Innovative Food Technologies 13(3) (2026) 307-324

Iranian Research Organization for Science and Technology (IROST)

Innovative Food Technologies

journal homepage: https://jift.irost.ir

Kinetic Modeling of Physicochemical Changes in Protein Bars Enriched with Aqueous and Ethanolic Rice Bran Extracts During Storage

Zahra Ashrafpour Ardakani[a], **Amir Pourfarzad**[*,bc]

[a] *M.Sc. Graduate, Department of Food Science and Engineering, Faculty of Agricultural Sciences, University of Guilan, Rasht, Iran.*
[b] ** Associate Professor, Department of Food Science and Engineering, Faculty of Agricultural Sciences, University of Guilan, Rasht, Iran.*
[c] ** Associate Professor, Department of Chemical Technologies, Iranian Research Organization for Science & Technology (IROST), Tehran, Iran.*

ARTICLE INFO

Keywords:
Rice bran extract;
Antioxidant activity;
Shelflife;
Kinetic modeling;
Protein bars

ABSTRACT

Protein bars are among popular, safe, and health-oriented food products; however, they may undergo physicochemical changes during storage, leading to a reduction in product quality and consumer acceptability. The application of natural compounds with antioxidant activity, particularly plant-derived extracts, is considered an effective strategy to control and mitigate undesirable changes. In the present study, aqueous and ethanolic rice bran extracts were incorporated as functional ingredients due to their antioxidant properties and richness in phenolic and flavonoid compounds, with the aim of improving the quality and stability of protein bars. The stability of protein bars enriched with rice bran extracts was evaluated in comparison with a control sample over a 28-day storage period at ambient temperature, with assessments conducted at 7-day intervals. Moisture content, water activity, acidity, peroxide value, and color changes were monitored, and appropriate kinetic models were selected based on the coefficient of determination and error indices. Kinetic modeling revealed that the diffusion model, linear model, logistic model, and Gompertz model provided the best fit for moisture content, water activity and acidity, peroxide value, and color change, respectively. Furthermore, the results indicated that the incorporation of rice bran extracts, particularly the ethanolic extract, effectively reduced undesirable changes, enhanced storage stability, and preserved higher product quality throughout the storage period. These findings demonstrate that the use of natural and safe functional ingredients can improve the physicochemical stability of food products and contribute to the development of healthier and more sustainable foods.

1. Introduction

In recent decades, profound changes in lifestyle patterns, including extended working hours and reduced time for meal preparation, have significantly altered dietary habits, leading to a decreased consumption of traditional foods and an increased demand for ready-to-eat products [1]. Concurrently, growing consumer awareness regarding the risk of chronic diseases such as cardiovascular disorders, type 2 diabetes, and various cancers has intensified the preference for natural, safe, and health-oriented food products [2]. The pursuit of healthier lifestyles, combined with the need for convenient and time-efficient food solutions, has encouraged the development of products that effectively balance nutritional quality and ease of consumption [3]. Within this context, food bars have experienced remarkable growth in the global food market in recent years. These products encompass a wide range of categories, including protein bars, breakfast bars, and granola bars, and have gained popularity primarily due to their convenience and ready-to-consume nature [1, 3]. In addition to their ease of use, food bars typically provide balanced amounts of macronutrients, such as proteins, fats, and carbohydrate [2]. Moreover, they are often enriched with dietary fiber, antioxidant compounds, and various vitamins, enabling them to contribute substantially to daily nutritional requirements despite their relatively low caloric content [2, 3].

Among different types of food bars, protein bars have emerged as suitable meal replacements owing to their ability to supply energy and support physiological recovery. These products are widely consumed by diverse population groups, particularly athletes and vegetarians, due to their high protein content and functional benefits [2]. Protein bars are classified as intermediate-moisture foods, generally exhibiting water activity values ranging from 0.5 to 0.8, with limited amounts of free water. This characteristic contributes to enhanced microbial safety and extended shelf stability, making protein bars attractive from both nutritional and safety perspectives [4, 5]

Maintaining the physicochemical stability and overall quality of food products throughout storage, particularly under ambient temperature conditions, represents one of the major challenges in the food industry [6, 7]. Various factors, including moisture variation, changes in water activity, lipid oxidation, and color degradation, can adversely affect product quality and limit shelf life. Accordingly, the incorporation of stabilizing agents is essential to preserve quality attributes during storage [8].

* Corresponding author: amir.pourfarzad@gmail.com
DOI: http://dx.doi.org/10.22104/IFT.2025.8033.2257
(Received: 03 December 2025, Received in revised form: 24 December 2025, Accepted: 27 December 2025)

In line with the increasing consumer preference for natural and safe ingredients, the use of natural compounds with antioxidant activity has gained considerable attention as an effective approach to both enhance product stability and address food safety concerns [2]. Among natural stabilizing agents, plant-derived extracts have been widely applied in food systems due to their potent antioxidant properties and high safety profile [9].

Among plant-derived extracts, rice bran extract has attracted considerable attention as a functional ingredient obtained from rice bran and extractable using various methods and solvents, including organic and aqueous systems. Among the commonly used solvents, ethanol and water are regarded as the most effective and widely applied extraction media due to their high extraction efficiency and food-grade safety [6]. Rice bran extract is a rich source of bioactive and antioxidant compounds and exhibits a wide range of biological activities, including anti-inflammatory, anticancer, and antimicrobial properties [7]. Consequently, this extract has found extensive applications in the food, pharmaceutical, and cosmetic industries [6]. In food systems, rice bran extract has been utilized primarily as a natural stabilizing and preservative agent, particularly in meat and meat-based products [8]. Additionally, it has been reported to contribute to color preservation through the inhibition of polyphenol oxidase activity, which is attributed to its flavonoid-rich composition [6]. Owing to these functional properties, rice bran extract has strong potential as a natural functional ingredient for improving the nutritional quality, textural characteristics, and antioxidant capacity of food products, especially in health-oriented formulations such as protein bars [9].

Despite numerous studies focusing on the formulation and development of protein bars, limited attention has been paid to the evaluation of quality changes during storage and the kinetic analysis of these products. Kinetic assessment of key parameters, including moisture content, water activity, acidity, peroxide value, and color change index, can provide valuable insights into product stability and degradation mechanisms. Therefore, the present study aimed to investigate the physicochemical and oxidative changes of protein bars enriched with aqueous and ethanolic rice bran extracts during a 28-day storage period at ambient temperature and to model these changes using appropriate kinetic models. The application of kinetic modeling in the evaluation of food quality behavior enables the prediction of shelf life, determination of optimal packaging and storage conditions, selection of suitable stabilizing agents, and optimization of product formulations. Accordingly, the findings of this study may serve as a scientific basis for the development of health-oriented food products with enhanced stability and quality in the food industry.

2.Materials and Methods

2.1. Materials

The raw materials used in this study included food-grade glycerin (KLK Co., Malaysia), brown rice flour (Giltaz Co., Iran), whey protein powder (Roisa online store, Iran), aqueous and ethanolic rice bran extracts (Giahkala Co., Iran), sunflower oil, and distilled water .All chemicals and reagents employed for analytical purposes were of analytical grade and included phenolphthalein, sodium hydroxide, chloroform, sodium thiosulfate pentahydrate, and sodium carbonate (Merck, Germany), as well as glacial acetic acid (Dr. Mojallali Co., Iran) and potassium iodide (Chem Center store, Iran).

2.2. Methods

2.2.1. Preparation of Aqueous and Ethanolic Rice Bran Extracts

The aqueous and ethanolic rice bran extracts were prepared using a soaking method at Giahkala Co. Stabilized and sieved rice bran was extracted separately with distilled water and absolute ethanol. Briefly, 25 g of rice bran was mixed with 100 mL of each solvent and agitated on an electric shaker at room temperature for 3 h. Subsequently, the content of each flask was subjected to a second extraction using 100 mL of the respective solvent containing 0.15% hydrochloric acid under the same conditions. The resulting extracts were combined and filtered through a 0.45 μm nylon membrane. Finally, the extracts were concentrated using a rotary evaporator at 45°C and stored for further use [10].

2.2.2. Preparation of Protein Bars

Protein bars were prepared using a cold-processing method at a controlled temperature of 25 °C to prevent the degradation of heat-sensitive compounds, including whey proteins and bioactive constituents present in the rice bran extracts. The formulation consisted of brown rice flour, whey protein concentrate, food-grade glycerin, sunflower oil, and distilled water, with the exact quantities presented in Table 1. Three types of samples were produced which contain a control (without rice bran extract), a sample enriched with aqueous rice bran extract, and a sample enriched with ethanolic rice bran extract. The composition and ratios of the enriched samples were determined based on prior optimization studies to enhance their nutritional, textural, and sensory properties. In the first step, the dry ingredients (whey protein concentrate and brown rice flour) were mixed for 3 min at 200 rpm to achieve preliminary homogeneity. Subsequently, the liquid ingredients, including the rice bran extracts, distilled water, glycerin, and sunflower oil, were gradually incorporated into the dry mixture and homogenized for 5 min at 50 rpm. The process was designed to minimize air incorporation and to ensure a uniform, compact texture in the final product. The resulting mixture was then poured into silicone molds with uniform dimensions (2 × 2 × 2 cm) and shaped accordingly. The formed bars were placed in sealed polyethylene terephthalate (PET) containers and stored at 25 °C for 28 days to reach moisture equilibrium before further physicochemical analyses [11-13].

Table. 1. Protein Bar Formulation

Ingredients	Control Protein Bar (g/100 g)	Fortified Protein Bar with Ethanolic Rice Bran Extract* (g/100 g)	Fortified Protein Bar with Aqueous Rice Bran Extract* (g/100 g)
Whey protein concentrate	38.66	38.66	38.66
Brown Rice Flour	19.33	19.33	19.33
Ethanolic Rice Bran Extract	0	1.00	0
Aqueous Rice Bran Extract	0	0	1.00
Glycerin	16.01	16.01	16.01
Sunflower Oil	9.80	9.80	9.80
Water	16.20	15.20	15.20

Fortified Protein Bars Contains 1% Ethanolic Rice Bran Extract and 1% Aqueous Rice Bran Extract

2.2.3. Moisture Content

The moisture content of the samples was determined using the oven-drying method. Initially, the used plates were thoroughly washed and dried at 105 °C for 30 min to remove any residual moisture. The plates were then cooled in a desiccator and weighed to obtain the initial weight. Subsequently, 4–5 g of finely chopped sample were placed on each plate and dried in an oven at 105 °C for 4 h. After drying, the plates were cooled in a desiccator and reweighed. To ensure complete drying and weight stabilization, the plates were returned to the oven for an additional 30 min and weighed again after cooling. The drying process was considered complete when consecutive weights did not differ [1]. Moisture content (%) was calculated using the following equation:

$$W_S-(W_2-W_1)/W_S)\times 100 \quad (1)$$

where W_s is the weight of the sample, W_1 is the weight of the plate after pre-drying in the oven, and W_2 is the combined weight of the plate and sample after 4 h of drying at 105 °C.

2.2.4. Water Activity

Water activity of the samples was measured using a LabTouch-aw water activity meter (NOVASINA, Switzerland) at 25 °C. Approximately 4 g of each sample was weighed and placed in the device, and the measurements were performed in triplicate. The final reported value was calculated as the mean of three replicates [2, 14].

2.2.5. Titratable Acidity

Titratable acidity of the protein bars was determined according to standard titration procedures. Five grams of each sample were accurately weighed and dissolved in 50 mL of distilled water. The resulting suspension was allowed to equilibrate at room temperature for 1 h. Subsequently, 0.5 mL of 1% phenolphthalein indicator was added, and the solution was titrated with 0.1 N sodium hydroxide until a faint pink color appeared, remaining stable for at least 30 s [15].

2.2.6. Peroxide Value

Peroxide value (PV) of the samples was determined following a standard iodometric titration method. First, a 0.01 M sodium thiosulfate solution was prepared by dissolving 26 g of sodium thiosulfate pentahydrate and 200 mg of sodium carbonate in 1 L of boiled distilled water, which was then diluted tenfold with distilled water. A 1% (w/w) starch indicator solution was prepared by dissolving the appropriate amount of starch in cold distilled water. A saturated potassium iodide solution was also prepared separately. For the assay, 4 g of each sample was accurately weighed and mixed with 10 mL of chloroform and 15 mL of glacial acetic acid under a fume hood. After 30 min, the mixture was filtered through a 125 mm diameter Whatman filter paper. Subsequently, 1 mL of freshly prepared potassium iodide solution was added dropwise to the filtrate with vigorous shaking, and the sample was kept in the dark for 5 min. Then, an equal volume of distilled water was added, followed by 0.5 mL of the starch indicator. Finally, the solution was titrated with 0.01 M sodium thiosulfate using a blank as reference. Peroxide value, expressed as milliequivalents of active oxygen per kilogram of sample, was calculated using the following equation:

$$PV = \frac{(V_1 - V_0)T \times 10^3}{M} \quad (2)$$

where V_1 is the volume of sodium thiosulfate solution used for the sample (mL), V_0 is the volume used for the blank (mL), M is the sample weight (g), and T is the molarity of the sodium thiosulfate solution [16].

2.2.7. Color Measurement

The color of the samples was evaluated using an image processing method. For each protein bar, three different regions were selected and photographed with a 64-megapixel Samsung M32 camera from a fixed distance of 9.5 cm under consistent lighting conditions. The raw RGB images were saved in JPEG format and processed using ImageJ software. Images were converted from the RGB color space to the CIELab coordinates using the appropriate plugin, and the L*, a*, and b* values were subsequently calculated [17]. The total color difference (ΔE) between the control and treated samples over different storage times was calculated using the following equation:

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \quad (3)$$

where L_0, a_0, and b_0 are the color parameters at the

initial time, and L, a, and b are the color parameters after the storage period.

2.2.8. Kinetic Analysis During Storage

To model and analyze the physicochemical and color changes of the samples over time, the data were processed and plotted using MATLAB software (version 2024). Fourteen different kinetic models were evaluated to fit the experimental data, and the goodness-of-fit for each model was assessed using the coefficient of determination (R^2), chi-square test, root mean square error (RMSE), and mean deviation error (MDE). The optimal model was selected based on the highest R^2 and the lowest fitting errors. This kinetic analysis provided a deeper understanding of product quality behavior over time and facilitated the validation of the optimized treatment under real storage conditions. The parameters mentioned above were calculated as follows [18]:

$$\chi 2 = \frac{\sum_{i=1}^{N}(HR_{exp,i}-HR_{pre,i})^2}{N-n} \quad (4)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(HR_{pre,i} - HR_{exp,i}) \quad (5)$$

$$RMSE = [\frac{1}{N}\sum_{i=1}^{N}(HR_{pre,i} - HR_{exp,i})^2]^{\frac{1}{2}} \quad (6)$$

where $HR_{exp.i}$ represents the experimentally obtained values of the physicochemical properties, and $HR_{pre,i}$ corresponds to the predicted values from the kinetic models. N denotes the number of observations, and n is the number of model constants. To assess statistical differences between the kinetic model coefficients of the control and optimized protein bar samples, an independent two-sample t-test was performed at a significance level of 0.05 [19].

3.Results and Discussion

3.1. Kinetic Analysis During Storage

During the storage of food products, numerous physicochemical properties undergo significant changes. Monitoring these changes provides a better understanding of product stability and is essential for predicting shelf life and determining optimal storage conditions [20]. One of the most reliable approaches for analyzing and modeling such changes is kinetic modeling, which allows the quantification of the rate and extent of parameter variations over time [21]. Commonly used kinetic models include linear, second-order, Arrhenius, and diffusion-based models, which are widely applied in food science to describe the behavior of changing properties. Model selection is typically based on experimental data analysis and evaluation of fit indices such as the coefficient of determination (R^2), root mean square error (RMSE), chi-square (χ^2), and mean bias error (MBE) [22, 23]

In the present study, fourteen empirical regression models—including linear, second-order, Weibull, Gompertz, Harris, rational, Newton, planar, logarithmic, exponential, logistic, quadratic, diffusion, and Fourier models—were applied to model the changes in physicochemical parameters of control and rice bran extract-enriched protein bars during storage. The statistical evaluation of the models, including fit indices and model coefficients, along with the comparative analysis of selected model coefficients between control and enriched samples, are presented in Tables 2 to 11.

3.2. Moisture

During the storage period, a decrease in moisture content is one of the most common physicochemical changes in food products, particularly in protein- or fiber-enriched formulations. This reduction typically results from water evaporation, moisture exchange with the environment, or structural changes in the product matrix, which may lead to firmer texture, reduced crispness, and diminished sensory quality [24]. In the present study, moisture variations were monitored in the control and rice bran extract-enriched protein bars over a 28-day storage period. The results indicated a decreasing trend in all three samples; however, the control exhibited the highest moisture loss. This can be attributed to the absence of protective bioactive compounds, leading to increased evaporation and limited moisture retention. The sample enriched with aqueous rice bran extract experienced a smaller decrease, likely due to the presence of polar, hydrophilic compounds in the extract. These compounds form hydrogen bonds with water molecules in the food matrix, thereby slowing down the rapid moisture loss [25]. Notably, the ethanolic rice bran extract-enriched sample exhibited the least reduction in moisture content. This superior performance can be associated with the higher concentration of ethanol-soluble phenolic compounds, such as γ-oryzanol, tocopherols, and tocotrienols, which not only possess strong antioxidant activity but also reinforce the protein network and reduce moisture permeability. These compounds create a hydrophobic barrier, thereby enhancing moisture retention and decreasing drying rates [26]. Overall, these findings suggest that the incorporation of rice bran extract, particularly in its ethanolic form, can serve as an effective strategy to improve moisture stability in food products.

To further analyze these changes, the moisture data were fitted to various kinetic models to identify the most appropriate model describing the moisture loss over time. Model performance was evaluated using fit indices, including the coefficient of determination (R^2), root mean square error (RMSE), chi-square (χ^2), and mean bias error (MBE). The model exhibiting the highest R^2 and the lowest errors was selected as the optimal kinetic model, as it provides the most accurate representation of the observed trend. As presented in Table 2, the two-stage diffusion model demonstrated the best fit for all samples, with high coefficients of determination (R^2 = 0.93511 for the control, 0.98388 for the sample containing 1% ethanolic extract, and 0.9540 for the sample containing 1% aqueous extract). This model also yielded the lowest

RMSE and χ^2 values across all samples, and thus was chosen as the final kinetic model. Kinetic studies on similar food products have indicated that moisture reduction during storage often follows nonlinear patterns, with diffusion-based models frequently providing the best fit—particularly when mass transfer within the dense food matrix is the primary rate-controlling process. Additionally, bioactive compounds present in plant extracts, especially hydrophilic phenolics, can significantly contribute to moisture retention by forming hydrogen bonds with water molecules in the matrix [24]. The mathematical expression of the diffusion model is given as follows:

$$C_t = a \exp(-bt) + (1-c) \exp(-cdt) \quad (7)$$

The diffusion model applied in this study comprises two stages: an initial rapid moisture loss phase followed by a slower reduction in the later stage. In this model, parameter a represents the fraction of free moisture at the initial stage, while b indicates the rate of rapid moisture loss in the first phase. The highest a value was observed in the ethanolic extract-enriched sample (0.417), indicating a higher proportion of free moisture in this formulation. Conversely, the aqueous extract-enriched sample exhibited the lowest a value (0.039), which can be attributed to the strong interaction of water molecules with polar, hydrophilic compounds present in the aqueous extract and the food matrix. The parameter b for the control sample (1.266) was the highest, reflecting the fastest initial moisture loss, whereas the ethanolic extract sample showed a markedly lower rate (0.0920), demonstrating the protective effect of this extract against rapid evaporation. The aqueous extract sample exhibited an intermediate behavior with b = 0.6438. In the second phase, parameter c represents the fraction of bound moisture available for reduction in the slower stage, and d denotes its rate of decrease. The ethanolic extract sample had the highest c value (0.8256), indicating more effective moisture retention, while the aqueous extract sample had the lowest c (0.8029). Similarly, the lowest d value was observed in the ethanolic extract sample (0.0008), reflecting the slowest moisture reduction rate, likely due to the presence of stabilizing antioxidant compounds such as γ-oryzanol and tocopherols. The control sample exhibited the highest d (0.0092), indicating faster moisture loss in the second phase. These results indicate that the ethanolic extract-enriched sample-maintained moisture more effectively across both phases due to a denser matrix structure and the presence of bioactive compounds.

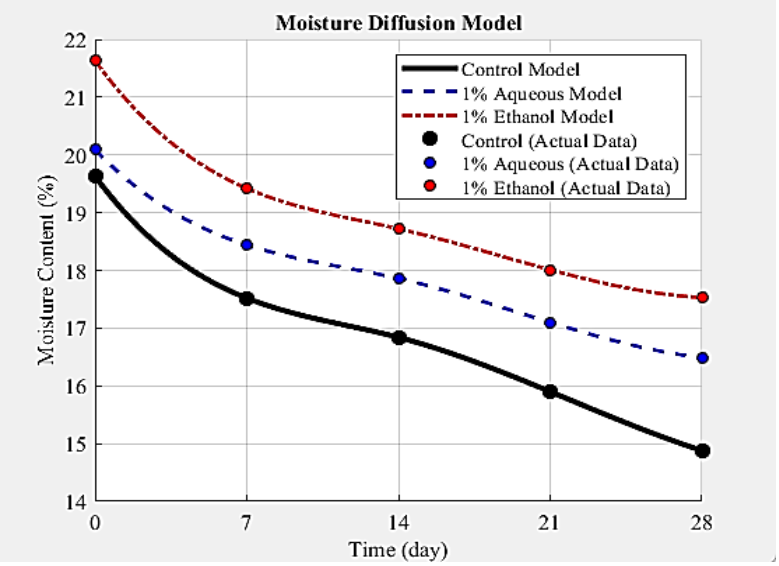

Fig. 1. Diffusion model fitting graph for Moisture changes in control and fortified protein bars during storage time

Beyond the statistical fit, the diffusion model parameters correspond closely with the experimental moisture trends. Specifically, the ethanolic extract sample, which exhibited the least moisture loss in raw data, also showed the lowest rate constants in both phases, confirming its efficacy in maintaining structure and minimizing evaporation. This protective effect can be attributed to hydrophilic antioxidant compounds capable of forming stable interactions with the matrix, thereby reducing water vapor permeability [27]. Similar findings were reported by Díaz et al. [28], who observed a decreasing trend in moisture over a 43-day storage period in protein bars, leading to increased hardness, reduced sensory quality, and lower consumer acceptance. The reduction was mainly attributed to moisture exchange between the product and the surrounding environment. Moreover, supplementation with polyphenol-rich extracts, such as cranberry extract, was found to significantly control moisture loss by stabilizing the protein–polyphenol interactions and maintaining the textural integrity of the product during storage. Therefore, the inclusion of polyphenol-rich extracts, such as ethanolic rice bran extract, not only improves the initial product quality but also plays a crucial role in preserving textural and moisture stability throughout storage [29].

Table. 2. Statistical analysis results of moisture modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model. No	Name	Model Equation	Constants			R^2		
			Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
1	Linear	$C_t = a + bt$	a=0.1918 b= -0.0015	-0.0014 0.2099	-0.0012 0.1893	0.89827	0.88563	0.93892
2	Quadratic	$C_t = a + bt + Ct^2$	a=0.0000 b= -0.0019 c=0.1933	0.0001 0.0030 0.2155	0.0000 0.0015 0.1992	0.90478	0.98214	0.94287
3	Harris	$C_t = 1 / (a + bt^c)$	a= 5.1082 b= 0.1230 c=0.7261	4.6218 0.1766 0.5594	4.9918 0.0625 0.8469	0.9227	0.98364	0.94769
4	Rational	$C_t = (a+bt) /(1+ct+dt^2)$	a=0.1963 b= 1.0021 c=5.3906 d= 0.0404	0.2163 0.9992 4.9708 0.0291	0.2009 1.0017 5.1303 0.0331	0.90478	0.98019	0.95488
5	Newton	$C_t = \exp(-at)$	a= -0.1865	-16.58	-0.1737	-606.3	-596.02	-889.89
6	Page	$C_t = \exp(-at^b)$	a =1.7823 b = -0.0040	1.6798 0.0041	-1.1726 0.0032	0.70241	0.80737	0.6604
7	Logarithmic	$C_t = a \exp(-bt) + c$	a=0.8884 b=0.0017 c=0.6964	0.8894 -0.0017 -0.6793	0.9112 -0.0014 -0.7128	0.89931	0.88961	0.93959
8	Exponential	$C_t = a (b - \exp(-ct))$	a=0.0011 b=153.4662 C=-0.0432	0.0010 194.0602 0.0273	0.0012 157.596 0.0528	-0.035	-0.023	-0.0493
9	Logistic	$C_t = a / (1 + b \exp(-ct))$	a =0.1808 b = -0.0554 c = 0.0000	0.5421 1.8579 0.0000	0.6178 2.4125 0.0000	-1.8694 e^{-9}	-3.9053 e^{-9}	-3.4907 e^{-10}
10	Two-term	$C_t = a \exp(-bt) + c \exp(-dt)$	a =0.0963 b =0.0086 c =0.0963 d= -0.0086	0.1054 -0.0077 0.1054 0.0077	0.0994 -0.0068 0.0994 0.0068	0.90298	0.9035	0.94171
11	Diffusion	$C_t = a \exp(-bt) + (1-c) \exp(-cdt)$	a =0.0087 b =1.0266 c =0.8121 d =0.0092	0.0417 0.0920 0.8256 0.0008	0.0039 0.6438 0.8029 0.0081	0.93511	0.98388	0.954
12	Weibull	$C_t = ab (x^{b-1}) (\exp(a (x^b))$	a=0.0850 b=0.9624	0.0863 0.9587	0.0863 0.9616	-68.476	-88.364	-117.34
13	Gompertz	$C_t = a \exp(-\exp(b(c-x)))$	a=0.2480 b=0.0251 c=36.1306	1.7715 0.0156 82.1055	0.2198 0.0519 17.4792	0.88751	0.96136	0.93052
14	Fourier	$C_t = a+b(\cos(cx)) + d(\sin(cx))$	a=2040.4290 b= -4290.1070 c=0.0001 d= -22.4813	1301.2676 -1301.0521 0.0003 10.2572	30501.8777 30501.6785 0.0000 59.7454	0.9043	0.98214	0.94287

Table. 2. (continued). Statistical analysis results of moisture modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model. No	Name	MBE			RMSE			χ^2		
		Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
1	Linear	7.2164 e^{-17}	4.996 e^{-17}	6.1062 e^{-17}	0.004	0.005	0.003	0.0006	0.0006	0.0002
2	Quadratic	-1.1102 e^{-17}	1.1102 e^{-17}	5.5511 e^{-18}	0.004	0.002	0.003	0.0006	0.0001	0.0002
3	Harris	3.4542 e^{-6}	-7.206 e^{-7}	3.8691 e^{-6}	0.004	0.001	0.002	0.0005	0.0001	0.0002
4	Rational	6.2186 e^{-6}	-1.2792 e^{-6}	3.0675 e^{-6}	0.003	0.002	0.002	0.0004	0.0001	0.0001
5	Newton	0.10263	0.10066	0.1026	0.375	0.370	0.375	5.7139	4.274	4.7714
6	Page	1.4726 e^{-6}	1.2818 e^{-6}	8.0147 e^{-7}	0.008	0.006	0.007	0.0021	0.0001	0.0015
7	Logarithmic	2.9021 e^{-5}	2.1719 e^{-6}	2.7544 e^{-6}	0.004	0.005	0.003	0.0004	0.0006	0.0002
8	Exponential	-7.416 e^{-5}	1.9015 e^{-5}	7.4499 e^{-5}	0.015	0.015	0.012	0.0070	0.0066	0.0045
9	Logistic	4.2802 e^{-9}	-3.9591 e^{-7}	1.9884 e^{-8}	0.015	0.015	0.012	0.0067	0.0061	0.0043

Model. No	Name	MBE			RMSE			χ^2		
		Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
10	Two-term	-2.9048 e^{-6}	-1.9015 e^{-5}	1.3197 e^{-6}	0.004	0.004	0.003	0.0006	0.0005	0.0002
11	Diffusion	0.00010964	2.3379 e^{-5}	0.000112	0.003	0.001	0.002	0.0004	0.0001	0.0001
12	Weibull	-0.11398	-0.12839	-0.12279	0.127	0.143	0.136	5.002	6.473	5.848
13	Gompertz	-3.923	0.0004	5.9222 e^{-5}	0.005	0.002	0.003	0.0007	0.0002	0.0002
14	Fourier	-1.6893 e^{-13}	1.5486 e^{-13}	-1.1837 e^{-11}	0.004	0.002	0.003	0.0003	0.0001	0.0002

3.3. Water Activity

Changes in water activity during storage vary depending on the product type and environmental conditions, and in some cases, water activity may increase over time due to moisture absorption from the environment, degradation of dry matter, or the presence of humectant additives [28]. In the present study, water activity of all samples exhibited an increasing trend over the 28-day storage period, with the highest increase observed in the control sample and the lowest in the sample enriched with aqueous rice bran extract. The reduced water activity in the rice bran extract-enriched samples can be primarily attributed to the presence of polyphenolic compounds and their interactions with proteins. These compounds limit the mobility of free water molecules by forming insoluble complexes and decrease the water-holding capacity of macromolecules [29-31]. Furthermore, the higher content of starch and fiber in the aqueous extract contributes to the formation of a dense three-dimensional network and modifies the viscosity, further restricting water molecule movement and reducing water activity [29, 32]. For kinetic modeling of these changes, the water activity data were fitted to various kinetic models, and the optimal model was selected based on the coefficient of determination (R^2), root mean square error (RMSE), chi-square (χ^2), and mean bias error (MBE). The results indicated that the linear model provided the best fit, exhibiting high coefficients of determination (R^2 = 0.97322 for the control, 0.97932 for the ethanolic extract, and 0.98021 for the aqueous extract) along with the lowest fitting errors. The mathematical expression of the linear model is as follows:

$$C_t = a + bt \quad (8)$$

In this linear model, the slope represents the rate of change in water activity, while the intercept corresponds to the initial value. The slope values for the control (0.0004), ethanolic extract (0.0003), and aqueous extract (0.0002) indicate that the control sample exhibited the fastest increase in water activity, whereas the aqueous extract-enriched sample showed the slowest. Similarly, the intercept values were 0.7769, 0.7736, and 0.7735 for the control, ethanolic, and aqueous extract samples, respectively, indicating that the control had the highest initial water activity, while the aqueous extract sample had the lowest. These findings demonstrate that the addition of polyphenol-rich rice bran extracts, particularly the aqueous form, effectively slows the rate of water activity increase by restricting water molecule mobility. The ethanolic extract exhibited an intermediate effect between the control and aqueous extract. This kinetic analysis aligns well with the experimental data, confirming the significant role of polyphenolic compounds in controlling water activity and enhancing product stability [28].

The kinetic modeling results showed excellent agreement with the observed trends, indicating that the selected linear model accurately describes the water activity behavior of the samples throughout the storage period. The data further confirm that the incorporation of polyphenol-rich rice bran extracts, especially the aqueous form, significantly reduces the slope of the increasing water activity trend compared to the control. This slower rate is primarily attributed to the polyphenolic nature of the extract, which limits water mobility by forming insoluble complexes with proteins, thereby reducing water-holding capacity within the macromolecular matrix [28, 30]. Additionally, the higher starch and fiber content in the aqueous extract contributes to a denser three-dimensional network and increased viscosity, further restricting water molecule movement and lowering water activity [31, 32]. Overall, besides the strong statistical fit, the analysis of the linear model parameters closely corresponds with the experimental observations. Notably, the aqueous extract-enriched sample, which exhibited the lowest raw data increase in water activity, also showed the lowest kinetic rate in the model. This agreement between experimental and modeled data confirms the effective role of polyphenolic compounds in reducing water activity and enhancing microbial stability, with the aqueous extract showing a more pronounced effect than the ethanolic form.

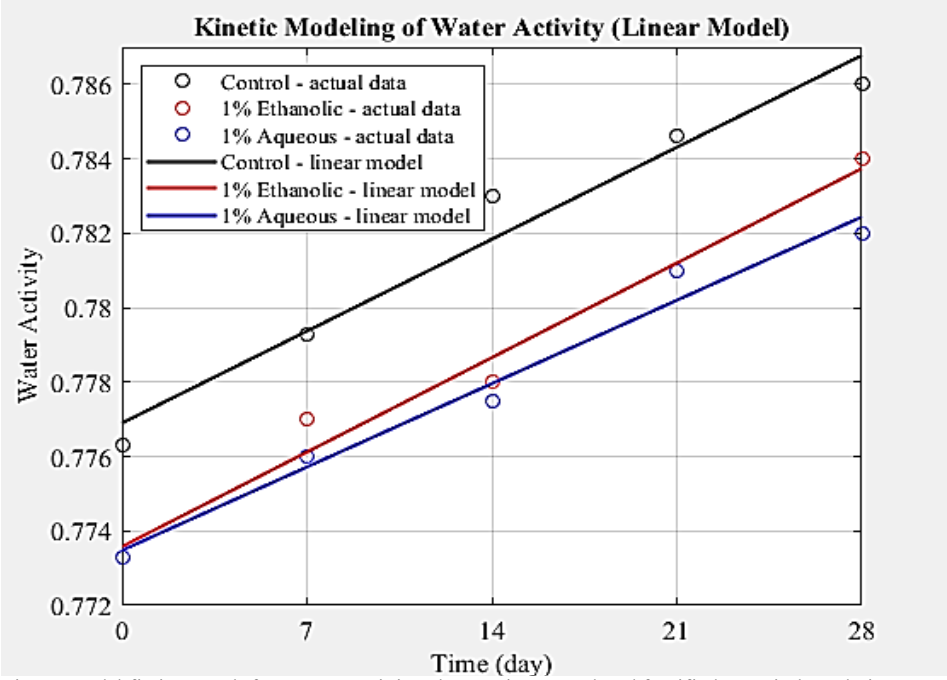

Fig. 2. Linear model fitting graph for Water Activity changes in control and fortified protein bars during storage time

Table. 3. Statistical comparison of the Diffusion model constants for moisture

Constant	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	p-Value
a	0.0087 [b]	0.0417 [a]	*0.0039* [c]	1.32×10^{-14}
b	1.0266 [a]	0.0920 [c]	0.6438 [b]	1.66×10^{-18}
c	0.8122 [a]	0.8256 [a]	0.8029 [a]	8.23×10^{-11}
d	0.0092 [a]	0.0008 [c]	0.0081 [b]	3.32×10^{-11}

*Values with different letters in each row indicates a significant difference at the 0.05 level, while values with the same letters are not significantly different

Table. 4. Statistical analysis results of water activity modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model. No	Name	Model Equation	Constants			R^2		
			Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
1	Linear	$C_t = a + bt$	a=0.7769 b=0.0004	0.7736 0.0003	0.7735 0.0002	0.97392	0.97929	0.98021
2	Quadratic	$C_t = a + bt + Ct^2$	a=0.0000 b= 0.0006 c=0.7761	0.0000 0.0003 0.7737	0.0000 0.0004 0.7733	0.96167	0.97887	0.97748
3	Harris	$C_t = 1 / (a + bt^c)$	a= 1.2790 b= 0.0000 c=0.0001	1.2843 0.0000 0.0002	1.2854 0.0000 0.0001	-1.3586 e^{-6}	-1.5565 e^{-8}	-1.1451 e^{-6}
4	Rational	$C_t = (a+bt) /(1+ct+dt^2)$	a=0.7763 b= 1.5805 c=2.0312 d= -0.0008	0.7733 1.5783 2.0386 -0.0009	0.7733 1.5777 2.0385 -0.0008	0.97622	0.98187	0.97894
5	Newton	$C_t = \exp(-at)$	a= -0.0121	-0.0123	-0.0124	-1232.9	-1229.2	-1577
6	Page	$C_t = \exp(-at^b)$	a =-0.2461 b = 0.0000	-0.2502 0.0000	-0.2511 0.0000	-2.0703 e^{-6}	-2.1675 e^{-6}	-1.0269 e^{-5}
7	Logarithmic	$C_t = a \exp(-bt) + c$	a=0.8069 b=0.0000 c=-0.0250	0.8064 0.0000 -0.0277	0.0759 0.0000 0.7020	-8.8196 e^{-5}	-9.1269 e^{-5}	-0.00016966
8	Exponential	$C_t = a (b - \exp(-ct))$	a=0.0133 b=59.3905 C=-0.0567	0.0142 55.3515 -0.0510	0.0126 62.2967 -0.0541	0.96413	0.92608	0.93659
9	Logistic	$C_t = a / (1 + b \exp(-ct))$	a =0.7903 b = 0.0182 c = -0.0440	0.7874 0.0187 -0.0423	0.7881 0.0194 -0.0315	0.96205	0.94825	0.97363
10	Two-term	$C_t = a \exp(-bt) + c \exp(-dt)$	a =0.3909 b =0.0000 c =0.03909 d= -0.0000	0.3893 0.0000 0.3893 0.0000	0.3890 -0.0000 0.3890 0.0000	-0.000151	-0.00012327	-0.00036662

Model. No	Name	Model Equation	Constants			R^2		
			Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
11	Diffusion	C_t = a exp (-bt) + (1-c) exp (-cdt)	a =0.0005 b =0.0000 c =0.2187 d =0.0000	0.0005 0.0000 0.2219 0.0000	0.0007 0.0000 0.2228 0.0000	-1.9854 e^{-6}	-1.4109 e^{-6}	-0.0042312
12	Weibull	C_t = ab (x^{b-1}) (exp (a (x^b))	a=0.1003 b=0.9070	0.1004 0.9073	0.1004 0.9073	-36342	-34927	-44671
13	Gompertz	C_t =a exp (-exp (b(c-x)))	a=0.7866 b=0.1345 c=7.4438	0.7845 0.0969 8.8733	0.7838 0.0892 8.4184	0.99829	0.9463	0.97788
14	Fourier	C_t = a+b(cos(cx)) + d(sin(cx))	a=0.7798 b= -0.0035 c=0.0784 d= 0.0784	1.0488 -0.2751 0.0026 0.1303	0.7775 -0.0040 0.0823 0.0025	0.96549	0.97927	0.98295

Table. 4. (continued). Statistical analysis results of water activity modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model. No	Name	MBE			RMSE			χ^2		
		Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
1	Linear	1.1102 e^{-16}	2.6645 e^{-16}	1.3323 e^{-17}	0.00069929	0.00052734	0.0004808	3.1244 e^{-6}	1.7888 e^{-6}	4.4827 e^{-6}
2	Quadratic	8.8818 e^{-17}	0	0	0.0002784	0.00052211	0.0004507	4.9644 e^{-7}	1.7548 e^{-6}	4.3037 e^{-6}
3	Harris	1.2033 e^{-6}	4.1125 e^{-11}	1.0461 e^{-6}	0.0035717	0.00036278	0.0032041	8.1582 e^{-5}	8.451 e^{-5}	6.5983 e^{-5}
4	Rational	1.6176 e^{-7}	1.7086 e^{-7}	1.7649 e^{-6}	0.00055076	0.00048842	0.000465	1.9387 e^{-6}	1.5318 e^{-6}	1.3864 e^{-6}
5	Newton	0.068267	0.06914	0.069144	0.12546	0.12724	0.12728	0.08332	0.085882	0.08592
6	Page	3.9533 e^{-8}	3.9069 e^{-8}	6.6281 e^{-8}	0.0035717	0.00036278	0.0032041	8.1583 e^{-5}	8.451 e^{-5}	6.5983 e^{-5}
7	Logarithmic	-2.4348 e^{-6}	-2.5388 e^{-6}	-2.3978 e^{-5}	0.0035719	0.003628	0.0032044	8.159 e^{-5}	8.4518 e^{-5}	6.5996 e^{-5}
8	Exponential	-8.3381 e^{-5}	-8.5848 e^{-5}	-6.9588 e^{-5}	0.00044993	0.00098633	0.00080684	1.3024 e^{-6}	6.2487 e^{-6}	4.1957 e^{-6}
9	Logistic	1.2909 e^{-5}	-2.1859 e^{-5}	-1.4224 e^{-5}	0.0003185	0.00082524	0.00052033	6.4964 e^{-7}	4.364 e^{-6}	1.7378 e^{-6}
10	Two-term	-1.3626 e^{-7}	-1.2792 e^{-7}	-1.7559 e^{-7}	0.003572	0.003628	0.0032047	8.1595 e^{-5}	8.4521 e^{-5}	6.6007 e^{-5}
11	Diffusion	2.7572 e^{-8}	2.4071 e^{-8}	1.438 e^{-7}	0.0035717	0.0036278	0.0032109	8.1583 e^{-5}	8.451 e^{-5}	6.6262 e^{-5}
12	Weibull	-0.60949	-0.6069	-0.60619	0.6809	0.678	0.67721	150.58	149.59	149.15
13	Gompertz	1.0885 e^{-7}	-1.3553 e^{-9}	2.9796 e^{-5}	0.00014779	0.00084067	0.00047659	1.3926 e^{-7}	4.5312 e^{-6}	1.4584 e^{-6}
14	Fourier	-8.8818 e^{-17}	1.5543 e^{-16}	-2.2204 e^{-17}	0.00023999	0.00052228	0.0004184	3.6743 e^{-7}	1.756 e^{-6}	1.1256 e^{-6}

3.4. Titratable Acidity

Titratable acidity is an indicator of the total acid concentration in a food product, determined by titration of intrinsic acids with a standard base [33]. This parameter serves as a critical marker for evaluating food quality and stability [34], and it can also indicate lipid degradation and product deterioration [35]. During the 28-day storage period, TA values in all samples exhibited an increasing trend. The rise in acidity is typically associated with the hydrolysis of lipids and the release of free fatty acids due to lipase activity, as well as oxidative reactions occurring during storage [36]The addition of rice bran extracts had a minor impact on Acidity, slightly reducing the rate of increase compared to the control sample. This limited effect may be influenced by factors such as rice bran variety, processing conditions, stabilization and storage, and extraction methods [37]. Moreover, the trends observed in the aqueous and ethanolic extract-enriched samples were similar, with no significant differences between them. This indicates that both extract types exert a comparable effect in mitigating oxidative reactions, thereby reducing free fatty acid formation. The polyphenolic and antioxidant compounds present in rice bran extracts play a key role in slowing the increase of TA by neutralizing free radicals and protecting lipids from oxidative degradation [31, 32]. In addition to the experimental evaluation, titratable acidity was analyzed kinetically to quantify its rate of change and behavior during the storage period. This analysis provides a better understanding of the effects of rice bran extracts on acidity progression and enables prediction of product performance over time. The data were fitted to several kinetic models, and the accuracy of each model was

assessed using the coefficient of determination (R^2), root mean square error (RMSE), chi-square (χ^2), and mean bias error (MBE). The optimal model was selected based on the highest R^2 and the lowest fitting errors, allowing quantitative description and prediction of Titratable acidity behavior during storage. Among the evaluated models, three—linear, second-order, and Gompertz—demonstrated high R^2 values, making them suitable for describing TA changes. However, the linear model was selected as the best-fitting model due to its lower error indices, in addition to its simplicity and superior predictive capability. The mathematical expression of the linear kinetic model is as follows:

$$C_t = a + bt \quad (9)$$

Table. 5. Statistical comparison of the Linear model constants for Water activity

Constant	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	p-Value
a	0.7769 [a]	0.7736 [b]	0.7735 [c]	0.0003
b	0.0004 [a]	0.0003 [a]	0.0002 [a]	0.061

*Values with different letters in each row indicates a significant difference at the 0.05 level, while values with the same letters are not significantly different

In this model, the slope coefficient (b) representing the rate of change in titratable acidity, was 0.0143 for all samples, indicating a similar rate of acidity increase across the different treatments. However, the intercept (a) differed among the samples, with the control showing an initial value of 1.00, while the aqueous and ethanolic rice bran extract-enriched samples had lower initial values of 0.90. This reduction in initial Acidity in the enriched samples can be attributed to the presence of antioxidant and polyphenolic compounds in the rice bran extracts, which mitigate oxidative reactions at the beginning of the storage period [31, 32]. Overall, the linear model accurately described the progression of titratable acidity throughout the storage period, making it a suitable choice for kinetic analysis of this parameter. The strong agreement between modeled and experimental data confirms the model's reliability in representing the actual behavior of acidity changes over time. These findings are consistent with those reported by Hatami et al., who also observed that the addition of both aqueous and ethanolic rice bran extracts did not significantly alter the titratable acidity of a probiotic beverage during storage [38].

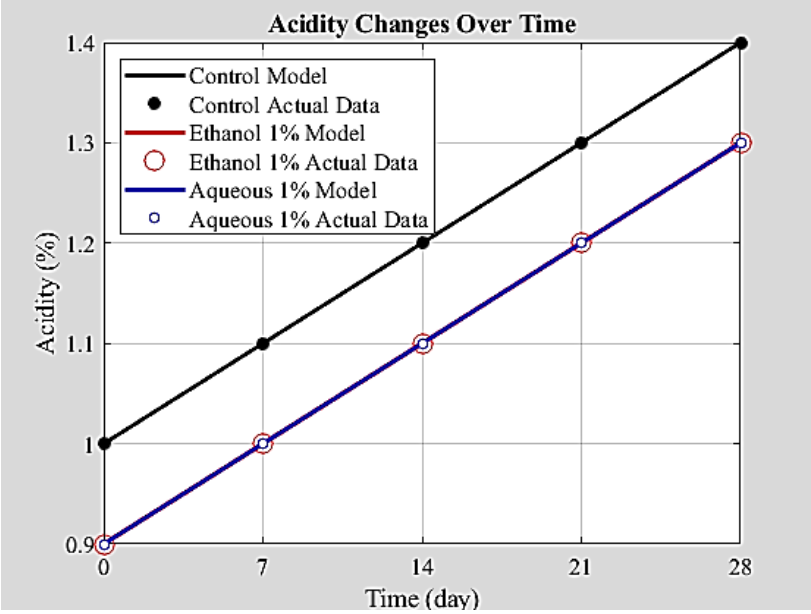

Fig. 3. Linear model fitting graph for Acidity Value changes in control and fortified protein bars during storage time

Table. 6. Statistical analysis results of Acidity modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model No.	Name	Model Equation	Constants			R^2		
			Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
1	Linear	$C_t = a + bt$	a=1.0000 b=0.0143	0.9000 0.0143	0.9000 0.0143	0.9999	0.99999	0.9999
2	Quadratic	$C_t = a + bt + Ct^2$	a= -0.0000 b=0.0143 c=1.0000	-0.0000 0.0143 0.9000	-0.0000 0.0143 0.9000	0.98722	0.99722	0.99470
3	Harris	$C_t = 1 / (a + bt^c)$	a= 0.8333 b= 0.0000 c=0.0000	0.9091 0.0000 0.0000	0.9091 0.0000 0.0000	-1.0374 e^{-10}	-4.0258 e^{-11}	-4.0258 e^{-11}

Model No.	Name	Model Equation	Constants			R^2		
			Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
4	Rational	$C_t=(a+bt)/(1+ct+dt^2)$	a=1.0000 b=12.1938 c=11.7535 d= -0.1105	0.9000 14.0633 14.9611 -0.1504	0.9000 14.0633 14.9611 -0.1504	0.99753	0.99709	0.99709
5	Newton	C_t =exp (-at)	a= 0.0000	0.0000	0.0000	-2	-0.50001	-0.5001
6	Page	C_t= exp ($-at^b$)	a =0.0000 b =0.0000	0.0000 0.0000	0.0000 0.0000	-2	-0.5	-0.5
7	Logarithmic	C_t =a exp(-bt) +c	a=0.0000 b=-0.0002 c=1.2000	0.0001 0.0000 1.0998	0.0001 0.0000 1.0998	-4.9671 e^{-7}	-7.1706 e^{-7}	-7.1706 e^{-7}
8	Exponential	C_t =a (b – exp(-ct))	a=4.4322 b=1.2249 c=-0.0034	2.7607 1.3239 -0.0056	2.7607 1.3239 -0.0056	0.99979	0.99939	0.99939
9	Logistic	C_t = a / (1 + b exp(-ct))	a =2.3226 b =1.3232 c =-0.0248	2.1838 1.4258 -0.0264	2.1838 1.4258 -0.0264	0.99998	0.9998	0.99998
10	Two-Term	C_t =a exp(-bt) +c exp(-dt)	a =0.6000 b =0.0000 c =0.6000 d= 0.0000	0.5500 0.0000 0.5500 0.0000	0.5500 0.0000 0.5500 0.0000	-3.7303 e^{-12}	-6.2675 e^{-10}	-6.2675 e^{-10}
11	Diffusion	C_t =a exp (-bt) + (1-c) exp (-cdt)	a =0.2187 b =0.0000 c =0.0187 d =0.0000	0.1191 0.0191 0.0191 0.0000	0.1191 0.0191 0.0191 0.0000	-1.2744 e^{-9}	-5.4478 e^{-10}	-5.4478 e^{-10}
12	Weibull	C_t =ab (x^{b-1}) (exp (a (x^b))	a=0.0999 b=0.8953	0.0975 0.8990	0.0975 0.8990	-59.941	-50.509	-50.509
13	Gompertz	C_t =a exp (-exp (b(c-x)))	a=7.8037 b=0.0037 c= 10.8162	7.7037 0.0037 10.8162	7.7037 0.0037 10.8162	0.9999	0.9999	0.9999
14	Fourier	C_t =a+b(cos(cx)) + d(sin(cx))	a= 1.2000 b=-0.1999 c=0.0082 d=1.7292	1.1000 -0.1999 0.0082 1.7292	1.1000 -0.1999 0.0082 1.7292	0.9865	0.9865	0.9865

Table. 6. (continued). Statistical analysis results of Acidity modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model No	Name	MBE			RMSE			χ^2		
		Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	بهینه Fortified (1% Aqueous)
1	Linear	3.1086 e^{-16}	3.5527 e^{-16}	3.5527 e^{-16}	4.0405 e^{-13}	4.0402 e^{-13}	4.0402 e^{-13}	7.4978 e^{-25}	8.2625 e^{-25}	8.2625 e^{-25}
2	Quadratic	4.4409 e^{-17}	-8.8818 e^{-17}	-8.8818 e^{-17}	2.1599 e^{-13}	2.1596 e^{-13}	2.1596 e^{-13}	2.2554 e^{-25}	2.2441 e^{-25}	2.2441 e^{-25}
3	Harris	1.4327 e^{-6}	8.942 e^{-7}	8.942 e^{-7}	0.14142	0.14142	0.14142	0.08333	0.090909	0.09090
4	Rational	3.864 e^{-5}	4.9376 e^{-5}	4.9376 e^{-5}	0.007022	0.007630	0.007630	0.0002016	0.0002598	0.0002598
5	Newton	-0.2	-0.1	-0.1	0.24495	0.17321	0.17321	0.3	0.15	0.15
6	Page	-0.2	-0.1	-0.1	0.24495	0.17321	0.17321	0.3	0.15	0.15
7	Logarithmic	4.2886 e^{-9}	-0.00011928	-0.00011928	0.14142	0.14142	0.14142	0.08333	0.090919	0.090919
8	Exponential	-3.6119 e^{-5}	-0.00070482	-0.00070482	0.002036	0.003498	0.003498	1.837e^{-5}	6.1152 e^{-5}	6.1152 e^{-5}
9	Logistic	5.7801 e^{-11}	-6.5605 e^{-5}	-6.5605 e^{-5}	0.0006461	0.0005006	0.0005006	1.5991 e^{-6}	1.1006 e^{-6}	1.1006 e^{-6}
10	Two-Term	5.7801 e^{-11}	-4.6188 e^{-8}	-4.6188 e^{-8}	0.14142	0.14142	0.14142	0.08333	0.090909	0.090909
11	Diffusion	-1.8807 e^{-7}	-1.6025 e^{-7}	-1.6025 e^{-7}	0.14142	0.14142	0.14142	0.08333	0.090909	0.090909
12	Weibull	-0.98318	-0.90315	-0.90315	1.104	1.015	1.015	432.58	356.81	365.81
13	Gompertz	2.3786 e^{-7}	2.3786 e^{-7}	2.3786 e^{-7}	3.102 e^{-5}	3.102 e^{-5}	3.102 e^{-5}	3.723 e^{-9}	4.0383 e^{-9}	4.0383 e^{-9}
14	Fourier	0	-1.5543 e^{-16}	-1.5543 e^{-16}	9.3795 e^{-5}	9.3795 e^{-5}	9.3795 e^{-5}	3.7072 e^{-8}	4.053 e^{-8}	4.053 e^{-8}

Table. 7. Statistical comparison of the Linear model constants for Acidity Value

Constant	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	p-Value
a	1.000 [a]	0.9000 [b]	0.9000 [b]	0.003
b	0.0143 [a]	0.0143 [a]	0.0143 [a]	1

*Values with different letters in each row indicates a significant difference at the 0.05 level, while values with the same letters are not significantly different

3.5. Peroxide Value

Peroxide value is a key indicator for evaluating primary lipid oxidation and typically exhibits a marked increasing trend during storage. In the initial stages, the rate of peroxide formation is relatively slow; however, as radical-driven autoxidation progresses through the initiation and propagation phases, the rate rises exponentially. Eventually, as the pool of reactive substrates such as polyunsaturated fatty acids becomes depleted, the increase slows or reaches a plateau, often resulting in an S-shaped curve. This kinetic behavior reflects the transition from a lag phase to a rapid propagation phase, and ultimately to a termination or equilibrium phase. Modeling this kinetic behavior is crucial for assessing antioxidant efficacy and protective performance in food products [17]. Similar studies, for instance, have reported increasing Peroxide Value in sunflower oil-containing crackers over storage, confirming the upward trend of this parameter [39].

In the present study, Peroxide Value was monitored throughout the storage period in all protein bar samples. Experimental data revealed that this parameter increased in all samples, with the highest increase observed in the control and the lowest in the ethanolic rice bran extract-enriched sample. The aqueous extract-enriched sample displayed intermediate values. The reduced rate of peroxide formation in the extract-enriched samples can be attributed to the presence of antioxidant compounds in rice bran extracts. These compounds, through electron donation, inhibit the formation of lipid alkoxyl radicals, thereby slowing the chain propagation of lipid oxidation. Furthermore, the stronger inhibitory effect of the ethanolic extract compared to the aqueous extract can be explained by its higher concentration of lipophilic antioxidants and favorable polarity. Lipophilic compounds such as tocopherols, tocotrienols, and γ-oryzanol more easily penetrate the lipid phase, allowing them to act directly at the site of oxidative reactions. Therefore, both extracts effectively reduced the rate of primary oxidation and controlled PV progression, with the ethanolic extract demonstrating superior antioxidative performance [40].

To model the kinetic changes of peroxide value during storage, the experimental data were fitted to various kinetic models. The performance of each model was evaluated using statistical indices including the coefficient of determination (R^2), root mean square error (RMSE), chi-square (χ^2), and mean bias error (MBE). The optimal model was selected based on the highest R^2 combined with the lowest error values, indicating the model's superior capability to accurately describe the observed data. The fitting results revealed that the logistic, rational, and exponential models exhibited the highest R^2 values among all tested models, indicating their suitability for describing this parameter kinetics. However, a more precise comparison using RMSE and χ^2 showed that the logistic model consistently had the lowest errors across all samples. Therefore, the logistic model was selected as the most appropriate kinetic model for describing PV changes during storage. The mathematical expression of the logistic model is defined as follows:

$$C_t = a / (1 + b \exp(-ct)) \quad (10)$$

Previous studies support similar trends in the kinetic modeling of peroxide value in lipid-containing food products during storage. For instance, research on meat products, dairy, and other foods rich in unsaturated fatty acids has shown that the logistic model can accurately describe the temporal increase in Peroxide Value [41]These findings indicate that the logistic model is not only suitable for the present study but also demonstrates high predictive capability across different food matrices for simulating lipid oxidation and peroxide formation. In the logistic model applied here, three key parameters (a, b, and c) were analyzed. Parameter a, representing the theoretical maximum Peroxide Value at the end of storage which was highest in the control sample (4.5405), indicating the greatest potential for peroxide accumulation, whereas the ethanolic extract sample showed the lowest value (3.3115), reflecting the most effective inhibition of lipid peroxidation. The aqueous extract sample (4.2616) exhibited an intermediate behavior. Parameter b, associated with the curve inflection and lag in the onset of this parameter increase, was highest in the ethanolic extract (3.2916) and lowest in the control (1.3996), with the aqueous extract showing an intermediate value (2.3117), indicating a delayed onset of peroxide accumulation in the ethanolic sample. Parameter c, representing the Peroxide Value growth rate over time, was highest for the ethanolic extract (0.0922), reflecting a relatively rapid initial increase, yet due to the lower a value, the final Peroxide Value remained lower over the long term. The control sample exhibited the slowest growth rate (0.0607), while the aqueous extract showed intermediate behavior (0.0656).

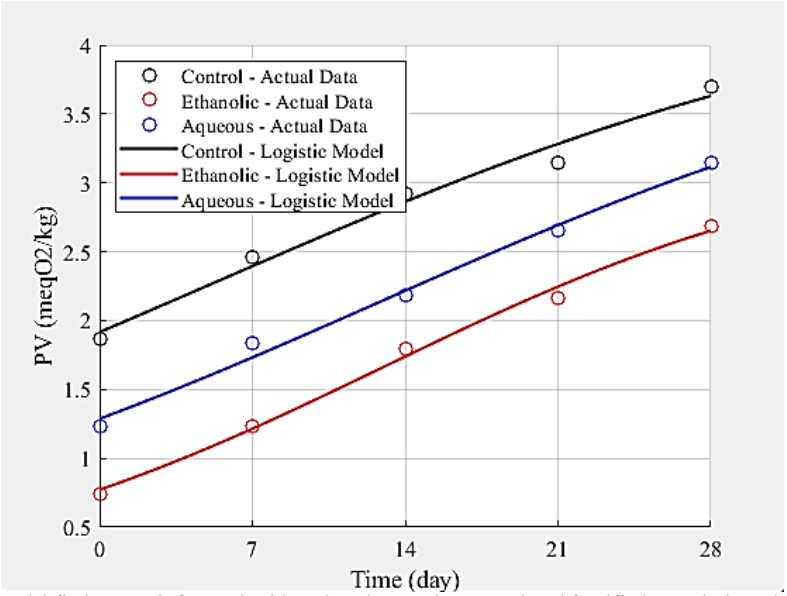

Fig. 4. Logistic model fitting graph for perioxide Value changes in control and fortified protein bars during storage time

These differences in this parameter kinetics among samples can be attributed to the presence of antioxidant compounds in the added rice bran extracts. These compounds effectively scavenge free radicals and inhibit the chain propagation of lipid oxidation. By donating electrons to lipid radicals such as alkoxyl and peroxyl radicals, these antioxidants slow down or terminate oxidative reactions, resulting in lower Peroxide accumulation in extract-enriched samples. The superior performance of the ethanolic extract compared to the aqueous extract can be explained by its higher content of lipophilic phenolic compounds extracted using ethanol. These lipophilic antioxidants are more compatible with the lipid phase and therefore more effective in protecting the lipid matrix against oxidation [40]. Overall, the analysis of logistic model parameters aligns well with the experimental data and confirms the inhibitory effect of rice bran extracts—particularly the ethanolic form—on lipid oxidation in protein bars

Table. 8. Statistical analysis results of Peroxide modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model No.	Name	Model Equation	Constants			R^2		
			Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
1	Linear	$C_t = a + bt$	a=0.0620 b=1.9497	0.0689 0.7594	0.0663 1.2800	0.98114	0.99669	0.99419
2	Quadratic	$C_t = a + bt + Ct^2$	a= -0.0005 b=0.0752 c=1.9034	-0.0002 0.0742 0.7406	-0.0002 0.0714 1.2623	0.98506	0.99722	0.99470
3	Harris	$C_t = 1 / (a + bt^c)$	a= 0.3549 b= 0.0001 c=0.0000	0.5800 0.0002 0.0000	0.4528 0.0001 0.0000	-2.0606 e^{-13}	-1.0636 e^{-13}	-1.068 e^{-13}
4	Rational	$C_t = (a+bt) /(1+ct+dt^2)$	a=1.8646 b=0.6794 c=0.2609 d= -0.0033	0.7395 0.0892 0.0125 -0.0002	1.2272 0.3670 0.1734 -0.0028	0.98198	0.99474	0.99160
5	Newton	$C_t = \exp(-at)$	a= 0.0000	0.0000	0.0000	-8.6119	-1.1226	-3.3293
6	Page	$C_t = \exp(-at^b)$	a =0.0000 b =0.0000	0.0000 0.0000	0.0000 0.0000	-8.6119	-1.1226	-3.3693
7	Logarithmic	$C_t = a \exp(-bt) + c$	a=0.0000 b= 0.0000 c=2.8171	0.0000 0.0000 1.7235	0.0000 0.0007 2.2081	-6.2949 e^{-11}	-3.0099 e^{-10}	-4.943 e^{-8}
8	Exponential	$C_t = a (b - \exp(-ct))$	a=4.5054 b=1.4208 c=0.0174	131.1833 1.0561 0.0056	12.221 1.1032 0.0059	0.98561	0.99722	0.99474
9	Logistic	$C_t = a / (1 + b \exp(-ct))$	a =4.5405 b =1.3996 c = 0.0607	3.3115 3.2916 0.0922	4.2616 2.3117 0.0656	0.9932	0.99735	0.99936
10	Two-Term	$C_t = a \exp(-bt) + c \exp(-dt)$	a =1.4086 b =0.0000 c =1.4086 d= 0.0000	0.8618 0.0000 0.8618 0.0000	2.2077 0.0000 0.0004 0.0000	-1.9811 e^{-12}	-1.1087 e^{-12}	-1.4715 e^{-12}

Model No.	Name	Model Equation	Constants			R^2		
			Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
11	Diffusion	C_t = a exp (-bt) + (1-c) exp (-cdt)	a =1.8432 b =0.0000 c =0.0260 d =0.0000	0.7422 0.0000 0.0187 0.0000	1.2331 0.0000 0.0249 0.0000	-1.036 e^{-11}	-4.8872 e^{-13}	-8.3777 e^{-13}
12	Weibull	C_t = ab (x^{b-1}) (exp (a (x^b))	a=0.1039 b=0.8686	0.0869 0.9027	0.0962 0.8843	-18.633	-6.0058	-10.386
13	Gompertz	C_t = a exp (-exp (b(c-x)))	a=5.4436 b=0.0233 c= -82.1051	8.4955 0.0125 -55.1098	5.9641 0.0190 -63.3846	0.98026	0.99708	0.99160
14	Fourier	C_t = a+b(cos(cx)) + d(sin(cx))	a= -215379.21894 b= 215379.12196 c=0.0000 d= 11349.0294	772302.966 772303.707 0.0000 3333.0534	-76878.39 25918.5411 0.0000 603.4742	0.98506	0.99722	0.99470

Table. 8. (continued). Statistical analysis results of Peroxide modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model No	Name	MBE			RMSE			χ^2		
		Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	بهینه Fortified (1% Aqueous)
1	Linear	$9.77e^{-16}$	$4.4409 e^{-16}$	$3.5527 e^{-16}$	0.085029	0.039306	0.05017	0.013799	0.0045045	0.0076437
2	Quadratic	$1.3323e^{-16}$	$-6.6613 e^{-17}$	$-4.4409 e^{-17}$	0.075681	0.036032	0.04793	0.009465	0.0034918	0.006321
3	Harris	$-6.3423e^{-10}$	$1.8498e^{-9}$	$-2.5457 e^{-10}$	0.61921	0.68291	0.65817	0.68052	1.3529	0.98091
4	Rational	-0.0001014	$-2.6446 e^{-6}$	$4.7012e^{-5}$	0.05106	0.35171	0.01664	0.011301	0.0066219	0.0105857
5	Newton	1.8171	-0.72356	-1.2081	1.9197	0.99494	1.3758	18.427	4.9495	9.4639
6	Page	1.8171	-0.72356	-1.2081	1.9197	0.99494	1.3758	18.427	4.9495	9.4639
7	Logarithmic	$-4.9124 e^{-6}$	$-1.183 e^{-5}$	$-2.0024 e^{-8}$	0.61921	0.68291	0.65817	0.68052	1.3529	0.98091
8	Exponential	$-1.0106 e^{-6}$	$-1.3985 e^{-8}$	$-2.5872 e^{-6}$	0.07429	0.03597	0.04775	0.008916	0.0034881	0.0062154
9	Logistic	0.00042475	0.0011162	0.000669	0.83124	0.04952	0.06030	0.00464	0.0003931	0.000544
10	Two-Term	$3.1306 e^{-9}$	$-1.3972 e^{-8}$	$-3.683e^{-9}$	0.61921	0.68291	0.65817	0.68052	1.3529	0.98091
11	Diffusion	$-2.2554 e^{-8}$	$-5.7772 e^{-12}$	$-4.7717 e^{-9}$	0.61921	0.68291	0.65817	0.68052	1.3529	0.98091
12	Weibull	-2.4279	-1.5588	-1.9466	2.7436	1.8076	2.2208	2739.2	1290.2	1822.2
13	Gompertz	-0.004513	0.0004162	-0.00069	0.087006	0.036924	0.06125	0.012734	0.0036455	0.0084291
14	Fourier	$6.9309 e^{-11}$	$1.9232 e^{-10}$	$-9.73 e^{-10}$	0.075681	0.036032	0.04793	0.009465	0.0034918	0.006321

Table. 9. Statistical comparison of the Logistic model constants for Peroxide Value

Constant	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	p-Value
a	4.5405 [a]	3.3115 [c]	4.2616 [b]	0.03
b	1.3996 [c]	3.2916 [a]	2.3117 [b]	0.02
c	0.0607 [c]	0.0922 [a]	0.0656 [b]	0.04

*Values with different letters in each row indicates a significant difference at the 0.05 level, while values with the same letters are not significantly different

3.6. Color Change (ΔE)

The ΔE index serves as a quantitative measure of color difference relative to the initial state and is widely used in food and material sciences, as color change is a key indicator of product quality. This index enables researchers to assess the effects of storage time, conditions, and additives on the color of food products in a measurable and comparable manner [42]. Experimental data indicated that ΔE values increased over the 28-day storage period in all samples, reflecting a gradual change in color relative to the initial state. This increase may result from chemical reactions such as phenolic oxidation, pigment degradation, or Maillard reactions [43]. Among the samples, the control exhibited the lowest color change, likely due to the absence of bioactive compounds such as flavonoids and phenolics, which are present in the extract-treated samples and participate in color-forming reactions during storage [44].

Comparing the rice bran extract-enriched samples, the ethanolic extract exhibited the highest ΔE values. This greater color change can be attributed to the higher concentration of flavonoids and phenolics in the ethanolic extract, as these compounds are more efficiently

extracted using ethanol and may undergo oxidative or Maillard reactions over time, resulting in more pronounced color changes [45]. In contrast, the aqueous extract exhibited lower ΔE values than the ethanolic extract, likely due to the lower content of color-active flavonoids and phenolics in the aqueous extract, as water is less efficient than ethanol in extracting these compounds [46].

Subsequently, the kinetics of ΔE during the 28-day storage period were analyzed. To describe the temporal behavior of color changes, the experimental data were fitted to various kinetic models, and statistical indicators, including the coefficient of determination (R^2), root mean square error (RMSE), and chi-square (χ^2), were calculated to evaluate the goodness of fit. Based on these evaluations, the Gompertz model exhibited the highest R^2 values (0.99997 for the control, 0.99768 for the ethanolic extract, and 0.99553 for the aqueous extract) and the lowest fitting errors. Therefore, it was selected as the most suitable model to describe ΔE changes throughout the storage period, with the mathematical equation expressed as follows:

$$C_t = a \exp(-\exp(b(c-x))) \quad (11)$$

The results indicate that the color change in the samples followed a nonlinear, sigmoidal pattern, with a slow initial rate that accelerated over time. Color changes in food materials typically exhibit a stepwise nonlinear behavior: at the early stages, the intensity of change is low; in the intermediate phase, the rate increases; and by the end of the storage period, it approaches a plateau. This three-phase pattern—comprising the initial lag phase, rapid growth phase, and final stable phase—naturally aligns with the mathematical structure of the Gompertz model. The Gompertz function is an asymmetric sigmoidal model that accurately captures temporal changes in parameters such as ΔE, simultaneously accounting for gradual onset, intermediate acceleration, and saturation behavior. Its asymmetry makes it more suitable than symmetric models like the logistic function for real-world color change dynamics, which often involve rapid increases followed by stabilization [45]. In a study on fish fillets under cold chain storage, color indices also exhibited time-dependent nonlinear behavior, supporting the use of nonlinear kinetic models for accurate representation of quality changes [46].

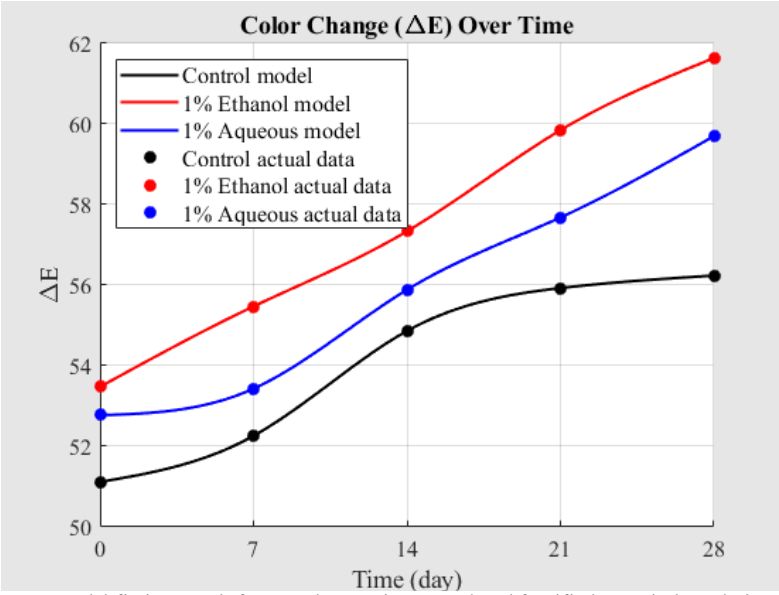

Fig. 5. Gompertz model fitting graph for ΔE changes in control and fortified protein bars during storage time

In this kinetic model, the parameter a represents the maximum ΔE and the overall extent of color change. The ethanolic extract sample exhibited the highest a value (68.94), indicating the greatest cumulative color change, likely due to the higher concentration of phenolic and flavonoid compounds extractable in ethanol. In contrast, the control sample showed the lowest a (56.31), reflecting greater color stability and limited change over time, while the aqueous extract sample had an intermediate value (61.98) [11].

The parameter b, representing the rate of color change, was highest in the control (0.2181), indicating a faster initial increase in ΔE, whereas the ethanolic extract showed a lower value (0.0499), reflecting a more gradual and continuous color change. The aqueous extract exhibited an intermediate rate (0.0970). Parameter c, related to the delay before the maximum rate of color change occurs, was higher in the extract-enriched samples than in the control, indicating a delayed onset of peak color change in these samples. Overall, the Gompertz model parameters demonstrate that both the intensity and pattern of color change varied among treatments, and the presence of bioactive compounds—particularly in the ethanolic extract—played a significant role in enhancing ΔE. Moreover, the modeled trends closely corresponded with experimental observations, confirming the consistency and reliability of the kinetic analysis [47].

Table. 10. Statistical analysis results of ΔE modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model No.	Name	Model Equation	Constants			R^2		
			Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)
1	Linear	$C_t = a + bt$	a=51.2993 b=0.1987	53.4162 0.2956	52.2762 0.2585	0.93124	0.99757	0.97899
2	Quadratic	$C_t = a + bt + Ct^2$	a= -0.0047 b=0.3295 c=50.8417	0.0003 0.2860 53.4498	0.0030 0.1747 52.5693	0.96651	0.99766	0.98798
3	Harris	$C_t = 1 / (a + bt^c)$	a= 0.0185 b= 0.0000 c=0.0000	0.0174 0.0000 0.0000	0.0179 0.0000 0.0000	0	-2.2204 e^{-16}	0
4	Rational	$C_t = (a+bt) /(1+ct+dt^2)$	a=50.8823 b=0.0002 c=-0.0060 d=0.0001	53.4723 0.0001 -0.00052 0.0000	52.7723 1233.511 23.7642 -0.1125	0.9695	0.99768	0.99487
5	Newton	$C_t = \exp(-at)$	a= 0.0000	0.0000	0.0000	-677.88	-372.62	-450.56
6	Page	$C_t = \exp(-at^b)$	a =0.0000 b =0.1310	0.0000 0.1310	0.0000 0.1310	-677.88	-372.62	-450.56
7	Logarithmic	$C_t = a \exp(-bt) + c$	a=0.0000 b=-18.9616 c=54.0816	0.0000 0.0000 57.5545	0.2844 0.0000 55.6106	-5.4346 e^{-8}	-1.664 e^{-12}	-1.0942 e^{-8}
8	Exponential	$C_t = a (b - \exp(-ct))$	a=3.7053 b=14.7958 c=-8.5075	5.0957 11.4948 8.5477	3.9025 14.522 8.5079	0.52849	0.484	0.36433
9	Logistic	$C_t = a / (1 + b \exp(-ct))$	a =54.7227 b =0.00725 c =8.7869	58.5737 0.0953 8.8007	56.6755 0.0739 8.7866	0.52849	0.484	0.36433
10	Two-Term	$C_t = a \exp(-bt) + c \exp(-dt)$	a =27.0416 b =0.0000 c =27.0416 d= 0.0000	0.0001 0.0000 25.3000 0.0000	27.9474 0.0000 27.9476 0.0018	-1.1253 e^{-11}	-121.2	-1.0081 e^{-11}
11	Diffusion	$C_t = a \exp(-bt) + (1-c) \exp(-cdt)$	a =53.0834 b =0.0000 c =0.0017 d =0.0000	56.5566 0.0000 0.0021 0.0000	54.8968 0.0000 0.0018 0.0000	-1.1057 e^{-11}	-8.6842 e^{-12}	-9.2426 e^{-12}
12	Weibull	$C_t = ab (x^{b-1}) (\exp(a(x^b))$	a=0.1625 b=0.7370	0.1604 0.7343	0.1585 0.7344	-577.55	-319.07	-383.6
13	Gompertz	$C_t = a \exp(-\exp(b(c-x)))$	a=56.3053 b=0.2181 c=8.8800	68.4906 0.0499 14.2166	61.9775 0.0970 15.2229	0.99997	0.99768	0.99553
14	Fourier	$C_t = a+b(\cos(cx)) + d(\sin(cx))$	a= 53.6607 b=-2.5937 c=0.1155 d=0.8012	57.7875 -4.2775 0.0528 4.2947	56.4856 -3.7715 0.0872 0.4330	0.99184	0.99068	0.99494

Table. 10. (continued). Statistical analysis results of ΔE modeling in protein bars enriched with aqueous and ethanolic rice bran extracts

Model No	Name	MBE			RMSE			χ^2		
		Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	Control	Fortified (1% Ethanolic)	Fortified بهینه (1% Aqueous)
1	Linear	1.5632 e^{-14}	1.8474 e^{-14}	1.1369 e^{-14}	0.53459	0.14435	0.37483	0.026096	0.0017816	0.013088
2	Quadratic	2.8422 e^{-15}	2.8422 e^{-15}	0	0.37311	0.14158	0.2835	0.013072	0.001699	0.0073865
3	Harris	-1.5204 e^{-10}	1.8808 e^{-10}	-6.0159 e^{-11}	2.0388	2.9298	2.5862	0.38429	0.7457	0.59829
4	Rational	0.0037291	0.0003902	0.00018495	0.35605	0.14106	0.1852	0.01188	0.0016824	0.0031012
5	Newton	-53.082	-56.555	-54.895	53.121	56.63	54.956	14109	16035	15101
6	Page	-53.082	-56.555	-54.895	53.121	56.63	54.956	14109	16035	15101
7	Logarithmic	-1.5295 e^{-8}	-3.7793 e^{-6}	-7.882 e^{-8}	2.0388	2.9298	2.5862	0.38429	0.7457	0.59829
8	Exponential	6.7129 e^{-11}	-1.2753 e^{-11}	-1.4921 e^{-12}	1.4	2.1046	2.0619	0.17875	0.37809	0.37508
9	Logistic	2.4268 e^{-8}	3.2763 e^{-9}	3.33 e^{-10}	1.4	2.1046	2.0619	0.17875	0.37809	0.37508
10	Two-Term	2.6928 e^{-8}	-32.254	2.133e^{-6}	2.0388	32.387	2.5862	0.38429	207.3	0.59829
11	Diffusion	-6.0685 e^{-8}	1.329 e^{-6}	-4.7717 e^{-8}	2.0388	2.9298	2.5862	0.38429	0.7457	0.59829
12	Weibull	-43.845	-46.846	-45.327	49.038	52.416	50.718	9.2241e^{3}	1.0614e^{6}	9.8781e^{3}
13	Gompertz	-2.0389 e^{-10}	-1.5191 e^{-7}	-4.9434 e^{-8}	0.011593	0.11917	0.17291	1.2034e^{-5}	0.0012289	0.0026715
14	Fourier	-1.4211 e^{-14}	-8.5265 e^{-14}	-1.1369 e^{-14}	0.18414	0.11431	0.18396	0.00311	0.0011369	0.0030454

Table. 11. Statistical comparison of the Gompertz model constants for ΔE

Constant	Control	Fortified (1% Ethanolic)	Fortified (1% Aqueous)	p-Value
a	56.3053 [c]	68.4906 [a]	61.9775 [b]	0.0001
b	0.2181 [c]	0.0499 [a]	0.0970 [b]	0.0001
c	8.8800 [c]	14.2166 [b]	15.2229 [a]	0.0002

*Values with different letters in each row indicates a significant difference at the 0.05 level, while values with the same letters are not significantly different

4. Conclusion

The results of this study indicate that the quality parameters of protein bars enriched with aqueous and ethanolic rice bran extracts—including moisture, water activity, peroxide value, titratable acidity, and color changes—underwent significant alterations during the 28-day storage period. The trends in the increase or decrease of these indices depended on the type of compounds present, oxidative stability, and the interactions within the product matrix. Kinetic modeling of these parameters revealed that the diffusion model best described moisture loss, the linear model accurately represented changes in water activity and titratable acidity, the logistic model fitted peroxide value evolution, and the Gompertz model effectively captured color change kinetics. Selecting these models not only enhanced the understanding of the qualitative behavior of the product during storage but also provided a reliable tool for predicting shelf-life under real storage conditions. The presence of phenolic and antioxidant compounds in rice bran extracts, particularly in the ethanolic form, improved the stability of quality attributes, controlled oxidative reactions, and contributed to prolonged shelf-life and enhanced product characteristics. These findings provide a scientific basis for the production of protein bars with extended stability and shelf-life, enabling manufacturers to make more accurate predictions using kinetic models. Future studies are recommended to explore the effects of varying storage conditions, relative humidity, packaging types, and the combined use of rice bran extracts with other plant extracts on the physicochemical stability and sensory properties of protein bars. Additionally, investigating kinetic changes over longer storage periods can further elucidate the qualitative behavior of the product, and an economic analysis comparing rice bran extracts with other additives could facilitate the development of healthier and more sustainable products.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

The authors gratefully acknowledge the support of the Guilan Science and Technology Park for funding this research through the Creativity and Innovation Grant (Grant No. 1404/236). We also thank Giltaz Food Industries Co. (Langrud, Guilan) for providing the raw materials required for this study.

References:

[1] Abdel-Salam, F.F., R.M. Ibrahim, and M. Ali, Formulation and evaluation of high energy-protein bars as a nutritional supplement for sports athletics. Am. J. Food Technol, 2022. 10: p. 53-65.

[2] Małecki, J., et al., Physicochemical, Nutritional, Microstructural, Surface and Sensory Properties of a Model High-Protein Bars Intended for Athletes Depending on the Type of Protein and Syrup Used. International Journal of Environmental Research and Public Health, 2022. 19(7): p. 3923.

[3] Srebernich, S.M., et al., Physico-chemical, sensory and nutritional characteristics of cereal bars with addition of acacia gum, inulin and sorbitol. Food Science and Technology, 2016. 36: p. 555-562.

[4] Banach, J.C., S. Clark, and B.P. Lamsal, Microstructural changes in high-protein nutrition bars formulated with extruded or toasted milk protein concentrate. Journal of food science, 2016. 81(2): p. C332-C340.

[5] Hassan, S.K., Quantitative and qualitative effects of proteins and natural sugars on hardening and color of high-protein nutrition bars during storage. EurAsian Journal of BioSciences, 2020. 14.(1)

[6] Jiang, Z., et al., High-protein nutrition bars: Hardening mechanisms and anti-hardening methods during storage. Food Control, 2021. 127: p. 108127.

[7] Dietrich, R.B., et al., Role of protein and lipid oxidation in hardening of high-protein bars during storage. Journal of Food Science, 2025. 90(1): p. e17657.

[8] Caporgno, M.P. and A. Mathys, Trends in microalgae incorporation into innovative food products with potential health benefits. Frontiers in nutrition, 2018. 5: p. 58.

[9] Shahidi, F. and P. Ambigaipalan, Phenolics and polyphenolics in foods, beverages and spices: Antioxidant activity and health effects–A review. Journal of functional foods, 2015. 18: p. 820-897.

[10] Peanparkdee, M. and S. Iwamoto, Bioactive compounds from by-products of rice cultivation and rice processing: Extraction and application in the food and pharmaceutical industries. Trends in Food Science & Technology, 2019. 86: p. 109-117.

[11] Ghasemzadeh ,A., et al., Comparative evaluation of different extraction techniques and solvents for the assay of phytochemicals and antioxidant activity of hashemi rice bran. Molecules, 2015. 20(6): p. 10822-10838.

[12] Cheetangdee, N. and S. Benjakul, Effects of rice hull phenolic extract on the stability of emulsions stabilized by rice bran protein hydrolysate. International Food Research Journal, 2017. 24.(4)

[13] Peanparkdee, M., J. Patrawart, and S. Iwamoto, Physicochemical stability and in vitro bioaccessibility of phenolic compounds and anthocyanins from Thai rice bran extracts. Food Chemistry, 2020. 329: p. 127157.

[14] Talemi, F.P., A. Pourfarzad, and S. Gheibi, Synergistic effects of bee pollen and propolis extract on protein bar properties: a multivariate chemometric analysis. Discover Food, 2025. 5(1): p. 1-29.

[15] Showkat, S., et al., Effect of mung bean and rice on physico-

chemical, sensory and microstructural properties of cereal bars. Carpathian Journal of Food Science and Technology, 2018. 10(4): p. 70-78.
[16] Turgut, S.S., E. Karacabey, and E. Küçüköner. Potential of image analysis based systems in food quality assessments and classifications. in 9th Baltic conference of food science and technology, Jelgava, Latvia. 2014.
[17] Okpala, C.O.R., et al., Lipid oxidation kinetics of ozone-processed shrimp during iced storage using peroxide value measurements. Food bioscience, 2016. 16: p. 5-10.
[18] Srisuk, N. and S. Jirasatid, Development of instant pumpkin-fingerroot drink powder and its shelf life modeling. Life Sciences and Environment Journal, 2023. 24(1): p. 161-182.
[19] Pourfarzad, A. and M.B. Habibi-Najafi, Optimization of a liquid improver for barbari bread: staling kinetics and relationship of texture with dough rheology and image characteristics .Journal of texture studies, 2012. 43(6): p. 484-493.
[20] Ling, J.K.U., et al., Thermal degradation of antioxidant compounds: Effects of parameters, thermal degradation kinetics, and formulation strategies. Food and Bioprocess Technology, 2022. 15(9): p. 1919-1935.
[21] Tuly, S.S., M. Mahiuddin, and A. Karim, Mathematical modeling of nutritional, color, texture, and microbial activity changes in fruit and vegetables during drying: A critical review. Critical Reviews in Food Science and Nutrition, 2023. 63(1 :(3p. 1877-1900.
[22] Choosuk, N., et al., Kinetic modeling of quality changes and shelf life prediction of dried coconut chips. Processes, 2022. 10(7): p. 1392.
[23] Demarco, F., et al., Effects of natural antioxidants on the lipid oxidation, physicochemical and sensory characteristics, and shelf life of sliced salami. Food and Bioprocess Technology, 2022. 15(10): p. 2282-2293.
[24] Kose, Y.E., Degradation kinetic modeling of bioactive compounds and enzyme activity in wheat germ during stabilization. LWT :153 .2022 ,p. 112501.
[25] Mikołajczak, N., M. Tańska, and D. Ogrodowska, Phenolic compounds in plant oils: A review of composition, analytical methods, and effect on oxidative stability. Trends in Food Science & Technology, 2021. 113: p. 110-138.
[26] Mokaizh, A.A.B., A.H. Nour, and K. Kerboua, Ultrasonic-assisted extraction to enhance the recovery of bioactive phenolic compounds from Commiphora gileadensis leaves. Ultrasonics Sonochemistry, 2024. 105: p. 106852.
[27] Surarit, W., et al., Evaluation of antioxidant activities and phenolic subtype contents of ethanolic bran extracts of Thai pigmented rice varieties through chemical and cellular assays. International Journal of Food Science and Technology, 2015. 50(4): p. 990-998.
[28] Diaz, J.T., E.A. Foegeding, and M.A. Lila, Whey protein-polyphenol aggregate particles mitigate bar hardening reactions in high protein bars. Lwt, 2021. 138: p. 110747.
[29] Zhang, K., et al., Covalent polyphenols-proteins interactions in food processing: formation mechanisms, quantification methods, bioactive effects, and applications. Frontiers in Nutrition, 2024. 11: p. 1371401.
[30] Tapia, M.S., S.M. Alzamora, and J. Chirife, Effects of water activity (aw) on microbial stability as a hurdle in food preservation. Water activity in foods: Fundamentals and applications, 2020: p. 323-355.
[31] Xue, H., et al., Research progress on the interaction of the polyphenol–protein–polysaccharide ternary systems. Chemical and Biological Technologies in Agriculture, 2024. 11(1): p. 95.
[32] Adrar, N.S., K. Madani, and S. Adrar, Impact of the inhibition of proteins activities and the chemical aspect of polyphenols-proteins interactions. PharmaNutrition, 2019. 7: p. 100142.
[33] Alba, K., G.M. Campbell, and V. Kontogiorgos, Dietary fibre from berry-processing waste and its impact on bread structure: a review. Journal of the Science of Food and Agriculture, 2019. 99(9): p. 4189-4199.
[34] Tyl, C. and G.D. Sadler, pH and titratable acidity, in Food analysis. 2017, Springer. p. 389-406.
[1] Gómez-Cortés, P., M. Juárez, and M.A. de la Fuente, Milk fatty acids and potential health benefits: An updated vision. Trends in Food Science & Technology, 2018. 81: p. 1-9.
[35] Mahboubifar, M., et al., Prediction of the acid value, peroxide value and the percentage of some fatty acids in edible oils during long heating time by chemometrics analysis of FTIR-ATR spectra. Journal of the Iranian Chemical Society, 2016. 13(12): p. 2291-2299.
[36] Cofrades, S., et al., Influence of the oil structuring system on lipid hydrolysis and bioaccessibility of healthy fatty acids and curcumin. Gels, 2023. 10(1): p. 33.
[37] Hatami, S., et al., Chemical and sensorial properties of probiotic beverage based on rice bran extract and honey. Biomass Conversion and Biorefinery, 2023. 13 :(6)p. 5151-5156.
[38] Manzocco, L., et al., Modeling the effect of the oxidation status of the ingredient oil on stability and shelf life of low-moisture bakery products: The case study of crackers. Foods, 2020. 9(6): p. 749.
[39] Bhat, F.M. and C.S. Riar ,Extraction, identification and assessment of antioxidative compounds of bran extracts of traditional rice cultivars: An analytical approach. Food chemistry, 2017. 237: p. 264-274.
[40] Jaimez-Ordaz, J., et al., Kinetic parameters of lipid oxidation in third generation (3G) snacks and its influence on shelf-life. Food Science and Technology, 2019. 39(Suppl. 1): p. 136-140.
[41] De Flaviis, R. and G. Sacchetti, A 50-Year Theoretical Gap on Color Difference in Food Science: Critical Insights and New Perspectives. Journal of Food Science, 2025. 90(6): p. e70317.
[42] Li, Q., et al., Indication of the color change on the oxidation properties of fragrant rapeseed oil during shelf storage. Food Chemistry: X, 2023. 20: p. 100908.
[43] Chaves, J.O., et al., Extraction of flavonoids from natural sources using modern techniques. Frontiers in chemistry, 2020. 8: p. 507887.
[44] Fu, X., et al., Assessment of Bioactive Compounds and Physiological Activities of Ethanolic and Aqueous Extracts from Black Rice, Black Rice Bran ,and Milled Black Rice. Applied Sciences, 2024. 14(22): p. 10200.
[45] Plaskova, A. and J. Mlcek, New insights of the application of water or ethanol-water plant extract rich in active compounds in food. Frontiers in Nutrition, 2023. 10: p. 1118761.
[46] Luna, M.P. and J.M. Aguilera, Kinetics of colour development of molten glucose, fructose and sucrose at high temperatures. Food Biophysics, 2014. 9(1): p. 61-68.