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Polymer Chemistry

Optimization of Tomato Shelf Life Using Pseudoprotein-Based Edible Coating

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Abstract. One of the primary challenges in storing agricultural products is the rapid deterioration of their nutritional and sensory qualities, which are associated with biochemical processes occurring in fruit, including respiration intensity, metabolic consumption of sugars and organic acids, vitamin degradation, and moisture loss. In modern food technology, edible coatings attract particular attention as an innovative and environmentally sustainable preservation tool. The aim of this study is to evaluate the effectiveness of a pseudoprotein-based edible coating during tomato storage and to optimize storage regimes using a mathematical design of experiments. Using a 7% ethanolic pseudoprotein solution, the effects of temperature, immersion time, and storage duration on the quality indicators of the fruit were assessed. The results show that applying the coating significantly slows the degradation of nutritional indicators and enables optimization of the storage process. Optimal conditions were identified that ensure preservation of the biochemical and organoleptic quality of tomatoes within a practically acceptable storage period. © *2026 Bull. Natl. Acad. Sci. Georg.*

Keywords: tomato, edible coating, pseudoprotein, preservation, shelf life

Introduction

Under current conditions, preserving the quality of agricultural products is one of the most important challenges for the food industry and agriculture. The natural ripening of fruits and vegetables and subsequent spoilage during storage cause not only the deterioration of morphological characteristics, but also a significant decrease in nutritional value. These changes are driven by complex biochemical processes occurring in the fruit, manifested in an increase in respiration intensity, the consumption of sugars and organic acids, the oxidative degradation of vitamins, and moisture loss.

An improper storage regime frequently leads to a significant deterioration in product quality, directly reducing marketability and resulting in economic losses (Scientific-Research Center of Agriculture, 2015). Accordingly, the development of preservation technologies capable of slowing physiological processes in agricultural products and maximizing the retention of nutritional value is of critical importance.

In recent years, the concept of edible coatings has been actively developed. It is based on forming a thin, biodegradable protective layer on the surface of the fruit that belongs to the food category. Such coatings act as a physical barrier to gases and moisture. In this direction, biopolymer systems are of special interest, including so-called pseudoproteins, which are characterized by high mechanical strength, adhesive ability, hydrophobicity, biodegradability, and biocompatibility, making them promising for use in agricultural product storage technologies (Momin et al., 2021; Moradinezhad et al., 2025; Tsitlanadze et al., 2004).

This paper is devoted to studying the effectiveness of a pseudoprotein-based edible coating during tomato storage and, through a mathematical experimental design, to determine optimal conditions.

Materials and Methods

Within the present study, to extend the shelf life of tomatoes, a so-called pseudoprotein (PP) was used – an innovative biomaterial developed in Georgia based on the α-amino acid L-leucine, a biomimetic of the poly(ester urea-co-ester amide) class (Tsitlanadze et al., 2004). It is characterized by a high Young's modulus (1.2 GPa) and good gas permeability, and it degrades into α-amino acids under the action of hydrolases (Yousefzade et al., 2020).

Various technological approaches are used to apply edible coatings to agricultural products, including dipping and spraying; the choice depends on the physical and chemical properties of the coating solution, the evaporation rate, and the ability to form a uniform layer. In this study, the PP edible coating was prepared in an ethanol solution, which enables a short dipping time, rapid drying at room temperature, and the formation of a thin, uniform layer on the fruit surface. The solubility of PP in ethanol simplifies the technological regime, while the sterilizing effect of ethanol can be regulated by changing the dipping time. The experiment used an optimal 7% coating concentration, determined in earlier studies through mathematical modeling (Jibladze et al., 2024).

In the scientific literature, the use of edible coatings dissolved in 96% ethanol for coating fruits is not reported; however, ethanol is often used in combination with water. Accordingly, there are no studies defining specific immersion times of samples in ethanolic solutions. In some studies, ethanol is typically used only for preparing extracts.

To determine the lower limit of immersion time, the study by Wesolowski (Wesolowski, 2019) was used, where 70% ethanol was used to treat the surface of tomato fruits for disinfection purposes. The maximum disinfecting effect against Salmonella bacteria was achieved in about 10 seconds, while increasing the immersion time no longer provided a significant improvement.

Considering that in our study ethanol is used not for fruit disinfection, but as a solvent for the pseudoprotein and to form a uniform coating on the surface, 30 seconds was considered to be an appropriate upper limit for immersion time. This duration ensures an even distribution of the pseudoprotein on the tomato surface, the formation of a uniform coating, and the avoidance of excessive ethanol impact.

As the experimental object, red table tomatoes (Solanum lycopersicum L.) purchased in the Gori Region were selected at the full ripeness stage. During sample selection, attention was focused on the uniformity of size and ripeness to minimize variation in experimental results.

Within the framework of mathematical design for the tomato storage experiment, the selected optimization parameters included total soluble solids content (TSS, °Brix), pH, titratable acidity (TA, %), and vitamin C content (mg/%).

All parameters were determined using standard methodologies in accordance with AOAC Official Methods (Danelia & Palavandishvili, 2017; Danelia et al., 2011). TSS was measured by refractometry. The pH was determined using the potentiometric method. TA was assessed by titration with a standardized 0.1 N NaOH solution to an endpoint of pH 7.0 and expressed as citric acid equivalents. Ascorbic acid content was determined by titration with 2,6-dichlorophenolindophenol following prior standardization of the reagent.

Table 1. Main characteristics of the experimental design

Factors	**X1, t (°C)**	**X2, immersion time (s)**	**X3, storage time (days)**
Base level	17	20	29
Variation interval	5	10	16
Upper limit	22	30	45
Lower limit	12	10	13

The factors affecting these optimization parameters were defined as: temperature (X_1, °C), immersion time (X_2, s), and storage time (X_3, days). The experiment was carried out in triplicate, and the results are presented as mean values. Storage was performed under two temperature regimes (10-12°C and 20-22°C), immersion time was 10 and 30 seconds, and storage duration was 13 and 45 days (Jibladze et al., 2023).

The main characteristics of the experimental plan and the factor levels are given in Table 1, while the experimental design matrices for each optimization parameter are presented in Tables 2, 3, 4, and 5. This approach encompasses all possible combinations of factor levels and forms the basis for subsequent regression modeling. In a 2^3 full factorial experiment, the transformation of natural variables measured in different units into coded variables is performed using appropriate coding rules. This ensures an objective determination of the magnitude of main effects and interactions, as well as their statistical significance (Jibladze et al., 2023).

Based on regression analysis, linear mathematical models of the tomato storage process were developed for all four quality parameters. The obtained models made it possible to quantitatively assess the effects of temperature, immersion time, and storage duration on the quality indicators and to determine the direction of changes. In accordance with the classical approach of mathematical design of experiments, the homogeneity of varian-

Table 2. Experimental design matrix for the optimization of total soluble solids content (TSS, °Brix)

Run No	**X_0**	**X_1**	**X_2**	**X_3**	**X_1X_2**	**X_1X_3**	**X_2X_3**	**$X_1X_2X_3$**	**Y_1**	**Y_2**	**Y_{avg}**	**Si^2**
1	2	3	4	5	6	7	8	9	10	11	12	13
1	+1	-1	-1	-1	+1	+1	+1	-1	5.3	5.54	5.42	0.0288
2	+1	+1	-1	-1	-1	-1	+1	+1	4.84	5.0	4.92	0.0128
3	+1	-1	+1	-1	-1	+1	-1	+1	5.02	5.18	5.1	0.0128
4	+1	+1	+1	-1	+1	-1	-1	-1	4.44	4.72	4.58	0.0392
5	+1	-1	-1	+1	+1	-1	-1	+1	4.37	4.59	4.48	0.0242
6	+1	+1	-1	+1	-1	+1	-1	-1	3.86	4.1	3.98	0.0288
7	+1	-1	+1	+1	-1	-1	+1	-1	4.0	4.24	4.12	0.0288
8	+1	+1	+1	+1	+1	+1	+1	+1	3.47	3.63	3.55	0.0128

Table 3. Experimental design matrix for the optimization parameter: pH

Run No.	**X_0**	**X_1**	**X_2**	**X_3**	**X_1X_2**	**X_1X_3**	**X_2X_3**	**$X_1X_2X_3$**	**Y_1**	**Y_2**	**Y_{avg}**	**Si^2**
1	2	3	4	5	6	7	8	9	10	11	12	13
1	+1	-1	-1	-1	+1	+1	+1	-1	4.11	4.19	4.15	0.0032
2	+1	+1	-1	-1	-1	-1	+1	+1	4.22	4.28	4.25	0.0018
3	+1	-1	+1	-1	-1	+1	-1	+1	4.26	4.3	4.28	0.0008
4	+1	+1	+1	-1	+1	-1	-1	-1	4.33	4.43	4.38	0.005
5	+1	-1	-1	+1	+1	-1	-1	+1	4.28	4.36	4.32	0.0032
6	+1	+1	-1	+1	-1	+1	-1	-1	4.38	4.47	4.425	0.00405
7	+1	-1	+1	+1	-1	-1	+1	-1	4.43	4.48	4.455	0.00125
8	+1	+1	+1	+1	+1	+1	+1	+1	4.52	4.58	4.55	0.0018

Table 4. Experimental design matrix for the optimization parameter: titratable acidity (TA, %)

Run No.	X_0	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	$X_1X_2X_3$	Y_1	Y_2	Y_{avg}	Si^2
1	2	3	4	5	6	7	8	9	10	11	12	13
1	+1	-1	-1	-1	+1	+1	+1	-1	0.52	0.56	0.54	0.0008
2	+1	+1	-1	-1	-1	-1	+1	+1	0.46	0.49	0.475	0.00045
3	+1	-1	+1	-1	-1	+1	-1	+1	0.47	0.51	0.49	0.0008
4	+1	+1	+1	-1	+1	-1	-1	-1	0.4	0.44	0.42	0.0008
5	+1	-1	-1	+1	+1	-1	-1	+1	0.33	0.37	0.35	0.0008
6	+1	+1	-1	+1	-1	+1	-1	-1	0.28	0.32	0.3	0.0008
7	+1	-1	+1	+1	-1	-1	+1	-1	0.27	0.31	0.29	0.0008
8	+1	+1	+1	+1	+1	+1	+1	+1	0.22	0.27	0.245	0.00125

Table 5. Experimental design matrix for the optimization parameter: Vitamin C (mg/100 g)

Run No.	X_0	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	$X_1X_2X_3$	Y_1	Y_2	Y_{avg}	Si^2
1	2	3	4	5	6	7	8	9	10	11	12	13
1	+1	-1	-1	-1	+1	+1	+1	-1	21.6	22.2	21.9	0.18
2	+1	+1	-1	-1	-1	-1	+1	+1	18.9	19.5	19.2	0.18
3	+1	-1	+1	-1	-1	+1	-1	+1	19.7	20.3	20.0	0.18
4	+1	+1	+1	-1	+1	-1	-1	-1	16.8	17.6	17.2	0.32
5	+1	-1	-1	+1	+1	-1	-1	+1	14.7	15.3	15.0	0.18
6	+1	+1	-1	+1	-1	+1	-1	-1	11.9	12.5	12.2	0.18
7	+1	-1	+1	+1	-1	-1	+1	-1	12.8	13.4	13.1	0.18
8	+1	+1	+1	+1	+1	+1	+1	+1	9.3	9.9	9.6	0.18

ces, the significance of regression coefficients, and the adequacy of the models were tested, confirming a statistically significant influence of all three factors on the optimization parameters.

For TSS, the following linear regression equation was obtained:

$$Y = 4.51875 - 0.26125X_1 - 0.18125X_2 - 0.48625X_3.$$

The analysis indicates that an increase in temperature, immersion time, and storage duration leads to a decrease in °Brix, which is associated with the metabolic consumption of sugars and other soluble components. From the perspective of storage technology, the optimal range of TSS in tomatoes is 4.0-5.5 °Brix, while lower values are linked to a deterioration of taste quality.

For pH, the model obtained is:

$$Y = 4.35125 + 0.05X_1 + 0.065X_2 + 0.08625X_3.$$

The analysis shows an opposite trend: increasing the factors causes an undesirable rise in pH, which is driven by the gradual breakdown of organic acids during storage. For tomatoes, an optimal level is pH 4.0-4.4, whereas values above 4.5 are already associated with the deterioration of organoleptic quality and reduced microbial stability.

For TA, the following model was obtained:

$$Y = 0.38875 - 0.02875X_1 - 0.0275X_2 - 0.0925X_3.$$

The study showed that increasing temperature, immersion time, and storage duration reduces the concentration of organic acids. Under unfavorable conditions, this value drops below the optimal range of 0.30-0.60%, indicating a loss of chemical and sensory quality of the product.

For vitamin C, the regression equation is:

$$Y = 16.025 - 1.475X_1 - 1.05X_2 - 3.55X_3.$$

This indicates that increasing temperature, immersion time, and storage duration decreases vitamin C content, which is expected given the oxidative degradation of ascorbic acid and other biochemical transformations. The optimal range of ascorbic acid content in tomatoes varies between 10-25 mg/100 g. The 21.9 mg/100 g recorded at the initial stage corresponds to a high-quality indicator,

Table 6. Series of optimization runs (steepest ascent method)

Run/Level	X_1: Temperature (°C)	X_2: Immersion time (s)	X_3: Storage time (days)	Y_1: TSS °Brix	Y_2: TA (%)	Y_3: pH	Y_4: Vitamin C (mg/100 g)
Base level	17	20	29				
Run 9	16	18	28	4.74	0.57	4.31	15.7
Run 10	16	17	28	4.8	0.58	4.3	16.0
Run 11	16	16	27	4.88	0.6	4.28	16.6
Run 12	16	15	27	4.96	0.61	4.27	17.0

whereas the 9.59 mg/100 g obtained on day 45 under unfavorable conditions indicates a decrease in nutritional value and falls below the lower limit.

Based on the regression analysis, it was established that optimization of the tomato storage process is achieved by reducing temperature, immersion time, and storage duration. All four quality parameters form an integrated system reflecting biochemical changes in the fruit during storage. Their combined assessment indicates that a low temperature, a short immersion time, and a relatively short storage period are the most favorable conditions for maintaining tomato quality.

The linear regression models built from the initial experimental design were applied to the Method of Steepest Ascent, the goal of which is to move factors in the direction where the optimization parameters improve jointly. This approach is particularly effective when the model obtained at the first stage describes the main trends of the process, and the optimal conditions are located within or near the initial experimental region.

In this study, the direction of steepest ascent was determined based on a joint analysis of all four quality parameters – TSS, pH, TA, and vitamin C. The linear models showed that quality improvement is achieved by decreasing temperature, immersion time, and storage duration. Accordingly, the steepest ascent trajectory was set toward reducing these three factors. Step sizes were selected by considering the absolute values of the regression coefficients (β), ensuring proportionality of factor changes according to the intensity of their influence. In particular, storage duration was identified as the strongest factor, so its step was chosen to be relatively small to avoid sharp quality degradation. Immersion time, as a more technologically flexible parameter, was changed with relatively larger steps (measured in seconds), while the temperature step was chosen moderately, taking into account realistic laboratory control capabilities.

Results and Discussion

The experimental results clearly demonstrated that the use of the PP coating significantly affects the dynamics of tomato quality indicators during storage. Analysis of TSS showed that increasing temperature, immersion time, and storage duration causes a gradual decrease in °Brix, which is associated with the metabolic consumption of sugars.

For pH, the opposite trend was observed: increasing these factors leads to an increase in pH, indicating the degradation of organic acids and a decrease in acidity. Changes in TA confirm this process, as under unfavorable conditions, the TA value drops below the optimal range.

Evaluation of TA confirmed that increasing temperature and prolonging storage reduce the total amount of organic acids, indicating a significant deterioration of the taste and chemical quality of the product. The decrease in TA logically corresponds to the increase in pH, highlighting the interrelationship between these two parameters.

Vitamin C content was found to be particularly sensitive, decreasing sharply under conditions of high temperature and prolonged storage. The obtained regression models enabled a quantitative assessment of the influence of each factor and the determination of the optimization direction.

Conclusion

Using mathematical modeling, linear regression equations were obtained for tomato storage with the application of the PP coating. Within the steepest ascent procedure, the optimal conditions for tomato storage were determined: temperature 16°C, immersion time 15 s, and storage time 27 days. These conditions represent a compromise between quality retention and a practically acceptable storage period.

These conditions ensure that TSS, TA, and vitamin C remain within normative ranges, while the pH is maintained within a safe range. The Method of Steepest Ascent not only confirms the trends obtained from the linear models, but also enables the identification of practically applicable optimal conditions, providing a solid theoretical and experimental basis for further improvement of technological regimes for storing tomatoes with an edible coating.

პოლიმერული ქიმია

პომიდვრის შენახვის ვადის ოპტიმიზაცია ფსევდოპროტეინული საკვები საფარით

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ნაშრომის მიზანია ფსევდოპროტეინზე დაფუძნებული საკვები საფარის ეფექტიანობის შეფასება პომიდვრის შენახვის პროცესში და შენახვის რეჟიმების ოპტიმიზაცია ექსპერიმენტის მათემატიკური დაგეგმვის მეთოდის გამოყენებით. აგროპროდუქტების შენახვის პერიოდში ერთ-ერთ მთავარ პრობლემას წარმოადგენს მათი კვებითი და სენსორული ხარისხის სწრაფი დაქვეითება, რაც დაკავშირებულია ნაყოფებში მიმდინარე ბიოქიმიურ პროცესებთან, მათ შორის, სუნთქვის ინტენსივობასთან, შაქრებისა და ორგანული მჟავების მეტაბოლურ ხარჯვასთან, ვიტამინების დეგრადაციასა და ტენის დანაკარგთან. თანამედროვე კვების ტექნოლოგიებში განსაკუთრებულ ყურადღებას იპყრობს საკვები საფარები, როგორც ინოვაციური და ეკოლოგიურად მდგრადი პრეზერვაციის საშუალება. 7%-იანი ფსევდოპროტეინული სპირტხსნარის გამოყენებით შეფასდა ტემპერატურის, ჩაყურსვისა და შენახვის დროის გავლენა ნა-

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