37 °C, 48 h, under shaking	Wang et al., 2023
Enterococcus durans A8-1	*	Broth MRS, 60 mg/l Na_2SeO_3, 37°C, 18 h, 200 rpm	Liu et al., 2022
Lactobacillus casei	Sperical, average size 200 nm	Broth MRS, 200 mg/l Na_2SeO_3, 37 °C, 48 h	Laslo et al., 2022
Lactobacillus acidophilus ML14	Sperical, average size 46 nm	Luria-Bertani broth, 6 mM Na_2SeO_3, 35 °C, 170 rpm, until the synthesis of NPs is completed	El-Saadony et al., 2021b
Pediococcus lolii	Sperical, average size 186.6 nm	Milk permeate, 200 ppm Na_2SeO_3, 37 °C, 24 h	Zommara et al., 2022
Lactobacillus brevis	Sperical, average size 188.7 nm		
Lactobacillus plantarum	Sperical, average size 125 nm		
Lactobacillus paracasei SCFF20	Sperical, polydisperse, 500.62 nm	Broth MRS, 100 mg/l Na_2SeO_3, 37 °C, 24 h, 120 rpm	Hu et al., 2023
Lactococcus lactis NZ9000	*	Broth MRS, 0.6 mM Na_2SeO_3, 30 °C, 24 h, 120 rpm	Chen et al., 2021

*There was no information.

Biosynthesis of gold nanoparticles by lactic acid bacteria

There is limited information related to the synthesis of AuNPs by lactic acid bacteria. Analyzed available materials, it should be noted that auric acid, $HAuCl_4$, of varying concentrations ranging from 1 to 10 mM is usually used as a biosynthesis precursor (Markus et al., 2016; Miran and Ali, 2024), and the biosynthesis itself is achieved using the

supernatant (Miran and Ali, 2024; Repotente, 2022) or biomass (Markus et al., 2016) of lactic acid bacteria, and the process of AuNPs biosynthesis is conducted at room temperature under agitation. It was shown that AuNPs could be synthesized by reducing chloroauric acid using lactic acid isolated from the probiotic strain *Lactobacillus acidophilus* (Repotente et al., 2022). In study of Kato et al. (2019) it was shown that synthesis of AuNPs in *L. casei* was induced by the cooperation of lacto-N-triose, lactic acid and glycolipids. Meanwhile, Markus et al. (2016) found that protein and functional groups (carboxylate) on *Lactobacillus kimchicus* DCY51 were responsible for the reduction of gold nanoparticles. Gold nanoparticles have spherical shape and size from 5 to 140 nm. Examples of the biosynthesis of AuNPs with lactic acid bacteria are given in Table 3.

Table 3

Biosynthesis of gold nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus kimchicus DCY51	Sperical, moderately polydisperse, 5–30 nm	Biomass, 1 мМ $HAuCl_4$, 30 °C, 12 h, 150 rpm	Markus et al., 2016
Lactobacillus acidophilus	Sperical, 6–12 nm	Supernatant, 7 mM $HAuCl_4$, 1.25 mg/ml calcium lactat, 48 h	Repotente et al., 2022
Lactobacillus paracasei	Sperical, average size 65.3 nm	Supernatant, 0.01M $HAuCl_4$, 25 °C, 24 h, pH 8.0, stirring for 2 h	Miran and Ali, 2024
Lactobacillus casei	Sperical, average size 68.2 nm		
Lactobacillus plantarum	Sperical, average size 139.67 nm		
Lactobacillus fermentum	Sperical, average size 127.29 nm		
Lactobacillus casei	7–56 nm, the size of the highest frequency was ≈ 30 nm	Biomass, 2g/l, 0.5 mM, auric acid (0.5 mM $K[AuCl_4]$), 24 h	Kikuchi et al., 2016

Biosynthesis of iron oxide nanoparticles by lactic acid bacteria

To obtain Fe_3O_4 NPs using lactic acid bacteria, a cytoplasmic extract is proposed to be used. Solution of ferrous sulfate, 0.001 M, served as a precursor for biosynthesis, and the biotransformation process occurs at 37 C for 3 weeks in the presence of 5% carbon dioxide. The formed Fe_3O_4 NPs had a spherical shape and size ranging from 10 to 15 nm. The first sign of the formation of iron oxide NPs was a change in the color of the iron sulfate solution from colorless to black (Torabian, 2018; Fani, 2018). Examples of the biosynthesis of Fe_3O_4 NPs using lactic acid bacteria are given in Table 4.

Table 4

Biosynthesis of iron oxide nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus casei PTCC 1608	Sperical, 10–15 nm	Cytoplasmic extract, 0.001 M solution of ferrous sulfate, 37 °C, 3 weeks, 5 % CO_2, pH 6.5	Torabian et al., 2018
Lactobacillus fermentum PTCC 1638	Sperical, 10–15 nm	Cytoplasmic extract, 0.001 M solution of ferrous sulfate, 37 °C, 3 weeks, 5 % CO_2, pH 6.5	Fani et al., 2018

Biosynthesis of zinc oxide nanoparticles by lactic acid bacteria

Biosynthesis of ZnO NPs is carried out using biomass (Yusof et al., 2020b) or culture liquid (Al-Zahrani et al., 2018; Selvarajan and Mohanasrinivasan, 2013; Yusof et al., 2020b). It was shown the possibility to obtain ZnO NPs using the cell-biomass or cell-free supernatant of zinc-tolerant *Lactobacillus plantarum* TA4 (Yusof et al., 2020b) added with solution of zinc nitrate, $Zn(NO_3)_2 \cdot 6H_2O$, containing dissolved ions of Zn^{2+}. Biotransformation using bacterial biomass was conducted at 37 °C for 24 h under agitation at 150 rpm, and at room temperature overnight using supernatant. Electronic microscope study showed that ZnO NPs biosynthesized with cell biomass had an irregular shape with average size of 191.8 nm, but a flower-like pattern was observed for ZnO NPs obtained using supernatant having average size of 291.1 nm. Proteins, carboxyl, and hydroxyl groups were detected on the surface of both types of NPs, which act as reducing and stabilizing agents. The authors suggested that reduction of Zn^{2+} to ZnO NPs was due to activity of proteins present in supernatant and biomass suspension in concentrations of 2.79±0.11 mg/mL and 1.94±0.20 mg/mL, respectively, as well as because of functional group present on the bacterial cell (Yusof et al., 2020b). Examples of the biosynthesis of ZnO NPs using lactic acid bacteria are given in Table 5.

Table 5

Biosynthesis of zinc oxide nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus plantarum TA4	An irregular shape, average size 191.8 nm	Biomass, $Zn(NO_3)_2 \cdot 6H_2O$ solution with Zn^{2+}, 37 °C, 24 h, 150 rpm	Yusof et al., 2020b
Lactobacillus plantarum TA4	A flower-like pattern, average size 291.1 nm	Supernatant, $Zn(NO_3)_2 \cdot 6H_2O$ solution with Zn^{2+}, room temperature, overnight	
Lactobacillus plantarum VITES07	Sperical, average size 7 nm	Supernatat, 0.1 M $ZnSO_4 \cdot H_2O$, 37 °C, 12 h, pH 6,0	Selvarajan and Mohanasrinivasan, 2013
Lactobacillus johnsonii	Sperical, 4–9 nm	Supernatant, 0.1 g/ml ZnO, 37 °C, 24 h	Al-Zahrani et al., 2018

Biosynthesis of titanium oxide nanoparticles nanoparticles by lactic acid bacteria

To obtain TiO_2 NPs, supernatant (culture liquid) of lactic acid bacteria are mainly used, and 0.025 M solution of TiO_2 is used as a precursor. Biotransformation occurs at temperatures 25 - 37 °C for 12 – 48 hours (Al-Zahrani et al., 2018; Hasan et al., 2023; Ibrahem et al., 2019; Jha et al., 2009). Formed nanoparticles mostly have spherical shape with size ranging from 4 to 90 nm. It was reported that synthesized TiO_2 nanoparticles remained stable without change in color after storage for three months at 4ºC (Ibrahem et al., 2019). Examples of the biosynthesis of ZnO NPs using lactic acid bacteria are given in Table 6.

Table 6

Biosynthesis of titanium oxide nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus johnsonii	Uneven, agglomerated, 4–9 nm	Cultural liquid, 0.025 M solution TiO_2, 37 °C, 24 h	Al-Zahrani et al., 2018
Leuconostoc mesenteroides subsp. *mesenteroides*	Sperical, average size 53.4–59.4 nm	Cultural liquid, 0.025 M solution TiO_2, 30 °C, 24 h	Hasan et al., 2023
Leuconostoc mesenteroides subsp. *cremoris*			
Leuconostoc pseudomesenteroides			
Lactobacillus spp.	Spherical, 8–35 nm, average size 30 nm	Biomass, 0.025M $TiO\cdot(OH)_2$ solution, room temperature 12–48 h	Jha et al., 2009
Lactobacillus rhamnosus	Sperical, 3–10 nm, average size 5.7±1.9 nm	Supernatant, 5M $Ti[OCH(CH_3)_2]4$, pH 8, 24 h	Abdel-Maksoud et al., 2023
Lactobacillus crispatus	Sperical or oval, average size 87.9 nm	Supernatant, 0.025 M solution TiO_2, 37 °C, 24 h, stitting	Ibrahem et al., 2019

Biosynthesis of copper and magnesium oxides nanoparticles by lactic acid bacteria

The CuO NPs were biosynthesized using biomass *Lactobacillus casei* subsp. *casei* as biological agent, 1 mM solution of copper sulphate as a precursor, at pH 6.0 at 37ºC for 48 hours until the medium turned from yellow to dark brown showing the formation of CuO NPs, spherical in shape magnesium oxide nanoparticles without any agglomeration (Kouhkan et al., 2020).

Biomass of the strain *Lactococcus* spp. was used for biosynthesis of magnesium oxide nanoparticles, while 0.1 M solution of magnesium nitrate, $Mg(NO_3)_2\cdot 6H_2O$, was used as a precursor (Suba et al., 2022). Examples of the biosynthesis of copper and magnesium metal oxide nanoparticles using lactic acid bacteria are given in Table 7.

Table 7

Biosynthesis of copper and magnesium oxides nanoparticles by lactic acid bacteria

Microorganisms	Shape, size	Conditions for biosynthesis	Reference
Lactobacillus casei subsp. *casei*	Sperical, uniform, average size 200 nm	Biomass, 1 mM solution of $CuSO_4$, pH 6.0, 37 °C, 48 h	Kouhkan et al., 2020
Lactoccocus spp.	Spherical, evenly dispersed, average size 32 nm	Biomass, 0.1 M solution of $Mg(NO_3)_2 \cdot 6H_2O$, 40 °C, 10 h	Suba et al., 2022

Antimicrobial activity of metal nanoparticles synthesized by lactic acid bacteria

Antibiotic resistance is one of the most serious threats to human health. It was estimated that more than 1.27 million people in the world died in 2019 because of antibiotic resistance (WHO, 2023). Six nosocomial pathogens designated by the acronym ESKAPE (*Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter species*) represent the great threat to humans because they possess high virulence being multidrug resistant (Mulani et al., 2019). Development of new antimicrobial agents as an alternative to antibiotics will be a possible solution of widespread antibiotic resistance. That is why the identified bactericidal properties of metal nanoparticles against pathogenic bacterial strains are very important for their practical applications in treating bacterial infections. Particularly important is the fact that metal nanoparticles have non-specific bacterial toxicity that makes it difficult to develop resistance by bacteria (Sánchez-López et al., 2020).

To achieve an antibacterial effect, nanoparticles need to come into contact with bacterial cell. Contact of a nanoparticle with a cell occurs due to electrostatic attraction, van der Waals forces, as well as receptor-ligand and hydrophobic interactions (Wang et al., 2017). Interaction of NPs with cell wall involves loss of cell wall and cell membrane integrity followed by NPs direct interference with several metabolic pathways required for bacteria viability. After that NPs cross the bacterial membrane and interact with the bacterial cell structures such as DNA, lysosomes, ribosomes, and enzymes generating oxidative stress via reactive oxygen species (ROS), changing cell membrane permeability, inhibiting of enzyme activity, damaging bacterial protein and DNA (Sharmin et al., 2021; Wang et al., 2017) (Figure 2).

Thus, by synthesizing AgNPs from the supernatant of *Lactobacillus acidophilu*s, Rajesh and co-authors (2015) developed environmentally friendly antibacterial components and proved their antibacterial properties when used against *Klebsiella pneumoniae*, causing cytolysis and destroying the bacterial cell membrane. It is known that the size of nanoparticles is a key parameter determining antimicrobial activity. Smaller particles possess higher surface-to-volume ratio, and large surface area of NPs is necessary for attachment to microbial cell and rapid penetration into cells. For most NPs it is found that their smaller size correlates with a greater biological activity and stronger antimicrobial effect (Shoeibi and Mashreghi, 2017). It was shown for laser Ag NPs that nanoparticles with an average size of 19 nm were more effective against *Escherichia coli* than fraction with size ranges from 19 to 47 nm. Comparative study on influence silver nanoparticles with size 5, 20 and 50 nm on human cells also showed the correlation of smaller size on NPs and its toxicity effect (Korshed et al., 2019)

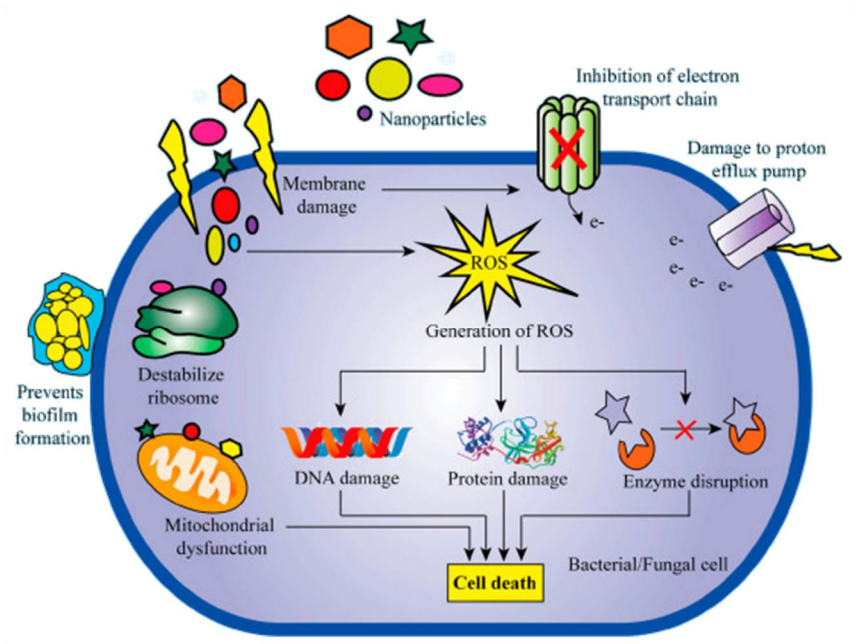

Figure 2. Schematic represents antimicrobial (bacteria and/or fungi) mechanisms of various nanoparticles (Sharmin et al., 2021)

Naseer et al. (2020) synthesized AgNPs from *Lactobacillus bulgaricus* and evaluated their antibacterial efficacy against *Staphylococcus aureus*, *S. epidermidis*, and *Salmonella typhi*. They showed that Gram-negative bacteria were more sensitive than Gram-positive bacteria to inhibition effect of silver nanoparticles. Some authors explained this phenomena that cell wall of Gram-negative bacteria have thinner wall and nanoparticles could penetrate easily inside the cell, damage cell membrane showing higher antimicrobial activity. Besides that, the cell wall of Gram-negative bacteria contains the lipopolysaccharides creating a greater negative charge of their cell wall in comparison with Gram-positive bacteria causing stronger adhesion of positively charged NPs on their surface (Bonnet et al., 2015). However, antimicrobial activity of SeNPs synthesized by lactic acid bacteria *Enterococcus faecalis* was shown against *Staphylococcus aureus* (Gram-positive) and was not shown against *Esherichia coli* (Gram-negative) (Shoeibi and Mashreghi, 2017). Syame with co-authors (2020) showed that inhibition zones of AgNPs synthesized using supernatant of *L. plantarum* were 16-18 mm against Gram positive bacteria, and 16-22 mm against Gram-negative; meanwhile AgNPs synthesized using supernatant of *L. brevis* were 16–21 mm against Gram-positive, and 13–22 mm against Gram-negative.

Antimicrobial activity of different metal nanoparticles synthesized by various lactic acid bacteria is shown in Table 8.

Table 8

Antimicrobial activity of nanoparticles synthesized by lactic acid bacteria

Microorganism	Test-culture	Gram	Nanoparticle	Inhibition zone, mm	MIC, μg/ml	Reference
Lactobacillus acidophilus	*Klebsiella pneumoniae*	Gram-	AgNPs, sperical, 4–50 nm,	16	60	Rajesh et al., 2015
Lactobacillus sp.	*Aspergillus flavus* *Aspergillus ochraceus* *Penicillium expansum* *Chromobacterium violaceum*	Fungi Fungi Fungi Gram-	AgNPs, sperical, 3–35 nm, average size 13.8 ±4.6 nm	12.4 ±0.6 12.9 ±0.8 15.9 ±1.0 18.0 ±0.7	*	Matei et al., 2020
Lactobacillus crustorum	*Staphylococcus aureus* *Listeria monocytogenes* *Bacillus cereus* *Fusarium oxysporum*	Gram+ Gram+ Gram+ Fungi	AgNPs, sperical, 10 nm	20.0 ±0.6 14.0 ±1.0 12.0 ±7.1 23.0 ±0.4	*	Sharma et al., 2022
Lactobacillus bulgaricus	*Staphylococcus aureus* *Staphylococcus epidermis* *Salmonella typhi*	Gram+ Gram+ Gram-	AgNPs, sperical, 30–100 nm	15 17 17	*	Naseer et al., 2020
Lactobacillus rhamnosus	*Chromobacterium v iolaceum* *Pseudomonas aeruginosa* *Serratia marcescens*	Gram- Gram- Gram-	AgNPs, sperical, average size 6.3 nm	13 10 7	13.3 26.5 53.1	Awadelkar eem et al., 2023
Lactobacillus plantarum	*Staphylococcus aureus* *Enterococcus faecalis* *Staphylococcus epidermis* *Staphylococcus aureus* *Clostridium perfringens* *Escherichia coli* *Klebsiella pneumoniae* *Pseudomonas aeruginosa* *Neisseria gonorrhoeae*	Gram+ Gram+ Gram+ Gram+ Gram+ Gram- Gram- Gram- Gram-	AgNPs, sperical, multifaceted, polydisperse, 5–40 nm	18 17 16 16 17 22 15 18 15	*	Syame et al., 2020

Microorganism	Test-culture	Gram	Nanoparticle	Inhibition zone, mm	MIC, μg/ml	Reference
Lactobacillus brevis	*Staphylococcus aureus*	Gram+	AgNPs, sperical, multifaceted, polydisperse, 5–40 nm	16	*	Syame et al., 2020
	Enterococcus faecalis	Gram+		21		
	Staphylococcus epidermis	Gram+		14		
	Staphylococcus aureus	Gram+		14		
	Clostridium perfringens	Gram+		17		
	Klebsiella pneumoniae	Gram-		15		
	Pseudomonas aeruginosa	Gram-		13		
	Escherichia coli	Gram-		22		
	Neisseria gonorrhoeae	Gram-		16		
Lactococcus lactis	*Pseudomonas aeruginosa*	Gram-	AgNPs, sperical, 5–50 nm, average size 19±2 nm	14 ±0.12	6.3	Viorica et al., 2018
	Staphylococcus aureus	Gram+		14 ±0.02	3.1	
	Staphylococcus epidermis	Gram+		16 ±0.05	3.1	
	Proteus mirabilis	Gram-		11 ±0.07	3.1	
Lactobacillus casei	*Bacillus sp.*	Gram+	AgNPs, *, 0.2–10 nm	24	*	Popoola and Adebayo-Tayo, 2017
	Streptococcus pyogenes	Gram+		22		
	Staphylococcus aureus	Gram+		15		
	Klebsiella sp.	Gram-		16		
	Pseudomonas aeruginosa	Gram-		13		
Enterococcus faecalis	*Staphylococcus aureus*	Gram+	SeNPs, sperical, 29–195 nm	8	*	Shoeibi and Mashreghi, 2016
Lactobacillus paracasei	*Candida albicans*	Yeast	SeNPs, hexagonal monodisperse, 91±1.8 nm	29 ±0.1	55	El-Saadony et al., 2021a
	Candida parapsilosis	Yeast		27 ±0.5	60	
	Candida krusei	Yeast		25 ±0.3	70	
	Candida glabrata	Yeast		23 ±0.4	65	
	Candida tropicalis	Yeast		24 ±0.5	70	
	Fusarium oxysporum	Fungi		26 ±0.2	50	
	Fusarium solani	Fungi		29 ±0.3	45	

Microorganism	Test-culture	Gram	Nanoparticle	Inhibition zone, mm	MIC, μg/ml	Reference
Lactobacillus rhamnosus	*Candida albicans* *Aspergillus niger*	Yeast Fungi	SeNPs, sperical, 20-60 nm	10 9	*	Rajasree and Gayathri, 2015
Lactobacillus acidophilus	*Candida albicans*	Yeast	SeNPs, sperical, 40-60 nm	4	*	
Lactobacillus plantarum	*Candida albicans* *Aspergillus niger*	Yeast Fungi	SeNPs, sperical, 60-80 nm	8 9	*	
Lactobacillus plantarum	*Candida albicans*	Yeast	SeNPs, sperical, 25–250 nm	28 ±0.5	*	Kheradmand, et al., 2014
Lactobacillus johnsonii	*Candida albicans*	Yeast		26 ±0.5	*	
Lactobacillus pentosus	*Escherichia coli* *Salmonella arizonae* *Salmonella tphimurium* *Staphylococcus aureus*	Gram- Gram- Gram- Gram+	SeNPs, sperical, average size 106.1 nm	11.5 13.2 9.0 10.1	*	Adebayo-Tayo et al., 2021
Pediococcus acidilactici	*Escherichia coli* *Klebsiella pneumoniae* *Staphylococcus aureus* *Bacillus subtilis*	Gram- Gram- Gram+ Gram+	SeNPs, sperical, 239 nm	17.5 ±0.8 13.4 ±0.9 27.9 ±1.2 16.2 ±1.1	*	Wang et al., 2023
Lactobacillus acidophilus	*Fusarium graminearum* *Fusarium cerealis* *Fusarium poae* *Fusarium avenaceum* *Fusarium culmorum* *Fusarium sporotrichioides*	Fungi Fungi Fungi Fungi Fungi Fungi	SeNPs, sperical, 46 nm	29 ±0.3 33 ±0.4 32 ±0.2 31 ±0.5 28 ±0.5 32 ±0.5	35 20 25 30 40 20	El-Saadony et al., 2021b
Lactobacillus plantarum	*Escherichia coli* *Salmonella sp.* *Staphylococcus aureus* *Staphylococcus epidermis*	Gram- Gram- Gram+ Gram+	ZnO NPs, *, average size 124.2 nm	19.3 ±0.6 16.7 ±1.2 19.0 ±1.0 17.7 ±0.6	*	Yusof et al., 2020b

Microorganism	Test-culture	Gram	Nanoparticle	Inhibition zone, mm	MIC, µg/ml	Reference
Lactobacillus rhamnosus	*Aspergillus favus* *Aspergillus versicolor* *Penicillium citrinum* *Aspergillus chinensis* *Aspergillus ustus* *Penicillium chrysogenum*	Fungi Fungi Fungi Fungi Fungi Fungi	Sperical, 3–10 nm, average size 5.7 ±1.9 nm 300 µg/ml	17.7 ±0.6 20.3 ±1.5 18.7 ±0.6 20.3 ±0.5 18.3 ±0.6 17.7 ±1.2	*	Abdel-Maksoud et al., 2023
Lactobacillus casei subsp. casei	*Staphylococcus aureus* *Pseudomonas aeruginosa*	Gram+ Gram-	CoO NPs, spherical, average size 200 nm	12 10	250 50	Kouhkan et al., 2020
Lactoccocus spp.	*Clostridium perfringens* *Clostridioides difficile* *Esherihia coli* *Salmonella typhi* *Candida albicans* *Aspergillus flavus*	Gram+ Gram+ Gram- Gram- Yeast Fungi	MgO NPs, spherical, average size 32 nm	26 ±0.5 24 ±1.4 23 ±2.3 22 ±0.1 21 ±1.5 20 ±2.3	*	Suba et al., 2022

*There was no informationi; MIC, Minimum inhibitory concentration

The data presented in Table 8 convincingly demonstrated the effectiveness of LAB-derived AgNPs against many antibiotic-resistant bacterial strains, including *Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus pyogenes, Klebsiella pneumoniae* and *Salmonella typhi* (Naseer et al., 2020; Popoola and Adebayo-Tayo, 2017; Rajesh et al., 2015; Sharma et al., 2022; Syame et al., 2020; Viorica et al., 2018).

According to data shown in Table 8 inhibition zone caused by AgNPs calculated for different lactic acid bacteria and different Gram-negative test cultures was 15.00±3.76 mm (N_1=17) with coefficient of variation 14.1%; meanwhile for Gram-positive test cultures it was 16.72±3.09 mm (N_2=18) with coefficient of variations 9.5%. Calculated coefficient of Student equals to 0.1971, meanwhile Student's t table at degree of freedom N_1+N_2-2=33 and significance level 0.05 is 2.0341. So, the differences are not significant. Thus, there appears to be no real difference in the inhibitory effect of silver nanoparticles synthesized by lactic acid bacteria on Gram-positive or Gram-negative bacteria.

In the study of Sharma et al. (2022) results of the biosynthesis of safe and inexpensive AgNPs by different probiotic strains such as *Lactobacillus plantarum* F22, *L. paraplantarum* KM1, *L. pentosus* S6, and *L. crustorum* F11 are presented. The effectiveness the obtained AgNPs to inhibit the growth of various bacterial and fungal pathogens, namely *Bacillus cereus, Listeria monocytogenes*, antibiotic-resistant *Staphylococcus aureus*, *Pythium aphanidermatum, Pythium parasitica* та *Fusarium oxysporum* has been shown. Among them, AgNPs, synthesized by *Lactobacillus crustorum* F11, showed strong inhibition against all pathogens, with maximum activity against *Staphylococcus aureus* and *Fusarium oxysporum* with inhibition zones 20±0.61 mm and 23±0.37, respectively (Sharma et al., 2012).

Ability of metal nanoparticles to suppress different strains of bacteria, yeasts, and molds, as it is shown in Table 8, could find application in medicine, veterinary, pharmaceuticals, plant pathogen control, cosmetics, and manufacturing of food packing materials.

Practical use of metal nanoparticles

An analysis of modern literature confirms the fact of significant progress in nanotechnology over the past two decades, which is reflected in the intensive growth of scientific research and the discovery of numerous methods for the development and use of metal NPs in various industries, in particular in medicine, pharmacy, biology, food and textile industries, agriculture and electronics (Rana et al., 2020).

AgNPs play a special role in modern anticancer therapy and are being explored for detection and diagnosis of malignant tumors (Pothipor, 2019), controlled and external drug delivery systems (Karuppaiah et al., 2020; Nigam et al., 2017). Nanosilver-based compounds are used as antimicrobial agents because they have the ability to penetrate biological membranes and exert local or systemic effects, thus being used for a variety of treatments, including dental and digestive pathologies, wound healing and burns (Mohler et al., 2018; Sim et al., 2018). Nanosilver-based compositions have proven effective therapeutic effects against several pathologies caused by clinically significant viruses, such as severe acute respiratory syndrome, SARS-CoV-2 (Balagna et al., 2020; Tremiliosi et al., 2020), papillomavirus (Rajawat and Malik, 2019), rotavirus (Adebayo-Tayo et al., 2019; Zhang et al., 2017) and other enteric viruses (Castro-Mayorga et al., 2017; Sofy et al., 2019).

SeNPs can be used for a wide range of targets. In particular, SeNPs have been found to have great potential in the treatment of diabetes and Alzheimer's disease, oxidative stress, inflammatory diseases such as rheumatoid arthritis, anti-tumor therapy, and serve as a protector against toxic substances, including heavy metals (Ferro, 2021; Khurana, 2015; Rehman et al., 2021). The possible development of dressings based on SeNPs to accelerate the healing of infected wounds has also been reported (Fang, 2023), the development of food additives for humans and veterinary needs (Malyugina et al., 2021), systems for detecting viruses, such as test strips for detecting anti-SARS-CoV-2 IgM and IgG in human serum and blood (Chen et al., 2022; Wang et al., 2020). Currently, the production of cosmeceuticals and nanocosmeceuticals for the care of skin, hair, nails and lips and protection against wrinkles, photoaging, hyperpigmentation, dandruff and hair damage with SeNPs is popular.

AuNPs. Based on a clinical study, gold nanoparticles have been shown to be useful for screening gastrointestinal tumors (Nejati et al., 2022). AuNPs are used for drug delivery, where light irradiation can trigger drug release at the target site (Tian et al., 2016). AuNPs

may also be useful for virus detection programs (Draz and Shafiee, 2018) as they have demonstrated antiviral activity against several viruses, such as hepatitis B virus, human papillomavirus, human rhinovirus, and even SARS-CoV-2 (Mehranfar and Izadyar, 2020).

Fe_3O_4 NPs explore biomedical approaches including magnetic resonance imaging, drug delivery, and hyperthermia therapy (Dadfar et al., 2019). Thus, Fe_3O_4 NPs are successfully used to coat optical instruments for solar energy (Tiquia-Arashiro and Rodrigues, 2016), in clinics as contrast agents for magnetic resonance imaging. Iron oxide nanoparticles have the dual ability to act as magnetic and photothermal agents in cancer therapy (Espinosa et al., 2016).

TiO_2 NPs and **ZnO NPs** have chemical stability, environmental properties and non-toxicity, and can be produced relatively cheaply. They are used in a variety of photochemistry applications, ranging from large-scale products to more complex programs. For example, in the case of environmental remediation, they have been used in water photoelectrolysis and dye-sensitive solar cells (El-Dafrawy et al., 2016). TiO_2NPs and ZnONPs also find application as UV filters in cosmetic products such as moisturizers, hair care products, makeup accessories, and sunscreens (Hameed et al., 2019).

CoO NPs as many other metal nanoparticles, such as AgNPs, MgO and TiO_2 NPs, are found application in dentistry due to their biophysicochemical functionalization, antimicrobial activity, and biocompatibility (Xu et al., 2022); in agriculture for protecting crops against pests and diseases and for delivery and controlled release of agrochemicals (pesticides and fertilizers) (Fincheira et al., 2023); in textile production, in wastewater treatment as a disinfectant, and can be used in solar energy conversion devices and electrochemical sensors (Woźniak-Budych et al., 2023).

MgO NPs are finding increasing attention for their application in medical and optical devices, drug delivery, antibacterial materials, toxic waste remediation, and manufacturing of petrochemical products. Due to their antibacterial, antifungal, anticancer, antidiabetic, and antioxidant abilities, biogenic MgONPs can be effectively used in biomedicine (Thakur et al., 2022).

Therefore, metal nanoparticles are widely used in various fields of human activity. Some areas of use of metal nanoparticles synthesized by lactic acid bacteria are presented in Table 9.

Table 9

Practical application of metal nanoparticles synthesied by lactic acid bacterium

NPs	Microorganisms	Practical application	Reference
AgNPs	*Lactobacillus plantarum* TA4 *Lactobacillus rhamnosus* MTCC-1423 *Lactobacillus crustorum* F11	Dressing components (Acticoat™, SilvaSorb™ Gel), catheter coating (SilverSoaker™ Catheter, Silverline® Drainage Catheters), targeted drug delivery vehicles, antimicrobial and antiviral agents	Awadelkareem et al., 2023; Gherasim et al., 2020; Yusof et al., 2020a

NPs	Microorganisms	Practical application	Reference
SeNPs	*Lactobacillus casei* ATCC 393 *Lactobacillus paracasei* HM1 *Lactobacillus paracasei* SCFF20	Packaging materials for food products, components of cosmetics, dietary supplements, food products, veterinary drugs, antioxidant, anti-inflammatory, antimicrobial agents	El-Saadony, 2021a; Hu, 2023; Xu, 2018
AuNPs	*Lactobacillus kimchicus* DCY51 *Lactobacillus acidophilus* USTCMS 1053 *Lactobacillus paracasei*	Anticancer therapy, targeted drug delivery, MRI contrast agents, antiviral agents	Markus, 2016; Miran and Ali, 2024; Repotente, 2022
Fe_3O_4 NPs	*Lactobacillus casei* PTCC 1608 *Lactobacillus fermentum* PTCC 1638	Coating optical instruments for solar energy	Fani et al., 2018; Torabian et al., 2018
ZnO NPs	*Lactobacillus plantarum* TA4 *Lactobacillus johnsonii*	Anticancer drugs, components of cosmetic products, targeted drug delivery vehicles, antimicrobial agents	Al-Zahrani et al., 2018 ; Yusof et al., 2020b
TiO_2 NPs	*Leuconostoc mesenteroides* subsp. *mesenteroides*	In photochemistry, components of cosmetics, antimicrobial agents	Hasan et al., 2023

Conclusions

Having carried out a detailed analysis of scientific literature for the period 2013-2024, it can be stated that there is a current permanently increasing interest in research and development in the field of production of metal nanoparticles by lactic acid bacteria using their biomass, cell lysate or free-cell supernatant. Lactic acid bacteria attract the attention of researchers as biosafe producers that make it possible to use for production of various metal nanoparticles in a relatively cheap process.

An assessment of data on the inhibitory effect of AgNPs synthesized by LABs on the growth of Gram-positive and Gram-negative bacteria showed the absence of significant differences in the sizes of inhibition zones of various representatives of both groups.

During the biosynthesis, intracellular or external accumulation of nanoparticles occurs, which in turn have different sizes, shapes and properties. Antimicrobial abilities of nanoparticles synthesized by lactic acid bacteria can find applications in many areas of human activity.

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Анотації

Економіка і управління

Ставлення чеського населення до маркування ГМО

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Вступ. Дебати навколо маркування генетично модифікованих організмів (ГМО) значною мірою пов'язані з потребою маркування та розумінням різних причин, які стоять за підтримкою або неприйняттям такого маркування.

Матеріали і методи. Досліджуються фактори, що впливають на ставлення до маркування ГМО, на основі репрезентативної вибірки чеського населення (N=884). Також досліджувався вплив інформації про генетично модифіковані харчові продукти (GMF), проблеми навколишнього середовища, передбачуваний вплив на здоров'я, харчові звички, фактори, які вважаються важливими під час купівлі. Для того, щоб визначити, як соціально-демографічні характеристики впливають на переваги маркування ГМО, застосовано порядковий регресійній аналіз.

Результати і обговорення. Майже третина респондентів не знайомі з GMF. Ще третина підтверджують, що вони знайомі з GMF, але не знають, що це означає. Майже вісімдесят відсотків респондентів не виявляють інтересу до GMF. З іншого боку, занепокоєння здоров'ям і рівень інтересу та інформації про ГМО значною мірою передбачають схильність респондентів перевіряти етикетки ГМО та знати вимоги до маркування продуктів із ГМО.

Поточний суб'єктивний стан здоров'я не був пов'язаний зі ставленням до маркування ГМО.

Необхідність маркування та схильність перевіряти етикетки респонденти мотивували такими чинниками, як суб'єктивний вплив виробництва харчових продуктів на навколишнє середовище і поточна екологічно свідома поведінка (переробка й управління екологічними відходами вдома). Крім того, індивідуальні харчові звички, наприклад покупки, впливають на суб'єктивну частку ГМО-продуктів, які респондент споживає.

Висновок. Це дослідження сприяє розумінню багатогранної динаміки, що лежить в основі ставлення громадськості до маркування ГМО, і дає цінну інформацію для політиків і зацікавлених сторін у поточних дебатах щодо генетично модифікованих продуктів.

Ключові слова: *ГМО, харчування, маркування, Чехія, харчовий профіль, білок.*

Процеси і обладнання

Моделювання процесу терморадіаційно-конвективного сушіння продуктів рослинного походження

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Вступ. Метою дослідження є розроблення основ моделювання процесів одночасного впливу терморадіації та конвекції при сушінні продуктів рослинної сировини.

Матеріали і методи. Матеріалом для сушіння обрано культивовані гриби, глід звичайний, зимові сорти яблук та яблучні снеки. Сушіння здійснюється в імпульсному режимі нагрів-охолодження, при цьому конвективний підігрів повітря забезпечується в конденсаторі теплового насоса, а терморадіаційний підігрів – радіаційно-інфрачервоними випромінювачами до заданої температури з довжиною хвилі в діапазоні 1,2–4 мкм зі щільністю потоку 8 кВт/м^2.

Результати і обговорення. Моделювання терморадіаційно-конвективного сушіння культивованих грибів здійснювали при зменшенні вологовмісту від 809 до 30% протягом 80 хв, а для глоду вологовміст зменшувався від 330 до 38% за 60 хв. Тривалість висушування яблучних снеків – 70 хв. Це на 10 хв більше порівняно з яблуками, що пов'язано з вмістом цукру в снеках і осмотичними властивостями цукру утримувати вологу.

Згідно з розробленою математичною моделлю процесу сушіння розрахована дифузійна здатність вологи, яка найбільша серед досліджуваних продуктів для культивованих грибів ($9{,}58\times10^{-4}$ м^2/с). Такий показник пояснюються найменшою щільністю (750 кг/м^3) і найбільшою пористістю гриба, що призводить до глибшого проникання інфрачервоного випромінювання з коефіцієнтом термодифузії $1{,}011\times10^{-3}$ 1/К. Коефіцієнт дифузії вологи для глоду становить $6{,}8\times10^{-7}$ м^2/с при щільності 1173,4 кг/м^3 Коефіцієнт термодифузії $0{,}51\times10^{-2}$ 1/К пояснюється тим, що плоди глоду кулястої форми і закладалися в сушарку насипом. Яблука і яблучні снеки при закладання в сушарку нарізались дольками 4–6 мм. Коефіцієнт дифузії вологи для яблук становить $8{,}48\times10^{-5}$ м^2/с при щільності 880 кг/м^3, коефіцієнт термодифузії – $3{,}096\times10^{-5}$ 1/К. Отримання яблучних снеків здійснювали шляхом бланшування долько яблук у цукровому сиропі перед сушкою, що призводило до зменшення коефіцієнта дифузії вологи до $8{,}28\times10^{-6}$ м^2/с, зростанні щільності до 965 кг/м^3, коефіцієнта термодифузії – до $4{,}06\times10^{-2}$ 1/К, якщо порівняти з дольками яблук.

Моделювання взаємодії конвективного і терморадіаційного енергопідведення в імпульсному режимі дає змогу забезпечити максимальний технологічний ефект.

Висновки. Математична модель терморадіаційно-конвективного сушіння дає змогу в аналітичній формі відображати основні риси одночасного впливу конвективного й терморадіаційного енергопідведення при сушінні високовологих матеріалів.

Ключові слова: *сушіння, математична модель, моделювання, культивовані гриби, глід, яблука.*

Харчові технології

Зміна хімічного складу екстрактів дикорослих ягід, що ростуть в Азербайджанській Республіці, внаслідок попереднього ферментативного оброблення їх м'якоті

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Вступ. Мета дослідження – визначити вплив ферментативної обробки м’якоті ягід кизилу, бузини, глоду, барбарису, малини на вміст у їх екстрактах аскорбінової кислоти, цукрів, поліфенолів і важких металів.

Матеріали і методи. Обробку ягід проводили ферментними препаратами пектолітичної та гліколітичної дії. Ідентифікацію біологічно активних компонентів у екстрактах проводили за допомогою високоефективної рідинної хроматографії з ультрафіолетовою та мас-спектрометричною детекцією.

Результати і обговорення. Застосування ферментних препаратів підвищило вихід соку з м’якоті ягід. Оптимальний віджим соку був досягнутий після 120-хвилинного періоду бродіння ягід барбарису і кизилу. Для бузини й малини оптимальні терміни становили 75 і 90 хв відповідно. Температура обробки 45 °С виявилася найбільш прийнятною для більшості ягід, за винятком барбарису, який показав кращі результати при температурі 60 °С. Застосування як окремих ферментних препаратів, так і їх комплексів позитивно вплинуло на вихід соку з усіх досліджуваних ягід. Для кизилу та глоду найефективнішою виявилася комбінація «Пектинекс BE XXL» та «Фруктосим П», а для бузини, барбарису та малини – «Амілаза АГ 300Л» та «Селлолюкс-А».

У соках, отриманих з ягід після ферментативної обробки, спостерігалося підвищення концентрації аскорбінової кислоти та цукрів. Ферментативна обробка призвела до значного підвищення загальної концентрації поліфенолів, а також вмісту окремих компонентів. Значне підвищення вмісту галової кислоти після ферментативної обробки спостерігалося в усіх пробах, де вона була виявлена. Виняток становили кумарини, концентрація яких після ферментативної обробки знижувалася.

Ферментні препарати в цілому позитивно впливають на вміст біологічно активних речовин у соках лісових ягід. Однак значного підвищення концентрації важких металів не спостерігалося. У більшості випадків найбільший позитивний ефект продемонструвало застосування мультиферментних комплексів.

Висновки. Отримані результати мають велике значення для технології переробки досліджуваних ягід, що свідчить про перспективність ферментативної мацерації для підвищення вмісту біологічно активних речовин у їх соку.

Ключові слова: *дикі ягоди, мацерація, рідинна хроматографія, аскорбінова кислота, поліфеноли, важкі метали, цукри.*

Біоактивні сполуки і потенційне застосування *алое вера* (L.) в харчовій промисловості

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Вступ. Мета огляду – охарактеризувати біологічно активні сполуки, які містяться в алое вера, і розглянути можливості його застосування в харчовій промисловості.

Матеріали і методи. Збір даних передбачав пошук у кількох базах, зокрема Google Scholar, ScienceDirect, PubMed, SpringerLink і Wiley Online Library. Пошукові запити охоплювали широкий діапазон термінів, таких як біоактивна сполука; алое вера; потенційне застосування алое вера в харчовій промисловості; протизапальні, антиоксидантні, антибактеріальні, протигрибкові, противірусні та антисептичні властивості біоактивних сполук алое вера.

Результати і обговорення. Алое вера багате різними компонентами, включаючи полісахариди (55%), цукри (17%), мінерали (16%), білки (7%), ліпіди (4%) і фенольні сполуки (1%). Ця рослина містить численні біологічно активні сполуки, такі як флавоноїди, фенолкарбонові кислоти, дубильні речовини, моно- і полісахариди (маннозо-6-фосфат, ацеманнан і глюкоманнан), поліфеноли, кумарин, проантоціанідин, алкалоїди, похідні антрахінону, алое-емодін, алоїн, алоезин, сапонін, хромони, β-каротин, вітамін С, вітамін Е, фермент брадикіназа, стероїди, що робить його цінною фармацевтичною і косметичною сировиною. Алое вера демонструє різноманітні переваги для здоров'я, оскільки має пом'якшувальні, протизапальні, антиоксидантні, протимікробні, протиглистні, протигрибкові та антисептичні властивості. Залежно від мети використання листя алое вера може бути оброблене цілим, шляхом механічного або ручного оброблення м'якоті для отримання гелю. Після цього гель можна використовувати для виробництва соків, концентратів і порошкоподібних продуктів.

Продукти з алое вера є натуральними функціональними інгредієнтами або добавками для збагачення харчових продуктів з рослинних джерел для покращення якості їжі, продовження терміну зберігання овочів і фруктів, покращення прийнятності їжі, посилення росту пробіотичних культур, а також можуть бути використані у фармацевтичній та косметичній промисловості. Основні сфери застосування алое вера в харчовій промисловості – виробництво харчових покриттів, консервування фруктів, напоїв, перероблення молочних, кондитерських виробів і продуктів спортивного харчування.

Висновок. Продукти з алое вера та його біологічно активні сполуки позитивно впливають на здоров'я людини, подовжують термін зберігання овочів і фруктів, посилюють ріст пробіотичних культур. Під час використання продуктів з алое віра варто дотримуватися основ харчової безпеки.

Ключові слова: *алое вера (L.), біоактивний, харчова промисловість.*

Удосконалення технології енергетичних батончиків антианемічного спрямування

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Вступ. Розроблено багатокомпонентну рецептуру енергетичних батончиків антианемічного спрямування з покращеними споживними властивостями.

Матеріали і методи. У дослідженні використовували модельні системи на основі зерна та горіхів, сухофруктів, меду і дієтичних добавок заліза. Хімічний склад енергетичних батончиків аналізували методами колориметрії, рідинної хроматографії та газової хроматомас-спектрометрії. Мікробіологічне дослідження проводили за загальноприйнятими методиками. Сенсорний аналіз проводили за розробленою 10-бальною шкалою.

Результати і обговорення. Додавання 1,0–3,0% ДЗД до рецептурної суміші збільшує вміст заліза в 1,27–1,29 раза; інших мінералів – на 1,52±0,75%; вітамінів – на 1,36±0,41%; золи – в 1,37–1,39 раза; білка – в 1,16–1,18 раза; вуглеводів – на 0,53±0,02%; жиру – на (3,40±0,02)%; покращує структуру – в (1,06–1,08) раза, поверхню – в 1,10–1,12 раза, консистенцію – в 1,15–1,17 раза, загальний бал – в 1,07 раза; знижує вологовміст – в (1,12–1,14) раза, активність води – в (1,13–1,15) раза, рівень освітлення, L*, – в 1,11 та 1,28 раза відповідно; показник a* (ступінь почервоніння) – в 6,78 та 8,56 раза відповідно; показник b* (ступінь жовтизни) – в 2,14 та 3,16 разів відповідно.

Додавання 1,0–3,0% ДЗД збільшує твердість на 5,6–6,0%; адгезивність – на 1,86–2,76%; когезійність – на (2,89–3,71)%; пружність (стійкість) – на (1,54–2,30)%; показник розжовування – на 1,76–2,62% відповідно; зменшує еластичність на 1,86±0,21%. Оптимальна масова частка ДЗД – 3,0%.

Пригнічення мікробної контамінації поверхні дослідних зразків енергетичних батончиків відбувається при введенні 3,0% дієтичної залізовмісної добавки.

Висновки. Високий функціональний і технологічний потенціал БАД заліза надає можливість рекомендувати його як стабілізатор, структуроутворювач і покращувач кондитерських виробів.

Ключові слова: *енергетичний батончик, антианемічний, БАД, залізовмісний.*

Біотехнологія, мікробіологія

Молочнокислі бактерії для синтезу наночастинок металів

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Вступ. Наночастинки металів (НМ) широко використовуються в різних галузях наукової та практичної діяльності. Біогенні металеві наночастинки привертають увагу своїми унікальними властивостями та відносно низькою вартістю виробництва, а молочнокислі бактерії – як їх біобезпечні продуценти.

Матеріали і методи. Було проведено аналіз наукової інформації щодо біосинтезу металевих наночастинок молочнокислими бактеріями та їх антимікробних властивостей.

Результати і обговорення. Для біосинтезу наночастинок важливим є вибір екологічного біологічного агента; солі металу, що слугуватиме попередником біосинтезу; нетоксичного матеріалу як покриваючого агента для стабілізації синтезованих наночастинок, факторів, що забезпечують оптимальні умови їх утворення, зокрема pH, температури, тиску, тривалості процесу, наявності перемішування, концентрації біологічного агента, концентрація солі-попередника, світла.

Молочнокислі бактерії належать до групи мікроорганізмів RG1 (біологічно безпечні) згідно з Директивою Європейського Союзу, тому вони привертають увагу як біобезпечні продуценти різних металевих наночастинок у відносно недорогому та доступному процесі біосинтезу НМ. Показана можливість використання молочнокислих бактерій у формі біомаси, клітинного лізату або безклітинному супернатанту (фільтрату). Всі синтезовані металеві наночастинки виявляють високу антимікробну активність проти патогенних штамів бактерій, що дуже важливо для практичного застосування НМ, особливо в умовах поширеного явища резистентності мікроорганізмів до антибіотиків. Також важливо, що наночастинки металів мають неспецифічну бактеріальну токсичність, що ускладнює виникнення стійких штамів до їх дії. Наночастинки металів, що синтезуються молочнокислими бактеріями, ефективні проти багатьох стійких до антибіотиків штамів бактерій, зокрема *Staphylococcus aureus, S. epidermidis, Streptococcus pyogenes, Klebsiella pneumoniae* and *Salmonella typhi*, а також проти грибів і дріжджів. Показано статистично доведену відсутність значних відмінностей в інгібуючій дії наночасток срібла, що синтезуються молочнокислими бактеріями, на грампозитивні та грамнегативні бактерії.

Висновок. Молочнокислі бактерії можуть слугувати біобезпечними продуцентами наночастинок різних металів, що мають сильні антимікробні властивості.

Ключові слова: *молочнокисла бактерія, наночастинка, метал, антимікробний.*

Instructions for authors

Dear colleagues!

The Editorial Board of scientific periodical
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A manuscript should describe the research work that has not been published before and is not under consideration for publication anywhere else. Submission of the manuscript implies that its publication has been approved by all co-authors as well as by the responsible authorities at the institute where the work has been carried out.

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Abstract. The **abstract** should contain the following mandatory parts:

Introduction provides a rationale for the study (2–3 lines).

Materials and methods briefly describe the materials and methods used in the study (3–5 lines).

Results and discussion describe the main findings (20–26 lines).

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Conclusions. The main conclusions should be drawn from results and be presented in a short Conclusions section.

Acknowledgments(if necessary)**.** Acknowledgments of people, grants, or funds should be placed in a separate section. List here those persons who provided help during the research. The names of funding organizations should be written in full.

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Мова статей – англійська.

Мінімальний обсяг статті – **10 сторінок** формату А4 (без врахування анотацій і списку літератури)**.**

Для всіх елементів статті шрифт – **Times New Roman**, кегль – **14**, інтервал – 1.

Всі поля сторінки – по 2 см.

Структура статті:

1**.** УДК**.**
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5. Анотація. **Обов'язкова** структура анотації:
   - Вступ (2–3 рядки).
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7. Основний текст статті. Має включати такі обов'язкові розділи:
   - Вступ
   - Матеріали та методи
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   - Висновки
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За необхідності можна додавати інші розділи та розбивати їх на підрозділи.

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Кількість авторів статті	Приклад цитування у тексті
1 автор	(Arych, 2019)
2 автора	(Kuievda and Bront, 2020)
3 і більше авторів	(Bazopol et al., 2022)

Приклад тексту із цитуванням: It is known (Arych, 2019; Bazopol et al., 2022), the product yield depends on temperature, but, there are some exceptions (Kuievda and Bront, 2020).
У цитуваннях необхідно вказувати одне джерело, звідки взято інформацію.
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Fordyce F.M. (2013), Selenium deficiency and toxicity in the environment. In: O. Selinus (Ed.), *Essentials of Medical Geology*, Springer, pp. 375–416, https://doi.org/10.14453/10.1007/978-94-007-4375-5_16

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