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MATHEMATICAL MODEL FOR FOOD FORMULATION WITH MICROGREENS GROWN USING IOT IN VERTICAL FARMING

Abstract. This study aims to develop a mathematical model for optimizing food formulations that incorporate microgreens grown using Internet of Things (IoT) technologies in vertical farming systems. In this research, a factorial experimental design was employed to study the influence of three variable factors on the quality indicators of food products, including protein content (Y1), fat content (Y2), carbohydrate content (Y3), and organoleptic evaluation (Y4). Regression equations were derived to describe the non-linear relationships between these factors and the quality indicators. The second-degree polynomial regression models demonstrated how the combination of variables affected food formulation optimization. The results showed that the application of IoT in vertical farming provides valuable real-time data, enabling the adjustment of growing conditions to maximize the nutritional and functional value of microgreens. The mathematical models developed in this study provide insights into the optimal composition of multicomponent food products, ensuring higher nutritional value, improved texture, and better overall product quality.

Keywords: IoT, vertical farming, microgreens, mathematical modeling, food formulation.

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Introduction. Modern trends in the food industry and agriculture demonstrate a growing interest in sustainable food production [1]. In the face of global climate change, population growth, and urbanization, humanity faces new challenges that require innovative approaches to food cultivation and production. One promising technology is vertical farming, which allows agricultural products to be grown in limited urban spaces while minimizing the use of land and water [2].

Of particular interest is the cultivation of microgreens – young plant shoots that are highly nutritious and possess antioxidant properties. Microgreens not only contain high concentrations of vitamins and minerals but are also becoming increasingly popular as an ingredient in various food products due to their organoleptic and health benefits. However, the effective integration of microgreens into food formulations requires the development of mathematical models that can optimize the composition of food products and their production processes. Studies dedicated to mathematical models for food product development explore ways to optimize ingredient composition and improve the nutritional value of foods [3]. Kumar et al. discuss methods that help predict product properties, such as taste, texture, and stability [4]. Valdramodos et al. show how models can predict changes in product quality depending on storage conditions and composition [5].

The integration of Internet of Things (IoT) technologies into vertical farming processes creates new opportunities for precise control over growing conditions, such as temperature, humidity, lighting, and nutrient solution composition. The use of IoT allows for the collection of large volumes of real-time data, which paves the way for more accurate and adaptive models to manage the microgreen growing process [6].

The aim of this study is to develop a mathematical model that incorporates data on microgreen cultivation using IoT technologies to optimize food formulations. Such a model will not only improve production processes but also enable the creation of more nutritious and environmentally sustainable food products.

The introduction of IoT in vertical farming, supported by mathematical modeling, could be an important step toward sustainable and highly efficient food production in urban environments, minimizing environmental impact and increasing the availability of healthy food to the population.

Materials and methods. To optimize the formulation and technology of food products, the impact of raw material content on organoleptic evaluation, and the mass fractions of proteins, fats, and carbohydrates was studied using the method of experimental mathematical factorial design.

While developing the system of indicators (factors), the influence of three factors on food product quality (Y1 – Protein, %; Y2 – Fat, %; Y3 – Carbohydrate, %; Y4 – Organoleptic evaluation, points) was examined: the amount of the main raw material (X1), the amount of plant additive (X2), and the amount of protein (X3) (Table 1).

Table 1

Variable factors of food products, their variation intervals and limit values

Variable factors	Designations	Levels			Variation interval
		-1	0	1	
Main raw material size, %	X1	82	84	86	2
Amount of vegetable mixture,%	X2	0,5	1	1,5	0,5
Protein hydrolyzate content,%	X3	3	5	7	2

According to a complete three-factor project of experiments, a study was carried out on the qualitative process of herodietic cooked sausage.

The regression equation obtained in a full factor experiment is expressed as a polynomial of the first degree:

$$y(x_1, \dots, x_k) = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_i x_i^2 + \sum_{\substack{i,j=1 \\ (i \neq j)}}^{k} b_{ij} x_i x_j \qquad (1)$$

The second-order XiXj terms in the equation for i≠j represent the effects of the combined interaction between Xi and Xj on the values of Y1,Y2,Y3 and Y4, in addition to their linear effects. The XiXj terms for i=j represent the nonlinear change in Y when the i-th argument changes.

Using Microsoft Excel 2013 and the Statistica 12.0 software package for mathematical processing of experimental data and removing insignificant coefficients, regression equations were obtained that adequately describe the dependence of technological factors (Y1, Y2, Y3, Y4) on food quality indicators (X1, X2, X3).

Research results and discussion. The regression equation for Y1 – protein, %, will look like this: $Y1 = 16{,}6932 - 0{,}2281 \cdot X2 + 0{,}5725 \cdot X3 + 0{,}0933 \cdot X2^2 - 0{,}0908 \cdot X2 \cdot X3 + 0{,}0021 \cdot X3^2$

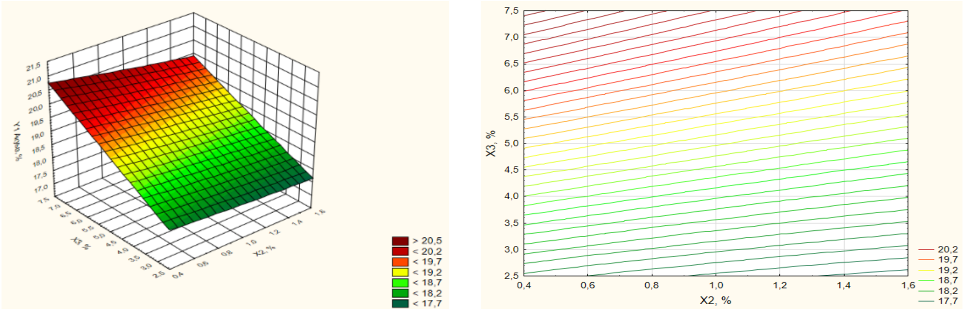

Fig. 1. Spatial surface and equal-level lines showing the effect of factors X2 and X3 on the optimization parameter Y1

The regression equation for Y2-fat, %, will look like this: $Y2 = 2569{,}6146 - 58{,}8813 \cdot X1 - 20{,}3808 \cdot X3 + 0{,}3383 \cdot X1^2 + 0{,}2427 \cdot X1 \cdot X3 - 0{,}0604 \cdot X3^2$

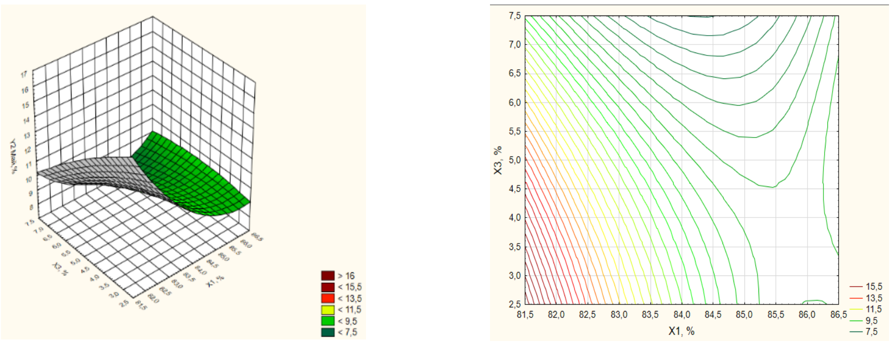

Fig. 2. Spatial surface and equal-level lines showing the effect of factors X1 and X3 on the optimization parameter Y2

The regression equation for Y3 – carbohydrate,%, is as follows:

$Y3 = 574{,}7104 - 13{,}5903 \cdot X1 - 5{,}6367 \cdot X2 + 0{,}0807 \cdot X1^2 + 0{,}0683 \cdot X1 \cdot X2 + 0{,}1178 \cdot X2^2$

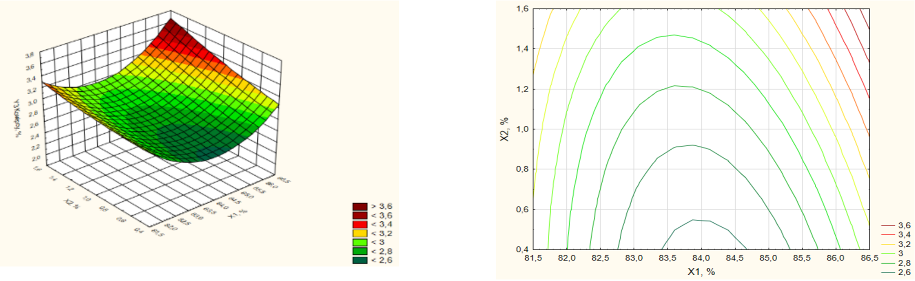

Fig. 3. Spatial surface and equal-level lines showing the effect of factors X1 and X2 on the optimization parameter Y3

Y4-organoleptic assessment, score, regression equation will look like this: Y4 = 3,7069 + 0,5806*X2 + 0,5861*X3 – 0,3333*X2^2 – 0,025*X2*X3 – 0,0708*X3^2

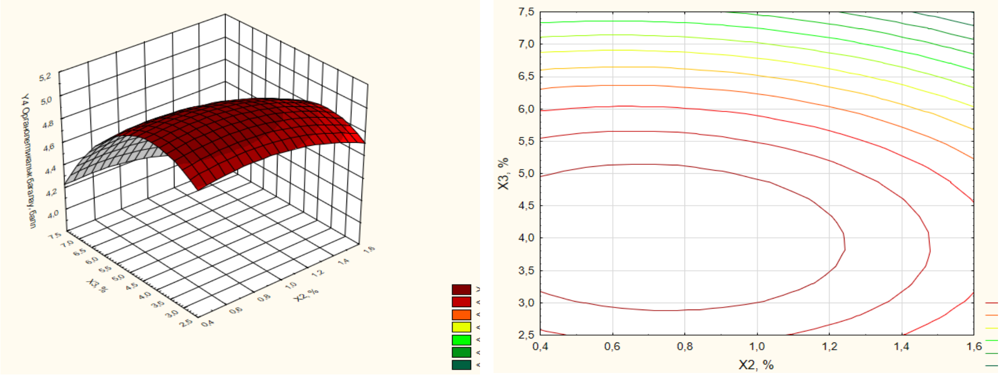

Fig. 4. Spatial surface and equal-level lines showing the effect of factors X2 and X3 on the optimization parameter Y4

According to Figures 1-4, the color markers indicate the value of the corresponding indicator through intensity. By using these markers, the range of variable values where the food quality indicators reach their maximum can be determined.

The obtained modeling results allowed for the scientific justification of the optimal composition of multicomponent factors for food preparation. The goal was to find the maximum of the objective function – the value of protein (Y1).

$$\begin{cases} Y_1 = f_1(x_1, x_2, x_3) \to max; \\ minx_i \le x_i \le maxx_i, i = 1,2,3; \end{cases} \tag{2}$$

The optimal results of the above problems and the numerical values of the lower and upper bounds are summarized in Table 2.

Table 2

Optimal solution of multicomponent factors for the preparation of food products

Variables	X1	X2	X3	У1	У2	У3	У4
Optimal values	86	1	7	19,0194	8,3794	3,1564	4,4127
Lower limit	82	0,5	3	17,12	7,46	2	4,2
Upper limit	86	1,5	7	20,92	15	3,68	5

Therefore, the optimal solution allows you to significantly improve the use of food products obtained in such conditions, since the border conditions are fully satisfied here.

By analyzing the relationships between food product indicators and the factors influencing them, it was determined that in most cases their non-linear nature corresponds to the conducted experiment. The search for multivariable dependencies was carried out under conditions of limited experimental data and a priori uncertainty regarding the form of regression functions for food quality indicators. In such cases, the regression equation is presented as a second-degree polynomial.

The behavior of food quality indicators, which vary depending on the composition of multicomponent factors, is shown in Figures 1-4. The same levels of the indicated values of food quality indicators are highlighted in the three-dimensional diagrams using a wireframe or various shading. When these surface diagram elements are identical, the levels have the same meaning.

The constructed surface diagram allows identifying the optimal combination of mixture components, which would be difficult to determine from the available data alone.

According to Figures 1-4, the contour lines of the equal levels of the convex and concave surfaces, described by equations, are shown for food product indicators. These diagrams made it possible to evaluate the hidden structure of each indicator's convex and concave surface and to identify the complex non-linear relationships between the variables under study.

Conclusion. Thus, based on the obtained regression equations, three-dimensional graphs were constructed that reflected the nonlinear relationship between variable factors and qualitative indicators. The optimal values for the combination of factors providing the maximum protein content (Y1) were: X1 = 86%, X2 = 1%, X3 = 7%. With these parameters, the protein content (Y1) reached a maximum of 190.194%, the fat content (Y2) was 83.794%, carbohydrates (Y3) – 31.564%, and the organoleptic score (Y4) – 44.127 points.

The use of these models allows us to scientifically substantiate the composition of multicomponent food products and achieve the best technological indicators, such as improving texture, increasing nutrient content and increasing organoleptic characteristics. This study demonstrated that the integration of IoT and mathematical modeling can significantly improve the efficiency and quality of food production, especially in an urban environment where vertical farming is a promising solution.

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ВЕРТИКАЛДЫ ЕГІНШІЛІКТЕ IOT КӨМЕГІМЕН ӨСІРІЛГЕН МИКРОШӨП ҚОСЫЛҒАН ТАҒАМДЫҚ РЕЦЕПТУРАСЫНЫҢ МАТЕМАТИКАЛЫҚ МОДЕЛІ

Аңдатпа. Бұл зерттеу вертикалды егіншілік жүйелерінде IoT технологиялары арқылы өсірілген микрошөп қамтитын азық-түлік қоспаларын оңтайландырудың математикалық моделін жасауға бағытталған. Бұл зерттеуде ақуыздың (Y1), майдың (Y2), көмірсулардың (Y3) және органолептикалық бағалаудың (Y4) құрамын қоса алғанда, тамақ өнімдерінің сапа көрсеткіштеріне үш айнымалы фактордың әсерін зерттеу үшін факторлық эксперименттік дизайн қолданылды. Регрессия теңдеулері осы факторлар мен сапа көрсеткіштері арасындағы сызықтық емес қатынастарды сипаттау үшін алынды. Екінші дәрежелі көпмүшелік регрессия модельдері айнымалылардың тіркесімі тағам құрамын оңтайландыруға қалай әсер еткенін көрсетті. Нәтижелер вертикалды егіншілікте IoT қолдану микрошөптің тағамдық және функционалдық құндылығын барынша арттыру үшін өсу жағдайларын реттеуге мүмкіндік беретін нақты уақыттағы құнды деректерді беретінін көрсетті. Осы зерттеуде әзірленген математикалық модельдер жоғары тағамдық құндылықты, жақсартылған құрылымды және өнімнің жалпы сапасын жақсартуды қамтамасыз ететін көп компонентті тағамдардың оңтайлы құрамы туралы түсінік береді

Тірек сөздер: IoT, вертикалды егіншілік, микрошөп, математикалық модельдеу, тағамдық құрам.

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МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ДЛЯ РАЗРАБОТКИ РЕЦЕПТУРЫ ПИЩЕВЫХ ПРОДУКТОВ С МИКРОЗЕЛЕНЬЮ, ВЫРАЩЕННОЙ С ИСПОЛЬЗОВАНИЕМ ИНТЕРНЕТА ВЕЩЕЙ В ВЕРТИКАЛЬНОМ ЗЕМЛЕДЕЛИИ

Аннотация. Это исследование направлено на разработку математической модели для оптимизации рецептур пищевых продуктов, включающей микрозеленые растения, выращенные с использованием технологий Интернета вещей (IoT) в системах вертикального земледелия. В этом исследовании был использован факторный экспериментальный подход для изучения влияния трех переменных факторов на показатели качества пищевых продуктов, включая содержание белка (Y1), жира (Y2), углеводов (Y3) и органолептическую оценку (Y4). Были выведены уравнения регрессии для описания нелинейных взаимосвязей между этими факторами и показателями качества. Модели полиномиальной регрессии второй степени продемонстрировали, как сочетание переменных влияет на оптимизацию рецептуры продуктов. Результаты показали, что применение Интернета вещей в вертикальном земледелии позволяет получать ценные данные в режиме реального времени, что позволяет корректировать условия выращивания для максимального повышения питательной и функциональной ценности микрозелени. Математические модели, разработанные в этом исследовании, позволяют получить представление об оптимальном составе многокомпонентных пищевых продуктов, обеспечивая более высокую питательную ценность, улучшенную текстуру и общее качество продукта.

Ключевые слова: IoT, вертикальное земледелие, микрозелень, математическое моделирование, рецептура продуктов питания.