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DEVISING A PRODUCTION TECHNOLOGY AND ASSESSING THE QUALITY OF GLUTEN-FREE ENERGY BARS WITH A GELLED LAYER

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The object of this study is the production of energy bars. The subject of the research is the production technology of gluten-free functional energy bars with a gelled layer based on millet flour, fruit puree, and functional additives. The task addressed is to select optimal ratios of components, providing stable organoleptic and textural characteristics of the product while preserving functional properties and the possibility of industrial scaling.

In designing the research plan, special attention was given to selecting optimal ingredient ratios and processing parameters to achieve a stable and high-quality product.

The development of energy bars involved the use of the following ingredients: a blend of oat and millet flour, fruit purée (apple, pear, plum) with the addition of agar-agar, cinnamon, mint, and ginger. Recipe optimization was carried out using the Response Surface Methodology (RSM), which allows for the identification of the best ingredient ratios.

Sensory analysis revealed that the most appealing taste characteristics were observed in bars containing cinnamon and mint. These samples received the highest scores for aroma, flavor, and texture. The highest antioxidant activity levels were recorded in samples containing cinnamon and apple (up to 82.8%). This is attributed to the high content of phenolic compounds in cinnamon, known for their strong antioxidant properties. Optimal texture parameters were achieved with a layer height of 12 mm – ensuring a balanced structure, a syrup content of 5% – preventing excessive stickiness, and a protein content of 7% – improving product firmness and elasticity. The samples with mint and cinnamon exhibited the lowest water activity (aw=0.68 – 0.72), making them more resistant to microbial spoilage and extending their shelf life.

The application of multi-criteria analysis methods and statistical experimental design allowed for the identification of key parameters influencing product quality

Keywords: energy bars, functional food products, response surface methodology, fruit puree, antioxidant activity

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1. Introduction

Modern nutrition trends emphasize functional foods that provide not only nutritional value but also additional health benefits. Functional energy bars are one such product, combining convenience with high antioxidant content, balanced texture, and attractive appearance.

The rise in celiac disease requires an expanded range of gluten-free products. Modern consumers also have high demands on the quality and nutritional value of products, including their antioxidant properties, texture, and shelf stability. The devised technology could make it possible to create gluten-free products with improved sensory and textural characteristics. Optimized formulations would provide higher antioxidant activity, which could increase the beneficial properties of products. The study of water activity and storage conditions will help increase the shelf life of products without the use of artificial preservatives. Functional food products, including energy bars, are one of the most promising areas in the food industry. Their development is based on a scientifically sound selection of ingredients that provide not only nutritional value but also additional beneficial properties. Thus, research into the development of gluten-free energy bars with gelled fruit layers is relevant as it contributes to the creation of functional food products that meet modern requirements for healthy nutrition and food quality.

2. Literature review and problem statement

Study [1] showed that elderberry extract increases the antioxidant properties of products. However, the authors did not investigate the effect of elderberry on texture and color stability during storage.

A study of the use of black elderberry dyes to enrich antioxidants and improve the organoleptic properties of products, including bars, was reported. Addition of a new dye (a mixture of elderberry fruits and flowers) to the jelly obtained during the study made it possible to increase the level of water-soluble antioxidant fraction by 27%, and fat-soluble antioxidants by 25% compared to jelly with the addition of fruit dye [2]. The study was limited to the use of the dye in jelly candies, which does not allow the results to be applied to other products without additional research. The lack of data on the behavior of the dye under various processing and storage conditions, as well as its interaction with other components of food products, hinders its widespread use.

In [3, 4], the effect of a mixture of betacyanins and anthocyanins on the color and antioxidant activity of products was studied. However, their effect on textural characteristics remained unclear. These studies analyze the combined effects of these compounds with texture-forming components such as agar-agar and fruit fillings.

Papers [5–7] focus on the analysis of antioxidant activity using the DPPH method. An unresolved issue is the lack of studies on the dynamics of antioxidant activity over time [5] and [6] since they are limited to single measurements using the DPPH method. Antioxidant activity is a key property of functional products since it helps protect the body from oxidative stress. The DPPH (2,2-diphenyl-1-picrylhydrazyl) method is a standard method for assessing the antioxidant activity of products. The DPPH methodology is based on measuring the ability of samples to neutralize free radicals by changing their absorption in the ultraviolet spectrum. This method is widely used to analyze fruits and functional products, including bars [6]. Extracts of hibiscus, pitahaya peel, and elderberry have high antioxidant activity and are successfully used to improve the functional properties of products [7]. Although hibiscus, dragon fruit, and elderberry extracts have high antioxidant activity, there are no systematic studies comparing their stability, technological compatibility, and impact on the organoleptic properties of various food matrices, including functional bars. In addition, the dynamics of changes in the antioxidant activity of such extracts during storage and processing have not been studied.

The texture of products plays a key role in their consumer perception. Energy bars should have optimal hardness, stickiness, and fragility. The textural properties of fruit products depend on their formulation and processing. For example, the addition of ginger and cinnamon improves the texture, making it denser and less sticky [8]. The use of gels and dietary fiber makes it possible to achieve a balanced texture, especially in combination with natural spices. In [9], it was shown that the addition of ginger and cinnamon reduces stickiness and improves the texture of functional snacks. However, their interaction with gelling agents such as agar-agar and pectin, which is important for products with a gelled structure, has not been considered.

Water activity (a_w) is a determinant of product stability and shelf life. Low water activity (< 0.92) prevents the growth of pathogenic microorganisms and improves product shelf life [10]. The a_w level is adjusted by using ingredients with a high dry matter content, such as dried fruits and cereals. However, according to [11], a decrease in a_w can negatively affect the texture of products, making them excessively hard and brittle. In addition, most studies, including [10], focus only on the effect of aw on microbiological stability, while the effect of this parameter on organoleptic properties and textural characteristics remains poorly understood.

Color parameters play an important role in the attractiveness of a product to consumers. Natural colors are gaining popularity due to the trend for everything natural and healthy. Color parameters play an important role in the perception of product quality. Natural colors, including grape, elderberry, and hibiscus extracts, are gaining popularity amid the clean label and healthy eating trends [12, 13]. The effect of pH and ionic strength on the color stability of grape anthocyanin extract in a model environment was investigated in [12], but no testing was performed in a food matrix. The use of anthocyanin extracts in bars was studied in [13] but the effect of heat treatment temperature on pigment degradation was not considered. Thus, the effect of technological factors (temperature, drying, storage) on the stability of natural colors in functional products remains insufficiently studied.

The textural properties of functional foods depend on their composition and production technology. Study [14] showed that the addition of protein and fiber ingredients significantly affects the textural, physical and color properties of extruded snacks. However, the work did not consider the gelled structures and their behavior over time, and did not analyze the effect of water activity on product stability. In addition, the stability of texture and color largely depends on storage conditions and changes occurring in products during storage. Optimization of storage conditions prevents color loss and improves the antioxidant properties of products.

Statistical analysis methods such as RSM (response modeling) and ANOVA (analysis of variance) are key tools for formulation optimization. RSM makes it possible to model the effect of process parameters on the functional and nutritional properties of products, which is confirmed by study [15], in which this method was used to optimize the composition of vacuum-impregnated candied nutmeg peel. However, the work did not take into account the textural characteristics and stability of the product, which is an important aspect in the development of functional snacks.

Optimization of process parameters is an important step in the development of functional products. In study [16], optimization of hydrothermal treatment of mogar grain was carried out to improve its nutritional and textural characteristics. However, the work did not consider the interactions of multicomponent systems with antioxidants, as well as the effect of water activity on product stability.

Our review of the literature [1–15] demonstrates that the development of gluten-free energy bars with natural components is a promising direction in the food industry. The cited publications over the last 5–10 years (Scopus, Web of Science, ScienceDirect) make it possible to highlight several key aspects, such as the use of natural sweeteners, the use of superfoods, gluten-free cereals, focusing on a low glycemic level and hypo allergenicity.

Thus, the main problem is the insufficient development of a comprehensive approach to the development of a gluten-free energy bar recipe, taking into account the influence of technological parameters, antioxidant activity, water activity, and organoleptic properties. Our study is aimed at eliminating this gap and devising a scientifically based production technology.

3. The aim and objectives of the study

The aim of our study is to devise a technology for producing a gluten-free energy bar with improved organoleptic characteristics and increased nutritional value due to the use of natural ingredients such as millet and fruit puree. This will create a functional product that meets modern requirements for healthy eating.

To achieve this goal, it is necessary to solve the following tasks:

– to determine the optimal ratios of ingredients and technological parameters of the recipe for energy bars with a gelled layer that ensure stable organoleptic and textural characteristics of the finished product.

– to study the antioxidant activity of the developed samples using the DPPH method;

– to evaluate the textural properties of the samples, including hardness, stickiness, gel strength, and fragility;

– to measure the level of water activity (a_w) and determine its effect on the stability and shelf life of the bars;

– to study the color characteristics of the samples using spectrophotometric methods.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the production of energy bars. The hypothesis of the study assumed that optimization of the ratios of cereals, fruit puree, spices, and texture-forming components makes it possible to obtain functional bars with high organoleptic and textural characteristics that are stable during storage.

The following assumptions and simplifications were adopted. Consumer preferences are determined based on the results of an organoleptic assessment by an expert group. The influence of technological factors not related to the recipe (e.g., packaging, external environment) is not considered in this study. All ingredients are introduced into the recipe in acceptable food quantities and do not have a toxicological or sensory negative effect. The assessment of the optimality of the recipe is based on the desirability model, which adequately reflects the complex consumer response to a set of parameters (taste, texture, structure, and stability).

To design functional energy bars, ingredients were selected that take into account the functional focus and consumer preferences.

The bars are based on millet and oats, which provide the product with high nutritional value. To enhance the functional properties, the following were added:

– fruits: plum, pear, apple;

– spices: cinnamon, ginger, mint;

– structure formers: agar-agar, which ensures texture stability.

4. 2. Experimental planning matrix

A planning matrix based on preliminary exploratory experiments was used to optimize the recipes. The experiment was conducted using the matrix, which made it possible to study the interaction of components and their effect on the properties of the product. The analysis and processing of the experimental data was performed using the ANOVA and RSM methods. Data planning and treatment were performed using the software Statistica 12.0 (USA).

To study the effect of process parameters on the quality of gluten-free energy bars, the following key variables were selected:

– agar-agar content (ag, %);

– lemon juice content (Ls, %);

– cooking time (t, min).

Each of the factors was varied at three levels (–1, 0, +1) in accordance with the experimental plan (Table 1). The purpose of the experiment was to determine the optimal parameters affecting the desirability of the final product.

Table 1

Effect of variables on product desirability

Factor	Level –1	Level 0	Level +1
Agar-agar (*ag*, %)	1.5	2.5	3.5
Lemon juice (*Ls*, %)	5.0	10.0	15.0
Cooking time (*t*, min)	3	5	7

Additionally, technological parameters such as the height of the bar layer, the content of syrup and protein components were studied and varied to find the optimal composition of the product. These parameters are given in Table 2.

Table 2

Levels of variance in technological parameters

Factor	Level –1	Level 0	Level +1
Layer height (mm)	8	12	16
Syrup content (%)	3	5	7
Protein content (%)	5	7	9
Cooking time (min)	3	5	7

A multi-criteria optimization method using the Response Surface Methodology (RSM) was used to determine the influence of variables. The desirability of the product was assessed based on analyses of textural characteristics, antioxidant activity, water activity, and organoleptic assessment.

4. 3. Organoleptic evaluation

At the first stage of the experiment, a selection of experimental samples was carried out based on the organoleptic evaluation. For this purpose, the products were tasted by an expert group. The evaluation was carried out on a five-point scale (taste, texture, color, aroma, general appearance). Based on the results of the organoleptic evaluation, 8 optimal samples were selected for further research.

Optimization of the energy bar recipe was carried out using multivariate analysis and calculation of the general desirability function, which makes it possible to take into account several target quality indicators at the same time – texture, stability, color, and water activity. Within the framework of the experiment, the following technological parameters were varied: layer height (*h*), syrup content (*s*), protein content (*p*), as well as auxiliary components – agar-agar, lemon juice, and cooking time. Optimal conditions were determined on the basis of mathematical models built based on the results of the experiment.

4. 4. Antioxidant activity

The DPPH method was used to evaluate the antioxidant activity: 10 g of each sample was dissolved in 80 ml of distilled water, infused for 20 minutes, and filtered. The DPPH solution was mixed with the sample filtrates and incubated for 1 hour. Absorption at 517 nm was measured, and percent inhibition was calculated.

4. 5. Textural properties

Texture analysis was performed using a texture analyzer.

Hardness: the force required to break the product was measured.

Stickiness and brittleness: adhesion and mechanical deformation forces were assessed.

4. 6. Color characteristics

The color parameters were studied using a spectrophotometer:

Measurements were made in the Lab color space (*L* – lightness, *a* – green-red spectrum, *b* – blue-yellow spectrum).

Spectral reflectivity in the range of 400–700 nm was additionally analyzed.

Equipment:

– UV-Vis spectrophotometer for antioxidant activity analysis;

– TA.XT Plus texture analyzer;

– AquaLab water activity analyzer.

Our product was based on millet and oats, which provide the product with high nutritional value, richness in fiber, and shelf stability.

5. Results of the study on devising an energy bar technology

5. 1. Determining the optimal ratio of ingredients and technological parameters of the energy bar recipe

The energy bar consists of two parts – a cereal base and a jelly layer. The differences are that the base was the same (a mixture of millet and oats), and the layer (different fruit puree (plum, pear or apple), agar-agar, lemon juice). During the organoleptic evaluation, 8 samples were selected that received the highest scores according to the following criteria:

– taste: balanced sweetness and rich aroma;

– texture: optimal combination of softness and bone crunch;

– appearance: attractive color and shape.

Samples with the addition of cinnamon and mint received the highest scores due to their harmonious taste profile. The combination of pear and cinnamon was found to be the preferred texture, providing moderate density and low stickiness. Parameters and modes were also investigated to obtain the preferred taste and overall sensory evaluation. Fig. 1 shows the desirability profiles for the energy bar base.

The plot (Fig. 1) shows the profiles for the predicted values and desirability of various bar recipe parameters:

– *h* (layer height, mm): Minimum desirability is observed as the layer height increases above 12 mm. This indicates that a lower layer height is preferred for stability and textural characteristics;

– *s* (syrup percentage): Desirability is highest at 5% syrup. Higher levels result in decreased desirability, likely due to excess stickiness or sweetness;

– *p* (protein percentage): Maximum desirability is achieved at 7% protein. Lower or higher protein levels reduce functionality or texture of the product.

The overall desirability of the product, according to the model, is highest at 12 mm layer height, 5% syrup, and 7% protein.

The plots (Fig. 2) confirm the optimality of the proposed recipe for obtaining a product with the best functionality and organoleptic characteristics. The data visualize the interactions of factors and their impact on the final product, which emphasizes the need for strict control of these parameters during production.

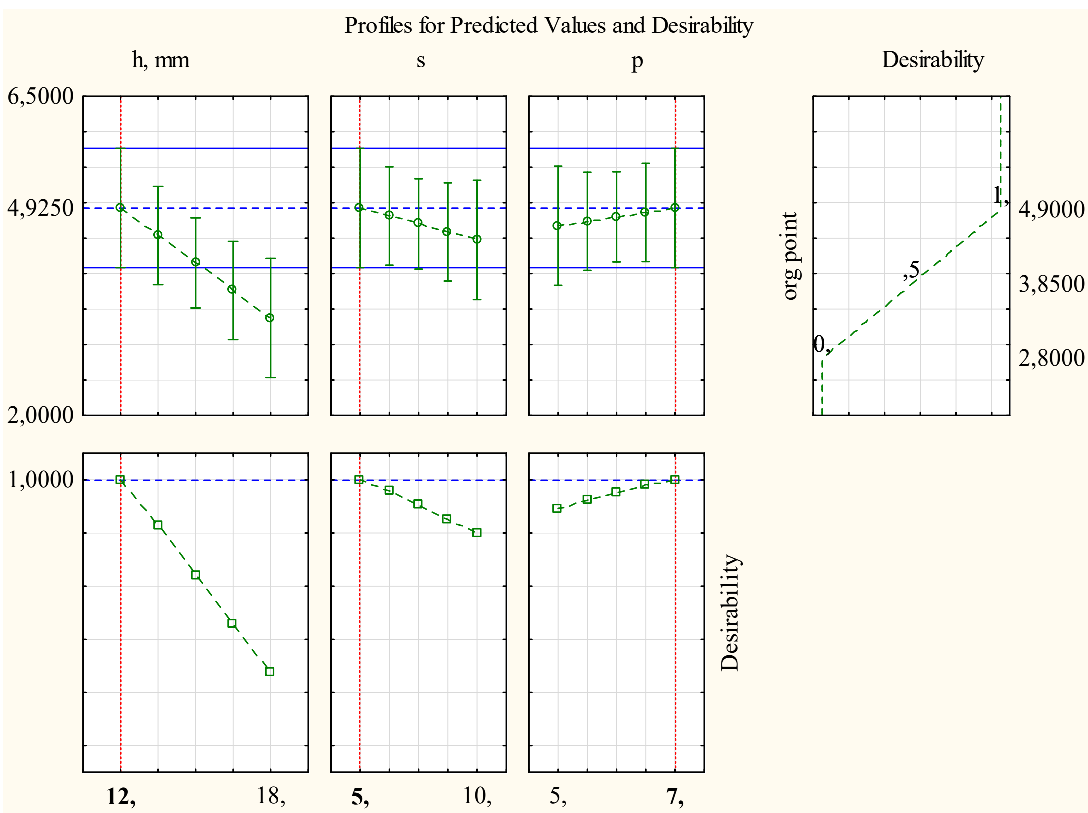

Fig. 1. Predicted value and desirability profiles for energy bar cereal base

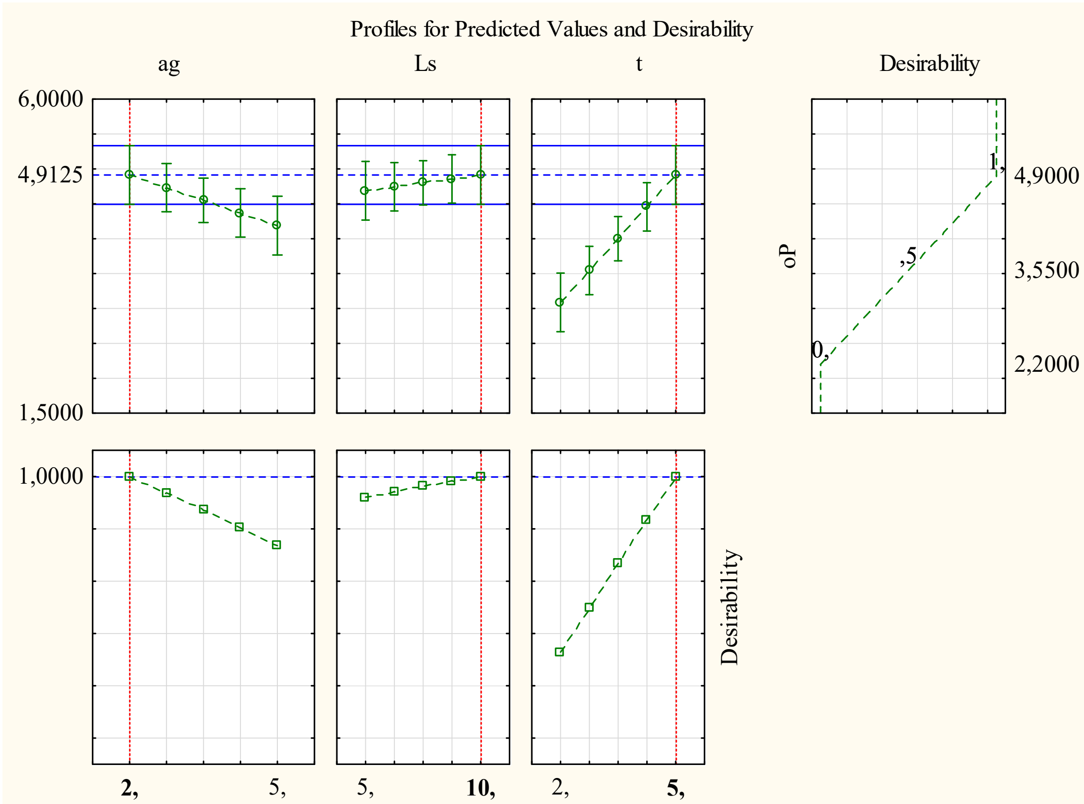

Fig. 2. Predicted value and desirability profiles for fruit interlayer

The plot above shows the predicted values and desirability profiles for the fruit layer. The effects of the variables agar-agar (*ag*), lemon juice (*Ls*), and cooking time (*t*) on the desirability of the product were considered.

Agar-agar (ag). The following ranges are desirable for this ingredient: 2–5%. Desirability is highest at 2% agar-agar. Increasing the concentration above 2% reduces desirability, probably due to excess density or excessive gelation of the layer.

Maximum desirability is achieved at 10% lemon juice. Reducing the lemon juice content below 10% leads to a deterioration in texture and a decrease in acidity, which may negatively affect the organoleptic properties.

Desirability increases with increasing cooking time and reaches a maximum at 5 minutes. This is due to a more stable structure and uniform distribution of ingredients during prolonged heating. The overall desirability of the product increases with the combination of parameters: agar-agar – 2%, lemon juice – 10% and cooking time – 5 minutes.

The best result is achieved due to the optimal texture, acidity, and stability of the fruit layer.

Thus, the optimal recipe for the fruit layer is: 2% agar-agar, 10% lemon juice, 5 minutes of cooking. This combination provides a balanced texture, attractive taste, and shelf stability. The selected parameters are easily adapted to large-scale production, improving the quality and perception of the product. In this case, the basis is fruit puree. Fig. 3 shows samples of energy bars.

Fig. 3 shows the experimental samples of energy bars created within the framework of our study. Each group of bars has a unique composition, which was developed to evaluate functional and organoleptic characteristics, such as texture, color, antioxidant activity and water activity. The color palette of the samples reflects the differences in the recipe, caused by the use of natural ingredients, such as fruits and spices, and confirms their high consumer appeal.

Fig. 3. Energy bar samples

Organoleptic evaluation showed that the highest marks were given to samples with the addition of cinnamon and mint. These samples were characterized by a pronounced aroma, pleasant sweetness, and balanced texture. The experts noted that the combination of fruit puree with agar-agar provided an optimal consistency, preventing excessive stickiness.

5. 2. Results of determining the antioxidant activity

The antioxidant activity of the studied samples was assessed by the DPPH method, and the results showed significant differences between the different formulations (Table 3).

The DPPH method made it possible to determine the level of antioxidant activity of different samples. The maximum value was recorded for Apple/Cinnamon (82.8%), which is due to the high content of phenolic compounds in cinnamon. The Apple/Mint (64.6%) and Pear (51.8%) samples also showed high activity rates, confirming the role of fruits and spices in increasing antioxidant potential.

Table 3

DPPH inhibition results, %

Sample	Mean % of DPPH inhibition	Activity category
Apple/Cinnamon	82.8%	Very high
Apple/Mint	64.6%	High
Pear	51.8%	Moderate
Pear/Cinnamon	36.3%	Average
Plum	16.4%	Low
Apple	16.5%	Low
Plum/Ginger	21.6%	Low
Apple/Ginger	13.0%	Very low

5. 3. Results of the evaluation of textural properties

The most important indicators of the texture of the studied samples are hardness, stickiness, gel strength, and brittleness. These parameters determine the organoleptic perception of the product and its behavior during chewing. The results of the texture tests are given in Table 4.

As can be seen from Table 4, the densest sample is Plum/Ginger (449.06 g), the softest was Apple/Ginger (119.86 g).

The sample with the least stickiness is Apple/Cinnamon (–8.22 g), the stickiest is Plum/Ginger (–19.58 g).

The maximum gel strength is for Plum/Ginger (80.964.9 g), and the minimum is for Plum (11.719.1 g). The most fragile samples are Pear/Cinnamon (7.61 mm) and Plum/Ginger (7.47 mm). The least fragile was Apple/Cinnamon (3.01 mm).

Texture measurements revealed that:

– the hardness was highest for the Plum/Ginger sample (449.06 g) and lowest for the Apple/Ginger (119.86 g);

– the stickiness was lowest for the Apple/Cinnamon (-8.22 g), making it the most convenient to consume;

– the jelly strength was highest for the Plum/Ginger (80,964.9 g), indicating increased texture stability.

5. 4. Results of water activity measurement

Water activity (a_w) is an important parameter determining the stability, microbiological safety, and shelf life of energy bars. During the experiment, a_w values were measured for various samples taking into account their recipe features and storage temperature. The data (Table 5) make it possible to select samples with better stability and determine the need for further preservation.

Table 5

Water activity and temperature of the samples under study

Sample	Water activity (a_w)	Temperature (t, °C)
Plum/ginger	0.85	23.3
Apple/cinnamon	0.97	22.1
Apple/ginger	0.83	22.5
Apple	0.95	23.3
Pear	0.90	23.8
Apple/mint	0.68	24.3
Pear/cinnamon	0.72	23.9
Plum	0.81	24.0

As can be seen from Table 5, the most stable samples are Apple/Mint ($a_w = 0.68$) and Pear/Cinnamon ($a_w = 0.72$) which showed low water activity, making them resistant to microbiological growth and suitable for long-term storage.

Plum/Ginger, Apple/Ginger, and Plum showed a_w values in the range of 0.81–0.85, indicating sufficient stability while requiring further evaluation for long-term storage.

Apple/Cinnamon ($a_w = 0.97$) has high water activity, which may increase the risk of microbiological growth. Additional preservation methods, such as reducing humidity or adding stabilizing ingredients, are recommended.

All samples were measured at temperatures in the range of 22.1–24.3°C, which corresponds to standard storage conditions.

Therefore, the following practical recommendations can be given.

To improve the stability of samples with high water activity ($a_w > 0.95$), it is advisable to increase the dry matter content (e.g., millet or oats) and implement barrier technologies to protect against moisture.

Samples with low activity ($a_w < 0.82$) can be used for long-term storage products without the use of additional preservatives.

These results emphasize the need to optimize formulations depending on the requirements for shelf life and storage conditions.

Table 4

Results of texture studies

Sample	Hardness (g)	S.D. (r)	C.V. (%)	Stickiness (g)	S.D. (r)	C.V. (%)	Gel strength (g)	S.D. (r)	C.V. (%)	Brittleness (mm)	Stickiness (g·sec)
Plum	300.18	0.00	0.00	–5.22	0.00	0.00	11,719.1	20,337.4	173.54	4.50	–523.79
Plum/Ginger	449.06	0.00	0.00	–19.58	0.00	0.00	80,964.9	0.00	0.00	7.47	–1,745.52
Pear	219.67	8.25	3.76	–19.23	3.57	18.59	99,658.9	0.00	0.00	5.91	–7,504.19
Pear/Cinnamon	234.78	0.00	0.00	–12.94	0.00	0.00	15,316.8	0.00	0.00	7.61	–3,319.79
Apple	154.45	0.00	0.00	–9.08	0.00	0.00	40,994.2	0.00	0.00	6.03	–2,802.39
Apple/Ginger	119.86	0.00	0.00	–16.44	0.00	0.00	88,577.0	0.00	0.00	3.03	–7,219.79
Apple/Mint	169.17	0.00	0.00	–19.23	0.00	0.00	34,878.2	0.00	0.00	6.08	–3,981.23
Apple/Cinnamon	155.52	0.00	0.00	–8.22	0.00	0.00	12,875.3	0.00	0.00	3.01	–3,314.67

5. 5. Color characteristics of samples using spectrophotometry

Color characteristics are a key aspect of the perception of the quality of energy bars. They not only affect the attractiveness of the product but also shape consumer expectations regarding its taste and texture. To assess the color of the samples, the Lab color model was used, including the parameters of lightness (*L*), hue (*a*), and saturation (*b*). The analysis included both basic fruit components and their combinations with spices (cinnamon, mint, ginger) (Table 6).

Table 6

Results of color characteristics analysis

Sample	*L* (lightness)	*a* (redness)	*b* (yellowness)
Plum	40.29	4.38	1.17
Plum	54.15	3.79	16.28
Plum/ginger	39.99	4.33	1.14
Plum/ginger	51.93	3.45	11.86
Pear	44.77	0.79	1.95
Pear	55.13	3.18	16.11
Pear/cinnamon	43.37	-0.20	1.58
Pear/cinnamon	46.82	5.55	10.44
Apple/cinnamon	44.01	0.29	3.85
Apple/cinnamon	41.67	4.02	7.11
Apple/ginger	41.05	0.47	3.82
Apple/ginger	50.47	3.24	13.06
Apple/mint	41.77	1.31	4.16
Apple/mint	47.31	0.70	7.81

As can be seen from Table 6, the lightest samples are Pear (55.13) and Apple/Ginger (50.47). High lightness indicates the dominance of the basic fruit component. The darkest are Plum/Ginger (39.99) and Apple/Mint (41.77). This may be due to the addition of spices such as mint or ginger, which affect the color.

Redness (a): the highest redness is in Pear/Cinnamon (5.55) and Plum (4.38), which is due to the influence of cinnamon and the richness of the fruit. The lowest redness is in Pear/Cinnamon (–0.20), which indicates a shift to the green spectrum due to the characteristics of the spicy additive.

Yellowness (b): the highest yellowness is in Plum (16.28) and Pear (16.11). This makes them visually appealing. The lowest yellowness was found in Plum/Ginger (1.14) and Apple/Ginger (3.82), which may indicate a less vibrant visual profile.

Practical recommendations:

– to improve lightness: It is recommended to increase the proportion of base fruits (e.g., pear or apple) in the recipe;

– to enhance reds and yellows: The addition of plum and cinnamon provides rich and warm shades suitable for visually bright products;

– for complex soft shades: The use of spice combinations such as mint and ginger gives the product a visually balanced profile.

These data can be used to optimize the recipe and improve the consumer appeal of energy bars.

Evaluation of the influence of variable factors on key quality parameters of energy bars.

The plot (Fig. 4) shows the profiles of predicted values and overall desirability depending on the variable parameters: layer height (*h*, mm), cooking time (*t*, min), syrup content (%) and protein content (%). The analysis was conducted to assess the influence of these factors on the target quality parameters of energy bars. This plot was constructed to analyze the multifactorial influence on the quality parameters of energy bars.

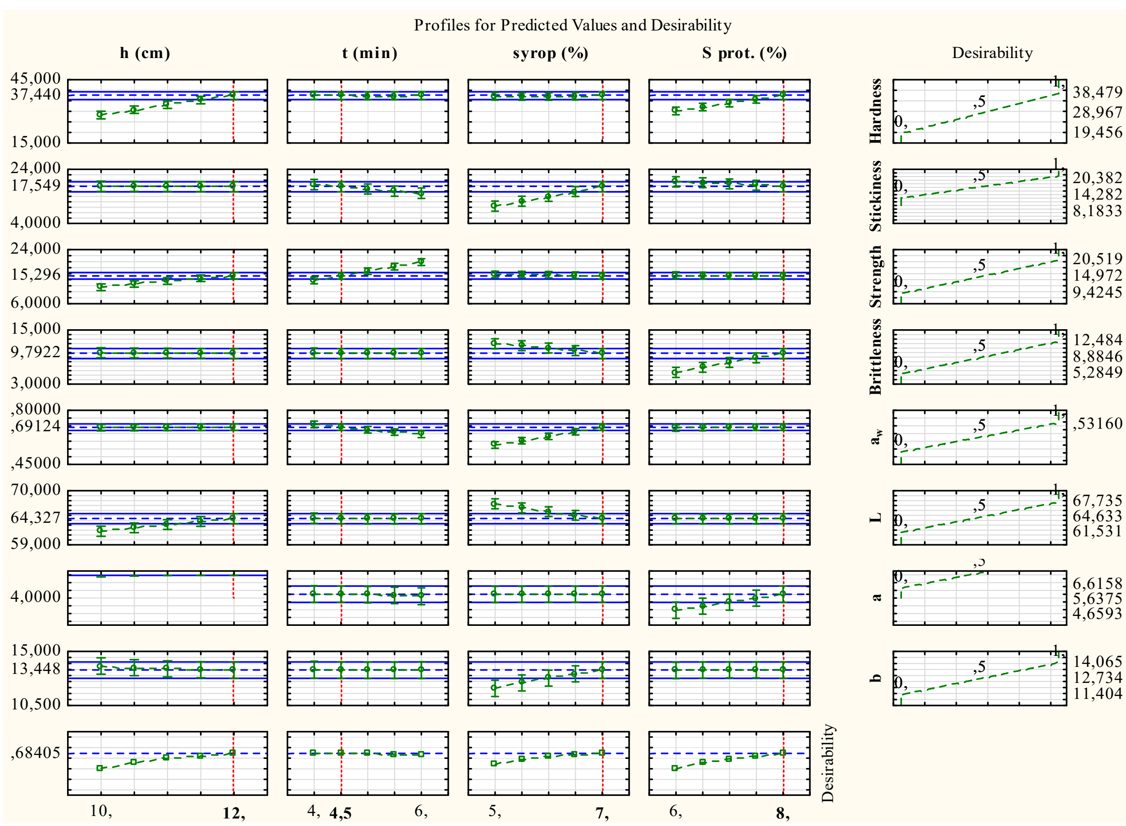

Fig. 4. Profiles of predicted values and overall desirability depending on the variable parameters: layer height (*h*, mm), cooking time (*t*, min), syrup content (%), and protein content (%)

The applied methodology, including the calculation of desirability, makes its possible to determine the optimal production conditions that meet all the target criteria, such as texture, stability, and appearance of the product. The plot demonstrates the influence of the key process parameters on the quality of energy bars. Based on the analysis, it can be stated that in order to achieve optimal product characteristics (texture, water activity, color), the following conditions should be followed: layer height: 12 mm; cooking time: 5 minutes; syrup content: 5%; protein content: 7%.

The results of our study could be used to develop and optimize the formulation of products with a functional purpose, ensuring a high level of quality and stability.

6. Discussion of results based on studying the formulation and technological parameters of gluten-free energy bars with a jelly layer

The comprehensive assessment of gluten-free energy bars has made it possible to identify the influence of formulation and technological factors on the quality of the product. The key properties were characterized – antioxidant activity, texture, water activity, color and organoleptic characteristics, the results of which are given in Tables 3–6 and Fig. 3.

Samples with the addition of cinnamon and mint showed the highest values of antioxidant activity (Table 3), especially the bar with apple and cinnamon (82.8%), which is explained by the high content of phenolic compounds. Comparatively high values for the sample with apple and mint (64.6%) can be explained by the synergistic effect of polyphenols and vitamin C, confirmed in [1, 5]. On the contrary, samples with ginger turned out to be less active (for example, Apple/Ginger – 13%), which may be associated with the instability of active substances during heat treatment [9].

The differences in textural characteristics (Table 4) were significant. The sample with plum and ginger showed the highest density and strength, which is explained by the high concentration of dry substances and increased gelation due to tannins. However, excessive hardness can reduce consumer appeal, especially for children, which is confirmed by the results of other studies [11, 14]. The sample with apple and cinnamon demonstrated a soft and balanced texture with minimal stickiness (–8.22 g), which makes it the most preferable. The high fragility of the bars with pear and cinnamon (7.61 mm) can be an advantage (ease of consumption) and a disadvantage (fragility during transportation).

Water activity (a_w) (Table 5) is a critical parameter in predicting shelf life. Minimum values were observed for apple/mint (0.68) and pear/cinnamon (0.72), which contributes to resistance to microbiological spoilage. aw values above 0.75, like apple/cinnamon (0.97), require additional stabilization measures (e.g., vacuum packaging), as noted in [17–20]. The obtained values confirm the effectiveness of the formulation solutions in terms of storage.

Color affects the first impression and perception of quality. Samples with pear and plum were characterized by high lightness ($L > 54$) (Table 6), and the addition of cinnamon contributed to an increase in the saturation of the red hue (a), making the product visually attractive. The least expressive samples were those with ginger – grayish and dull shades, as also noted in [12]. The addition of natural berry-based dyes can improve this parameter.

According to the results of the organoleptic evaluation (Fig. 3), the best indicators were observed in the samples with mint and cinnamon, which received high scores for aroma, texture, appearance, and aftertaste. Using the desirability criterion (Fig. 4) has made it possible to determine the optimal technological parameters: layer height – 12 mm, syrup – 5%, protein – 7%; for the interlayer – agar-agar 2%, lemon juice 10%, cooking – 5 min. Unlike [14, 15], in which optimization was carried out according to one or two criteria, this work implements a multifactorial approach taking into account the textural, functional, and visual properties of the product.

The selected recipe parameters provide a balanced combination of technological stability, visual appeal, and functionality, which is confirmed by experimental data.

The limitations of the study are related to the fact that the experiments were carried out under laboratory conditions; shelf life, bioavailability of antioxidants were not assessed, and the effect of packaging was not considered. The product's behavior under logistical and long-term storage conditions requires further study.

Disadvantages include the lack of a consumer panel for organoleptic evaluation and a limited number of repetitions, which makes it difficult to calculate statistical reliability for some parameters.

The development of the study can be aimed at:

1) scaling the technology to production lines with automatic parameter control;

2) studying stability under different storage conditions;

3) targeted development of products for individual groups (children, athletes, diabetics);

4) inclusion of functional additives (prebiotics, natural dyes), which is especially important in the context of growing demand for functional food.

7. Conclusions

1. As a result of the selection and analysis of ingredients, the optimal recipe and technological parameters were established, providing balanced properties of gluten-free energy bars: layer height – 12 mm, syrup content – 5%, protein – 7%; composition of the gelled layer – 2% agar-agar, 10% lemon juice, cooking – 5 minutes. It was found that protein and lemon juice have the greatest positive effect on the final quality, while exceeding the proportion of syrup and layer height reduces consumer characteristics.

2. Evaluation of antioxidant activity by the DPPH method showed that the highest activity was demonstrated by samples with the addition of cinnamon and mint. The presence of cinnamon contributed to achieving activity of up to 82.8%, which is due to the high content of phenolic compounds. Mint showed a moderate positive effect. Samples with ginger had significantly lower indicators, which is probably due to the instability of its antioxidant components during heat treatment.

3. The measured textural characteristics showed wide variability depending on the type of fruit puree and spices. The apple and cinnamon samples had the best structural balance: soft texture, low stickiness, and sufficient elasticity. The plum and ginger samples demonstrated high density and gel strength, which reduces the convenience of consumption, especially for children.

4. The water activity study showed that the apple/mint and pear/cinnamon samples had a_w values below 0.75, indi-

cating their potential resistance to microbiological spoilage and suitability for storage without preservatives. High a_w values for other samples indicate the need for additional stabilization measures.

5. The color characteristics of the samples varied depending on the composition. The pear and plum samples had high lightness and a natural appearance. The addition of cinnamon contributed to an increase in the saturation and redness of the hue, making the product visually attractive. The least aesthetically pleasing samples were those with ginger, which requires correction of visual perception during industrial development.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

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

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