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Artificial Intelligence-Powered Optimization and Milk Permeate Upcycling for Innovative Sesame Milk with Enhanced Probiotic Viability and Sensory Appeal

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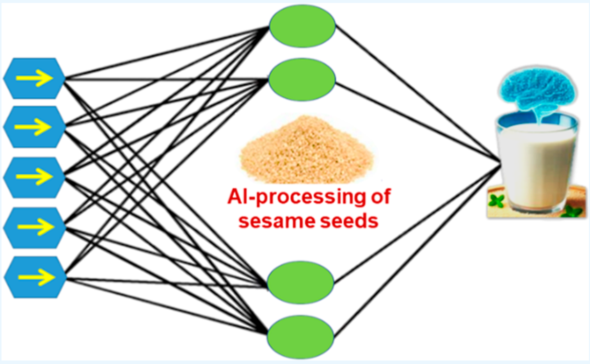

ABSTRACT: Consumer demand for plant-based alternatives drives innovation in nondairy beverages. This study explores the development of a novel sesame milk with enhanced functionality using an artificial neural network (ANN) and milk permeate integration. An ANN model effectively optimized water-based sesame milk (WSM) extraction, maximizing total solids (T.S.) recovery. The ANN model's predicted T.S. yield (99.65%) closely matched the actual value (95.18%), demonstrating its potential for optimizing high-yield production. Furthermore, milk permeate was incorporated (5:1 ratio) to create permeate-based sesame milk (PSM), which supported the growth of lactic acid bacteria, suggesting its potential as a growth medium for future probiotic applications. PSM also displayed superior nutritional value and sensory characteristics compared to WSM. These findings highlight the promise of ANN-powered optimization and milk permeate integration for creating innovative sesame milk alternatives with enhanced probiotic viability and sensory appeal. Future research should focus on ANN optimization of alternative-based-plant milk, including permeate-based sesame milk production, the health benefits of LAB fermentation, and consumer preferences for flavors and textures. Optimizing fermentation and LAB selection remain key for commercial success.

1. INTRODUCTION

Milk is a widely recognized source of essential macro- and micronutrients including fats, proteins, carbohydrates, calcium, selenium, riboflavin, vitamin B12, and pantothenic acid. However, limitations in global accessibility, deficiencies in specific micronutrients like iron and folate, and health concerns such as milk allergy, lactose intolerance, and hypercholesterolemia have driven the exploration of alternative beverages with comparable or superior nutritional profiles to conventional milk.[1]

Plant-based foods are gaining significant traction due to their dual benefits: promoting health and sustainability. Packed with essential nutrients such as protein, healthy fats, vitamins, fiber, minerals, and antioxidants, they offer a cost-effective way to improve your diet and reduce your environmental footprint. Research suggests that plant-based diets can significantly reduce chronic disease risks.[2] A prime example of this trend is plant-based milk alternatives, derived from plants such as cereals, legumes, nuts, and oil seeds. These versatile beverages resemble cow's milk in appearance and consistency, offering a nutritious and versatile option for various dietary needs. Their rise in popularity is driven by both health and ethical concerns, making them ideal for individuals with lactose intolerance, dairy allergies, or those following vegan or plant-based diets for religious or personal reasons.[3−5] However, the nutritional content varies depending on the source plant and processing methods.[6] Therefore, it is important to monitor the quality of the product during the various processing steps.

Sesame seeds (*Sesamum indicum* L.), a vital oilseed crop, are gaining significant attention for their potential in plant-based milk alternatives due to their rich nutritional profile and functional properties.[7] These tiny powerhouses are packed with essential amino acids, healthy fatty acids (including omega-6), vitamins (including vitamin E), minerals (including calcium, magnesium, and iron), and various beneficial compounds like sesamol and lignans.[8,9] Their antioxidant, anti-inflammatory, and potential health benefits related to blood pressure, cancer, and heart health further solidify their

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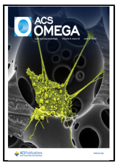

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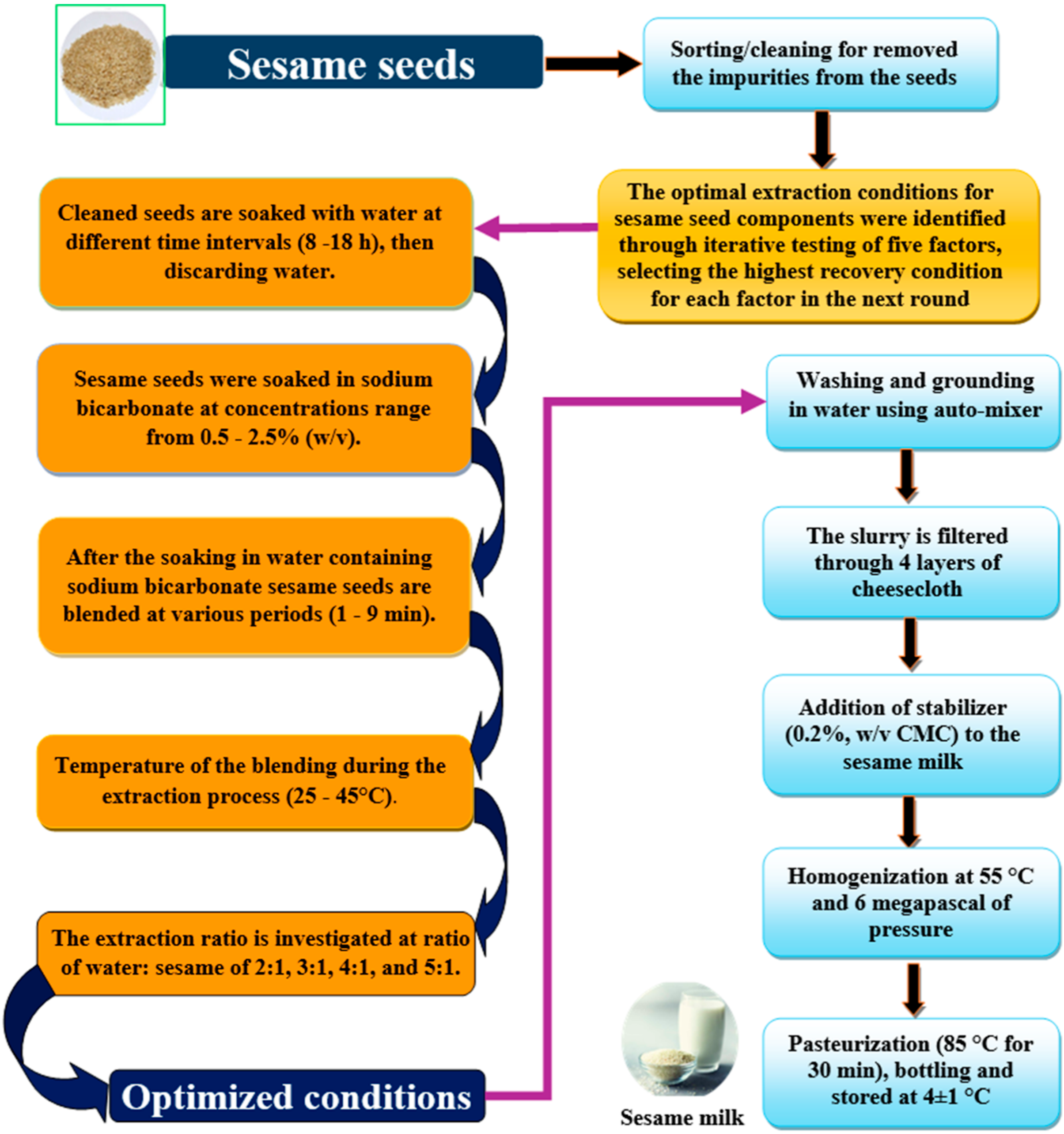

Figure 1. Flow diagram for sesame milk preparation with complete details of the processing parameters.

appeal.[10,11] One key advantage of sesame over other plant-based milk sources like legumes is its minimal "beany" flavor, a common deterrent for some consumers. Additionally, sesame milk offers good dispersion stability and avoids flatulence issues sometimes associated with other alternatives.[11,12] These factors position sesame as a promising candidate for overcoming the challenges faced by existing plant-based milk options.

While vegan milk production can be susceptible to higher microbial contamination compared to dairy due to naturally occurring microorganisms,[13] probiotic fermentation offers a solution. It not only introduces beneficial bacteria but also enhances the final product in several ways. Fermentation improves the nutritional value by increasing protein content and vitamin availability through microbial growth and vitamin synthesis.[14−16] Additionally, it enhances the solubility and absorption of minerals and vitamins through the production of short-chain fatty acids and organic acids.[16] These combined effects contribute to improved aroma, taste, texture, and stability of the final product.[13]

Ultrafiltration, a key process in dairy production, generates a valuable byproduct, called permeate. Once viewed as waste, permeate is now recognized for its potential due to its inherent health benefits and nutritional content.[17] This liquid stream is rich in lactose (65−85%), water-soluble vitamins, and essential minerals like sodium, potassium, calcium, magnesium, and zinc.[18] Permeate offers a triple win for the dairy industry since it acts as a nutritional enhancer, a cost-effective substitute, and a versatile ingredient. Its lactose and electrolytes can enrich fermented products and beverages, boosting their overall value.[18,19] Permeate can also replace skim milk in various applications, like sports drinks, providing a cost-effective source of electrolytes for postworkout recovery.[20] Furthermore, permeate's unique composition opens doors for its use beyond dairy, promoting innovation and adding value across the food and beverage industry.[21]

Artificial neural networks (ANNs) have emerged as a powerful and versatile tool within machine learning, offering a significant alternative to traditional modeling approaches.[22−24] Inspired by the human brain, ANNs excel at identifying complex patterns and deviations in the data. Through an intelligent backpropagation process, ANNs refine their internal models to achieve the desired outcome, enhancing accuracy and demonstrating their effectiveness compared to other methods.[25−27] ANNs achieve this by constructing computational models with interconnected nodes in hidden layers, mimicking the human brain's information processing capabilities. This empowers them to learn intricate data patterns and make data-driven decisions. Building an ANN model involves defining the network architecture, creating hidden layers with appropriate neuron counts and then training the network to learn the data patterns. Finally, the model goes through validation and verification before deployment for predictions.[22,24,27]

This research explores the development of a novel sesame-based milk alternative using ANN to optimize the formulation process for this milk. Subsequently, the approach incorporated underutilized milk permeate to further enhance its nutritional value, potential probiotic growth, and the overall appeal of the final product. A comprehensive evaluation assessed the physicochemical properties, viability of probiotics, and sensory characteristics of sesame-based milk, aiming to establish its potential as a viable and appealing dairy alternative.

2. MATERIALS AND METHODS

2.1. Biological Materials. Sweet white sesame seeds (*Sesamum indicum* L.), variety; Shandaweel 3, known as sesamum or benniseed, member of the family *Pedaliaceae*, were kindly provided from the Crops Research Institute, Agricultural Research Center, Giza, Egypt, during the 2022 growing season.

Ultrafiltered milk permeate was genteelly obtained from the Dairy Technology Unit, Dairy Department, Faculty of Agriculture, Mansoura University, Egypt. The milk permeate was immediately heated in a water bath at 80 °C for 10 min, cooled to 4 °C, and then kept frozen at −20 °C until use.

A freeze-dried yogurt starter commercial product (ABT-5) was provided by Chr. Hansen Laboratories, Copenhagen, Denmark. The starter culture of ABT-5 contains the probiotic bacteria; *Lactobacillus acidophilus*, *Bifidobacterium bifidum*, and *Streptococcus thermophilus*.

2.2. Chemicals. Sodium bicarbonate ($NaHCO_3$) and carboxymethyl cellulose (CMC) were provided by El-Gomhouria Co. for Drugs and Medical Supplies, Cairo, Egypt.

2.3. Processing and Recovery of Sesame Milk. *2.3.1. One Variable at a Time Approach.* Sesame milk was prepared according to the description of Ikya, Gernah, Ojobo, and Oni[28] with some modifications after the impurities were removed from the whole seeds. Several extraction conditions for sesame seeds were investigated. Five variables were studied. The investigated factors include the soaking time (h), sodium bicarbonate concentration in the soaking water (%), blending time (min), the temperature of extraction (°C), and the extraction ratio (water: sesame). The OVAT approach was employed, wherein the optimal conditions for the factor under investigation were implemented in subsequent experiments.

Experiments were carried out to select the best formulation for the targeted sesame milk, as described in Figure 1. Sesame seeds were soaked in water, then water was discarded, and the seeds were washed and ground with a specific ratio of tap water using an auto mixer. After each experiment, the slurry of sesame milk was filtered through four layers of cheesecloth. 0.2% (w/v) of CMC was added to the sesame milk and was homogenized at 55 °C and a pressure of 6 megapascal. Homogenized sesame milk was pasteurized at 85 °C for 30 min and stored in the fridge at 4 ± 1 °C before further analysis. The recovery (%) of sesame constituents in the resultant extracts was calculated as follows (eq 1)

$$\text{recovery \%} = \frac{\text{amount of the constituent in the extract}}{\text{amount of the same constituent in the seeds}} \times 100 \tag{1}$$

2.3.2. Investigated Factors. The first variable tested was the soaking time. Cleaned sesame seeds were transferred into large transparent plastic pails and soaked with water at different time intervals (8, 10, 12, 14, 16, and 18 h).

The second tested variable was the addition of sodium bicarbonate. Sesame seeds were soaked in sodium bicarbonate solution at concentrations of 0.5, 1.0, 1.5, 2.0, and 2.5% (w/v) before blending.

Blending time was the third investigated variable in which, after the soaking period, sesame seeds in water containing 0.5% (w/v) sodium bicarbonate for 16 h were blended at various periods (1, 3, 5, 7, and 9 min).

The fourth variable was the temperature of blending during the extraction process. The soaked sesame seeds were blended at various temperatures of water, being 25, 30, 35, 40, and 45 °C. According to the highest recovery of sesame seed components in the extract, the temperature of blending water was chosen.

Finally, the extraction ratio of water to soaked sesame was investigated during the extraction process. Sesame seeds were soaked in water containing 0.5% sodium bicarbonate for 16 h and blended with water at 35 °C. Raw sesame seeds were soaked in water at various ratios of water: sesame of 2:1, 3:1, 4:1, and 5:1.

2.3.3. Measurement of Chemical Properties. For each parameter, samples were analyzed in three replicates. The content of moisture, total solids (T.S.), fat, total protein, ash, titratable acidity, and pH were assayed as described by ref 29. Carbohydrate was estimated by subtracting protein, total solids, fat, and ash from 100.

2.4. ANN Modeling of Sesame Milk Extraction. The data of the OVAT experiments were employed as historical data for feeding and training ANN. A platform for a fully connected neural network was created. The fully connected multilayer perceptron algorithm is composed of three layers. The input layer with five neurons represents the five tested variables (soaking time of sesame seeds, sodium bicarbonate concentration, blending time of the soaked sesame seeds, extraction temperature, and water-to-sesame extraction ratio). The output layer with one neuron [the net yield of total soluble solids (T.S.) %]. A third hidden layer (h) was constructed between the output and input layers. The suitable number of hidden layers (1 or 2) were tested. The number of nodes (neurons) were examined in a range from 3 to 10. All nodes shared the same hyperbolic tangent sigmoid (NTanH) activation function. The NTanH activation function's nonlinearity effectively captures complex patterns in the sesame milk extraction data. Its output range (−1 to 1) normalizes neuron outputs and speeds up learning, making it ideal for predicting the T.S. yield.

The data were randomly divided into training and validation data sets, with a holdback proportion of 0.6667/0.3333. The training set, consisting of 52 runs, was utilized to minimize prediction errors and authenticate neural weights. The validation data set comprising 26 runs served the purpose of halting ANN training and selecting the best model. An additional third external data set was employed to test the robustness of the ANN and assess its prediction capabilities.

To mitigate overfitting and improve the generalization of the ANN model, the squared penalty method (L2 regularization) was used at a learning rate of 0.1 to facilitate efficient convergence and achieve optimal performance. The model underwent training through 5000 to 10,000 iterations using the ANN, guided by a trial-and-error procedure based on a random search approach through the defined range for layers (1 and 2) and neurons (3−10) parameters.

The optimal ANN architecture and prediction performance were deduced upon reaching the minimum values for prediction error metrics, including the mean absolute deviation (MAD), the root average squared error (RASE), and the sum of squared errors (SSEs), coupled with the highest value of the coefficient of determination (R^2), the predicted outputs were then closely aligned with the actual values of T.S. %.

2.5. Preparation of Permeate-Based Sesame Milk.

The ideal conditions for preparing water-based sesame milk were applied, which achieved the highest recovery of sesame components, replacing water with milk permeate in a 5:1 ratio.

2.6. Evaluation of Sesame Milk.

2.6.1. Growth of Probiotic Bacteria in Sesame Milk. The potential of probiotic bacteria to ferment sesame milk was investigated. The ABT-5 starter culture (*L. acidophilus*, *B. bifidum*, and *S. thermophilus*) was activated following standard protocol.[30] Briefly, 2% (w/v) of the freeze-dried culture was inoculated into 100 mL of sterile, reconstituted skimmed milk (spray-dried, low heat, France). This mixture was incubated at 37 °C for 24 h, allowing it to reach a specific level of acidity (until gel formation) to ensure proper activation. Subsequently, 100 mL of sterile skimmed milk was inoculated with 2 mL of the activated probiotic culture and incubated at 37 °C for 24 h until gelation occurred.

The prepared sesame milk was then evaluated as a growth medium for lactic acid bacteria (LAB). Flasks containing 100 mL of sterilized sesame milk and reconstituted skim milk (as a standard control) were inoculated with 2% active LAB culture and then incubated at 37 °C for up to 10 h. The probiotic bacterial counts (*S. thermophilus*, *B. bifidum*, and *L. acidophilus*) were determined on selective media at 2 h intervals, pH value of the fermented milk was measured as well.

To quantify the individual bacterial strains in the probiotic culture, specific media and incubation conditions were employed. *S. thermophilus* was enumerated on M17 agar medium (Biolife, Bolzano, Italy) under aerobic conditions at 37 °C for 48 h.[31] In contrast, *B. bifidum* and *L. acidophilus* required anaerobic incubation (Anerocult A system; Merck, Darmstadt, Germany) at 37 °C for 72 ± 1 h. *B. bifidum* was grown on MRS-NNLP medium (Sigma Chemical Co., Castle Hill, Australia), while *L. acidophilus* was cultured on MRS-sorbitol agar medium (Sigma-Aldrich, Missouri, USA).[31,32] The final results were expressed as the logarithmic number of colony-forming units per gram of sample (log cfu/g).

2.6.2. Sensory Evaluation. The sensory properties of sesame milk were evaluated by a panel of 12 highly trained panelists. The evaluation was conducted one time, directly assessing the fresh sesame milk extraction. To ensure the integrity of the study, the ethical guidelines for sensory evaluation were adhered to as outlined by the Institute of Food Science and Technology.[33] All panelists were volunteers who had provided informed consent, were informed of their right to withdraw at any time, and were selected based on their sensory analysis expertise.

A standardized protocol was followed to prevent bias and ensure the health and safety of the panelists. This included blind testing with samples coded with random three-digit numbers and maintaining a controlled environment to minimize external influences. The recruitment of trained panelists and adherence to ethical guidelines underscored our commitment to conducting sensory evaluation with scientific rigor and ethical responsibility.

2.7. Software, Statistical Analysis, and Mathematical Modeling.

All experiments were performed in triplicate, and the data were presented as the mean ± standard deviation (SD). The OVAT data underwent statistical analysis using CoStat software (version 6.4, CoHort Software, USA). The experimental design employed was a one-way, completely randomized design. Subsequently, a one-way ANOVA was conducted, followed by mean comparisons between treatments using Tukey's honest significant difference test, at a significance level of $\alpha \leq 0.05$. The data of OVAT were employed for executing machine learning procedures and defining the topology of ANN. The training, validation, and testing protocols of the ANN, along with statistical analysis and the calculation of optimum predicted conditions, were conducted with the aid of JMP Pro 17 (SAS Institute Inc., Cary, NC) software.

3. RESULTS AND DISCUSSION

3.1. Chemical Composition of Sesame Seed.

It was necessary to analyze the gross chemical composition of the sesame seeds used in this study. The results in Table 1 show that moisture, lipids, crude protein, carbohydrate, fiber, and ash contents for sesame seeds were 5.03, 50.87, 19.30, 21.32, 6.71, and 3.48%, respectively. These results are a line with the previous studies,[34,35] with slight variations in the chemical composition that could be due to climatic conditions, maturity of plants, and variety as well as analytical methods. The nutrients, particularly crude protein and fiber contents of sesame seed, were very high to warrant their consideration for

Table 1. Some Chemical Constituents of Sesame Seeds

chemical constituent	percentage
moisture	5.03 ± 0.15
total solid	94.97 ± 0.25
total lipid	50.87 ± 0.35
crude protein	19.30 ± 0.27
total carbohydrates	21.32 ± 0.32
fiber	6.71 ± 0.25
ash	3.48 ± 0.20

Table 2. Effect of Soaking Time on the Recovery Percentage of Sesame Seed Constituents Extracted in Water[a]

time (h)	recovery, %						
	T.S.	fat	protein	carbohydrate	ash	acidity	pH
8	67.90 ± 0.21^{e}	49.07 ± 0.53^{d}	61.15 ± 0.42^{f}	66.91 ± 0.61^{e}	49.90 ± 0.92^{e}	0.10 ± 0.02^{d}	6.84 ± 0.97^{a}
10	68.99 ± 0.12^{d}	50.60 ± 0.25^{c}	63.05 ± 0.82^{e}	67.62 ± 0.43^{d}	50.51 ± 0.44^{d}	0.11 ± 0.04^{c}	6.82 ± 0.55^{ab}
12	69.98 ± 0.14^{c}	52.13 ± 0.27^{b}	63.59 ± 0.38^{d}	68.34 ± 0.82^{c}	50.95 ± 0.67^{c}	0.11 ± 0.02^{c}	6.78 ± 0.27^{b}
14	70.41 ± 0.15^{b}	52.34 ± 0.61^{ab}	64.66 ± 0.34^{c}	69.40 ± 0.82^{ab}	51.25 ± 0.64^{b}	0.12 ± 0.03^{b}	6.72 ± 0.72^{c}
16	71.07 ± 0.12^{a}	52.54 ± 0.61^{a}	66.82 ± 0.82^{a}	69.05 ± 0.32^{b}	51.70 ± 0.43^{a}	0.13 ± 0.01^{a}	6.70 ± 0.34^{c}
18	70.74 ± 0.11^{b}	52.34 ± 0.52^{ab}	65.47 ± 0.43^{b}	69.76 ± 0.37^{a}	51.70 ± 0.61^{a}	0.13 ± 0.04^{a}	6.70 ± 0.62^{c}

[a] The level of the other tested variables was fixed at 0% $NaHCO_3$, 3 min of blending time, 25 °C, and 3:1 of water: sesame seeds ratio. For each column, means superscripted with different letters indicate significant differences based on the Tukey test ($\alpha \leq 0.05$, $n = 3$).

Table 3. Effect of Sodium Bicarbonate on the Recovery Percentage of Sesame Seed Constituents Extracted in Water[a]

$NaHCO_3$, %	recovery, %						
	T.S.	fat	protein	carbohydrate	ash	acidity	pH
0.00	$71.07 + 0.12^{c}$	52.54 ± 0.42^{b}	66.82 ± 0.61^{d}	69.05 ± 0.46^{f}	51.70 ± 0.52^{c}	0.11 ± 0.01^{a}	6.78 ± 0.64^{e}
0.50	$73.92 + 0.09^{ab}$	53.16 ± 0.34^{a}	71.40 ± 0.25^{b}	70.12 ± 0.61^{e}	52.00 ± 0.82^{b}	0.07 ± 0.01^{b}	6.87 ± 0.26^{e}
1.00	$74.14 + 0.05^{a}$	52.95 ± 0.24^{ab}	71.94 ± 0.62^{a}	71.18 ± 0.72^{d}	52.30 ± 0.64^{a}	0.05 ± 0.01^{c}	7.24 ± 0.82^{d}
1.50	$73.86 + 0.05^{b}$	51.93 ± 0.62^{d}	71.40 ± 0.24^{b}	71.89 ± 0.82^{c}	52.14 ± 0.62^{ab}	0.03 ± 0.01^{d}	7.52 ± 0.82^{c}
2.00	$74.03 + 0.04^{a}$	52.13 ± 0.25^{c}	71.29 ± 0.82^{bc}	73.32 ± 0.34^{a}	51.40 ± 0.52^{d}		7.89 ± 0.61^{b}
2.50	$73.92 + 0.09^{ab}$	52.03 ± 0.42^{cd}	70.86 ± 0.64^{c}	72.61 ± 0.92^{b}	51.10 ± 0.47^{e}		8.23 ± 0.67^{a}

[a] The level of the other tested variables was fixed at 16 h soaking time, 3 min of blending time, 25 °C, and 3:1 of water: sesame seeds ratio. For each column, means superscripted with different letters indicate significant differences based on the Tukey test ($\alpha \leq 0.05$, $n = 3$).

Table 4. Effect of Blending Time on the Recovery Percentage of Sesame Seed Constituents Extracted in Water[a]

blending time (min)	recovery, %						
	T.S.	fat	protein	carbohydrate	ash	acidity	pH
1	$72.82 + 0.05^{e}$	52.13 ± 0.36^{e}	70.59 ± 0.82^{e}	59.79 ± 0.43^{e}	50.21 ± 0.72^{e}	0.07 ± 0.01^{c}	6.87 ± 0.92^{a}
3	$79.94 + 0.17^{d}$	65.93 ± 0.92^{d}	74.63 ± 0.61^{d}	64.42 ± 0.72^{d}	54.98 ± 0.55^{d}	0.08 ± 0.02^{b}	6.81 ± 0.34^{b}
5	$86.95 + 0.10^{c}$	67.98 ± 0.52^{c}	80.29 ± 0.67^{c}	69.76 ± 0.94^{c}	64.25 ± 0.63^{c}	0.08 ± 0.02^{b}	6.81 ± 0.72^{b}
7	$87.61 + 0.22^{b}$	69.51 ± 0.54^{b}	80.83 ± 0.64^{b}	70.47 ± 0.85^{b}	65.74 ± 0.72^{b}	0.09 ± 0.03^{a}	6.79 ± 0.63^{c}
9	$88.04 + 0.12^{a}$	71.04 ± 0.52^{a}	81.37 ± 0.34^{a}	71.18 ± 0.95^{a}	66.34 ± 0.72^{a}	0.09 ± 0.02^{a}	6.79 ± 0.69^{c}

[a] The level of the other tested variables was fixed at 16 h soaking time, 0.5% $NaHCO_3$, 25 °C, and 3:1 of water: sesame seeds ratio. For each column, means superscripted with different letters indicate significant differences based on the Tukey test ($\alpha \leq 0.05$, $n = 3$).

use to complement plant-based products to meet the recommended daily nutrient intake of humans.[11]

3.2. Factors Affecting Sesame Milk Recovery. The OVAT approach was employed to examine the optimal level of the chosen factors influencing sesame milk recovery, whereby the optimal conditions for the variable under investigation were implemented in subsequent experiments.

3.2.1. Soaking Time. The process for manufacturing nondairy milk alternatives involves the soaking of raw material in the proper volume of pure water. The soaking step is done to hydrate the raw material before grinding and further processing. Data presented in Table 2 show that the longer seeds were soaked, the greater the recovery percentages of total solids, fat, carbohydrates, protein, and ash.

In accordance, when tiger nuts are soaked in water, the extraction yield of tiger nut milk increases.[37] A previous study on peanut seeds soaking for up to 72 h, noticed that the components recovered from peanut seeds increased when soaked for more than 18 h, but an undesirable flavor appeared due to the development of yeast and fungal growth when soaked for more than 24 h.[36] Soaking raw materials for nondairy milk production, like peanuts, soybeans, and almonds, for 12 to 18 h before grinding softens them through heat-induced modifications in biomolecules such as starch, pectin, and protein. This process also helps inactivate enzyme inhibitors, improving the digestibility and nutrient bioavailability of the resulting milk.[38,39]

Therefore, in the current study, the maximum component recovery of total solids, fat, carbohydrates, and protein was pronounced by soaking the seeds for 16 h, which was chosen in subsequent trials.

3.2.2. Addition of Sodium Bicarbonate. Data presented in Table 3 show that the addition of sodium bicarbonate to soaking water at 0.5 and 1% (w/v) increased the recovery percentages of total solids and proteins of the sesame extract. Results revealed that the pH of sesame milk increased while acidity decreased as the concentration of $NaHCO_3$ in soak water was increased. There were also slight effects on fat, carbohydrates, and ash. Whereas sesame seed proteins are generally less soluble in water, their solubility increases in alkaline solutions Thus, the increase in total dry matter is probably due to an increase in pH of sesame seeds during soaking in water containing $NaHCO_3$ that led to increased protein solubility during blending process.[40,41] It has been observed that the use of $NaHCO_3$ reduces off-flavor and increases the stability of the sesame milk substitute.[42]

3.2.3. Blending Time. The study of the third factor (blending time) was done on soaked sesame seeds for 16 h in water containing 0.5% (w/v) sodium bicarbonate as the best conditions to achieve the highest recovery. As shown in Table

Table 5. Effect of Extraction Temperature on the Recovery Percentage of Sesame Seed Constituents Extracted in Water[a]

temperature (°C)	recovery, %						
	T.S.	fat	protein	carbohydrate	ash	acidity	pH
25	86.95 + 0.10^{e}	67.98 ± 0.52^{e}	80.29 ± 0.64^{d}	69.76 ± 0.93^{c}	64.25 ± 0.72^{e}	0.07 ± 0.01^{a}	6.87 ± 0.85^{a}
30	88.26 + 0.08^{d}	70.74 ± 0.64^{d}	83.52 ± 0.55^{b}	70.47 ± 0.36^{b}	65.90 ± 0.84^{c}	0.07 ± 0.01^{a}	6.87 ± 0.63^{a}
35	90.89 + 0.33^{a}	74.62 ± 0.65^{c}	84.06 ± 0.57^{a}	74.38 ± 0.85^{a}	67.25 ± 0.67^{a}	0.07 ± 0.02^{a}	6.87 ± 0.67^{a}
40	89.80 + 0.05^{b}	75.64 ± 0.85^{b}	83.25 ± 0.67^{b}	69.05 ± 0.75^{d}	66.49 ± 0.66^{b}	0.07 ± 0.03^{a}	6.87 ± 0.75^{a}
45	88.76 + 0.07^{c}	76.15 ± 0.72^{a}	82.45 ± 0.62^{c}	67.62 ± 0.73^{e}	64.71 ± 0.77^{d}	0.07 ± 0.02^{a}	6.87 ± 0.74^{a}

[a] The level of the other tested variables was fixed at 16 h soaking time, 0.5% $NaHCO_3$, 5 min of blending time, and 3:1 of water: sesame seeds ratio. For each column, means superscripted with different letters indicate significant differences based on the Tukey test ($\alpha \leq 0.05$, $n = 3$).

Table 6. Effect of Extraction Ratio on the Recovery Percentage of Sesame Seed Constituents Extracted in Water[a]

water to sesame	recovery, %						
	T.S.	fat	protein	carbohydrate	ash	acidity	pH
2:1	58.73 + 0.12^{d}	49.65 ± 0.67^{d}	61.13 ± 0.82^{d}	70.57 ± 0.34^{d}	52.89 ± 0.92^{d}	0.07 ± 0.02^{a}	6.87 ± 0.72^{b}
3:1	77.86 + 0.05^{c}	59.49 ± 0.85^{c}	78.14 ± 0.43^{c}	74.38 ± 0.71^{c}	66.49 ± 0.69^{c}	0.07 ± 0.03^{a}	6.87 ± 0.45^{b}
4:1	86.60 + 0.15^{b}	62.67 ± 0.34^{b}	90.81 ± 0.38^{b}	82.09 ± 0.75^{b}	75.93 ± 0.64^{b}	0.05 ± 0.01^{b}	6.93 ± 0.44^{a}
5:1	92.37 + 0.08^{a}	68.97 ± 0.62^{a}	91.35 ± 0.49^{a}	84.18 ± 0.67^{a}	76.86 ± 0.61^{a}	0.04 ± 0.01^{c}	6.95 ± 0.66^{a}

[a] The level of the other tested variables was fixed at 16 h soaking time, 0.5% $NaHCO_3$, 5 min of blending time, and 35 °C. For each column, means superscripted with different letters indicate significant differences based on the Tukey test ($\alpha \leq 0.05$, $n = 3$).

4, the recovery percentages of sesame constituents rose with the increase of the blending time up to 9 min, and most of this increase occurred in the first 5 min. Furthermore, this treatment had slight effects on the acidity and pH of the extract. Although the recovered sesame components increased with increasing blending time, this affected the flavor and taste, which was unsuitable. So, the blending time should not exceed 5 min.

Increasing the blending time leads to a higher recovery of sesame components as it promotes greater fragmentation and mashing of soaked seed tissue, facilitating the release of carbohydrates, proteins, and fats from the cells. However, extended blending beyond 5 min results in an undesirable vegetable flavor, likely caused by accelerated breakdown of cell walls and subsequent dissolution of cellulose and hemicellulose.[43]

3.2.4. Temperature of the Extraction Process. Data from Table 5 suggest that increasing the extraction medium temperature to 35 °C improves the yield of sesame constituents. This aligns with observations in soy milk production, where higher temperatures enhance protein solubility, leading to a greater protein recovery during extraction. However, excessively high temperatures can lead to partial gelatinization of the extracted proteins. Therefore, 35 °C was selected as a compromise to achieve optimal yield while minimizing protein denaturation.[44]

3.2.5. Extraction Ratio. The recovery percentage of sesame milk in relation to the water-to-seed ratio was explored (Table 6). The increase of the extraction ratio up to 5:1 enhanced greatly the recovery percentages of the sesame constituents. These results may be attributed to the increase of the amount of the solvent, i.e., continuous phase, which had slight effects on reducing the acidity and increasing pH of the extract.

The stability of oilseed milk, such as sesame milk, is an important quality scale that is a necessity for consumer acceptance. Despite the increase of the percentage of recovery with the increase of the percentage of water, the pH of the extract increased until it reached 6.95 at a ratio of 5:1 and this is not acceptable to the consumer, but at ratios of 2:1 and 3:1, the pH was acceptable, which is 6.87. The optimal conditions for the preparation of high-quality sesame milk are a pasteurization temperature of 74.70 °C, gum concentration of 0.09 g/100 g, emulsifier level of 0.44 g/100 g, pH of 6.68, and homogenization pressure of 1.81 MPa.[42]

Based on the findings above, it is evident that the optimal conditions for producing sesame milk, which meets chemical standards, involve soaking sesame seeds in a 0.5% sodium bicarbonate solution for 16 h. Subsequently, blending the soaked seeds with water at 35 °C in a ratio of 1:5 for 5 min yields favorable results.

3.3. Modeling Sesame Milk Production by ANN. To maximize the sesame component yield during extraction, T.S. was selected as an evaluation method. T.S. provides a strategic advantage by encompassing all nonaqueous components, ensuring a high yield of valuable constituents. Moreover, T.S. measurement is faster and more cost-effective compared to individual component analysis, making it ideal for efficient large-scale extraction processes. However, both the extraction profile and sensory evaluation were defined after the optimization.

Performing OVAT is a valuable experimental approach to identify optimal conditions for a specific process. Once obtaining the optimum conditions are obtained through OVAT, utilizing ANN on the same data can offer several advantages. ANN excels in capturing complex interactions and nonlinear relationships that may be overlooked in the isolated examination of variables. By leveraging the ANN, researchers can achieve higher predictive accuracy, especially when extrapolating to conditions not explicitly tested in OVAT experiments. The network's ability to simultaneously consider multiple variables enables a more refined optimization of the overall process, addressing potential synergies or dependencies between factors. Furthermore, ANN facilitates robustness testing, evaluating the model's performance on unseen data to assess its reliability.[26,45]

ANNs are prized for empirical modeling due to their ability to accurately capture relationships between input and output variables, regardless of nonlinearity, where ANNs excel in extracting knowledge from data without a predefined fitting function, accommodating various nonlinear functions, includ-

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Table 7. Illustrates the Maximization of Total Solids Recovered from Sesame Seeds Extracted in Water through the Modeling of the Investigated OVAT Data by an ANN[a]

	Variable					Total solids yield, %			
Trial	X1	X2	X3	X4	X5	Experimental	ANN-predicted	Residual	Kind*
1	8	0.0	3	25	3	67.88	67.75	0.13	a
2	10	0.0	3	25	3	68.89	68.67	0.22	a
3	12	0.0	3	25	3	69.86	69.71	0.15	a
4	14	0.0	3	25	3	70.57	70.58	-0.01	b
5	16	0.0	3	25	3	71.08	71.20	-0.12	b
6	18	0.0	3	25	3	70.78	71.63	-0.85	a
7	16	0.0	3	25	3	71.08	71.20	-0.12	b
8	16	0.5	3	25	3	73.88	74.69	-0.81	b
9	16	1.0	3	25	3	74.12	75.68	-1.56	a
10	16	1.5	3	25	3	73.92	75.40	-1.48	a
11	16	2.0	3	25	3	74.02	74.64	-0.62	a
12	16	2.5	3	25	3	73.86	73.58	0.28	a
13	16	0.5	1	25	3	72.88	73.92	-1.04	a
14	16	0.5	3	25	3	79.92	74.69	5.23	a
15	16	0.5	5	25	3	86.90	87.27	-0.37	a
16	16	0.5	7	25	3	87.46	88.99	-1.53	a
17	16	0.5	9	25	3	87.91	87.87	0.04	a
18	16	0.5	5	25	3	86.89	87.27	-0.38	b
19	16	0.5	5	30	3	88.33	85.76	2.57	a
20	16	0.5	5	35	3	90.76	86.34	4.42	b
21	16	0.5	5	40	3	89.82	87.85	1.97	a
22	16	0.5	5	45	3	88.68	89.19	-0.51	a
23	16	0.5	5	35	2	58.62	59.08	-0.46	b
24	16	0.5	5	35	3	77.84	86.34	-8.50	a
25	16	0.5	5	35	4	86.46	86.37	0.09	a
26	16	0.5	5	35	5	92.31	92.92	-0.61	a
1	8	0.0	3	25	3	68.12	67.75	0.37	a
2	10	0.0	3	25	3	69.12	68.67	0.45	a
3	12	0.0	3	25	3	69.94	69.71	0.23	b
4	14	0.0	3	25	3	70.28	70.58	-0.30	a
5	16	0.0	3	25	3	70.95	71.20	-0.25	a
6	18	0.0	3	25	3	70.62	71.63	-1.01	b
7	16	0.0	3	25	3	71.18	71.20	-0.02	a
8	16	0.5	3	25	3	74.02	74.69	-0.67	b
9	16	1.0	3	25	3	74.20	75.68	-1.48	a
10	16	1.5	3	25	3	73.84	75.40	-1.56	a
11	16	2.0	3	25	3	74.07	74.64	-0.57	b
12	16	2.5	3	25	3	73.88	73.58	0.30	a
13	16	0.5	1	25	3	72.78	73.92	-1.14	a
14	16	0.5	3	25	3	79.78	74.69	5.09	a
15	16	0.5	5	25	3	86.89	87.27	-0.38	a
16	16	0.5	7	25	3	87.86	88.99	-1.13	b
17	16	0.5	9	25	3	88.07	87.87	0.20	a
18	16	0.5	5	25	3	87.06	87.27	-0.21	a
19	16	0.5	5	30	3	88.27	85.76	2.51	a
20	16	0.5	5	35	3	90.64	86.34	4.30	b
21	16	0.5	5	40	3	89.74	87.85	1.89	a
22	16	0.5	5	45	3	88.78	89.19	-0.41	b
23	16	0.5	5	35	2	58.86	59.08	-0.22	a
24	16	0.5	5	35	3	77.92	86.34	-8.42	b
25	16	0.5	5	35	4	86.76	86.37	0.39	a
26	16	0.5	5	35	5	92.46	92.92	-0.46	a
1	8	0.0	3	25	3	67.70	67.75	-0.05	a
2	10	0.0	3	25	3	68.96	68.67	0.29	a
3	12	0.0	3	25	3	70.14	69.71	0.43	b
4	14	0.0	3	25	3	70.38	70.58	-0.20	b
5	16	0.0	3	25	3	71.18	71.20	-0.02	a
6	18	0.0	3	25	3	70.82	71.63	-0.81	a
7	16	0.0	3	25	3	70.95	71.20	-0.25	a
8	16	0.5	3	25	3	73.86	74.69	-0.83	b
9	16	1.0	3	25	3	74.10	75.68	-1.58	a
10	16	1.5	3	25	3	73.82	75.40	-1.58	b
11	16	2.0	3	25	3	74.00	74.64	-0.64	a
12	16	2.5	3	25	3	74.02	73.58	0.44	a

Table 7. continued

Trial	Variable					Total solids yield, %			Kind*
	X1	X2	X3	X4	X5	Experimental	ANN-predicted	Residual	
13	16	0.5	1	25	3	72.80	73.92	-1.12	b
14	16	0.5	3	25	3	80.12	74.69	5.43	a
15	16	0.5	5	25	3	87.06	87.27	-0.21	b
16	16	0.5	7	25	3	87.51	88.99	-1.48	a
17	16	0.5	9	25	3	88.14	87.87	0.27	b
18	16	0.5	5	25	3	86.90	87.27	-0.37	a
19	16	0.5	5	30	3	88.18	85.76	2.42	a
20	16	0.5	5	35	3	91.27	86.34	4.93	a
21	16	0.5	5	40	3	89.84	87.85	1.99	a
22	16	0.5	5	45	3	88.82	89.19	-0.37	B
23	16	0.5	5	35	2	58.71	59.08	-0.37	B
24	16	0.5	5	35	3	77.82	86.34	-8.52	A
25	16	0.5	5	35	4	86.58	86.37	0.21	B
26	16	0.5	5	35	5	92.34	92.92	-0.58	B

[a] The table provides a comparison between experimental and predicted values. *The data were partitioned into a training group consisting of 52 runs (a) and a validation group comprising 26 runs. X1; soaking time (h), X2; $NaHCO_3$ (%), X3; blending time (min), X4; temperature (°C), and X5; water: sesame seeds ratio.

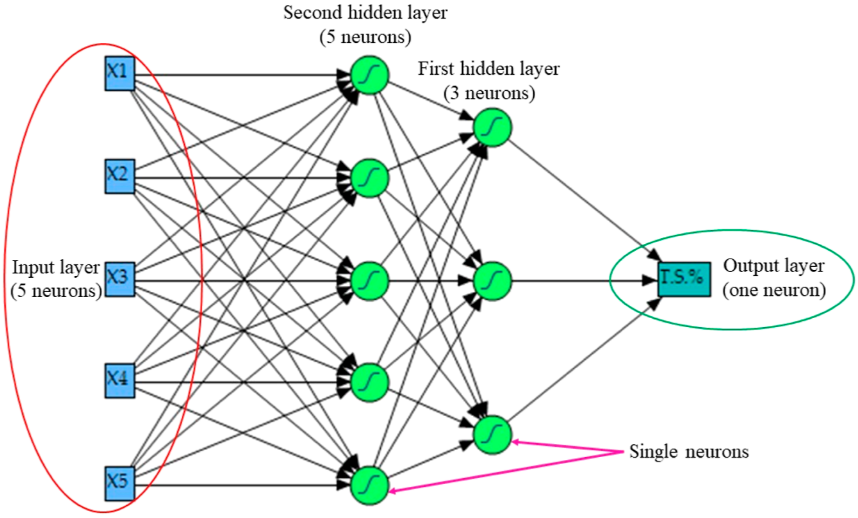

Figure 2. General layout of the ANN for T.S. % recovery extracted from sesame seeds. The diagram shows the input layer contained five neurons, i.e., X1; soaking time (h), X2; $NaHCO_3$ (%), X3; blending time (min), X4; temperature (°C), and X5; water: sesame seeds ratio. The hidden layer contains three (for the first hidden layer) and five (for the second hidden layer) neurons, having a hyperbolic tangent sigmoid function (*S*) designated as NTanH(3) and NTanH2(5). The output layer had one neuron (T.S. %).

ing quadratic ones. Despite the common perception that ANNs require a large number of experimental trials, recent findings suggest their effectiveness even with fewer data points, highlighting their adaptability and robustness in empirical modeling.[22,25,46]

3.3.1. OVAT Data Arrangement. The data obtained from OVAT trials on the T.S. yield of sesame seeds extracted in water served as historical data for the construction of the ANN model. Table 7 illustrates the arrangement of OVAT data during the feeding of the ANN. After the training process of ANN, the data present a comprehensive comparison between experimental and ANN-predicted values across multiple trials, aiming to explore optimal extraction conditions for sesame seed constituents. The observed low residual (error) values underscore the accuracy of the ANN model in predicting total solid yield, signifying its reliability. Additionally, the consistently low residuals suggest the efficiency of the ANN model in enhancing total solids recovery. The incorporation of essential variables (X1−X5) enhances the study's depth.

3.3.2. ANN Topology. To develop an optimal ANN model, the response data from OVAT was utilized. The ANN model employed a multilayer feed-forward architecture with various configurations of hidden layers and neurons. A range of ANN parameters was tested to identify the best-performing architecture. The training and validation processes were iterated until the model achieved an optimal performance.

The final, best-performing ANN configuration utilized a learning rate of 0.1, employed the squared penalty method for regularization, and incorporated a hold-back validation approach, where 33.33% of the data was reserved for validation. This strategic data partitioning ensures the model's generalizability and robustness. Overall, this optimized ANN model, built on the OVAT data, serves as a valuable tool for refining and optimizing sesame seed constituent extraction processes.

The ANN topology (Figure 2) illustrates the general layout of the ANN model used for predicting the total solids yield extracted from sesame seeds based on five input variables. The ANN topology contains one input layer with five neurons

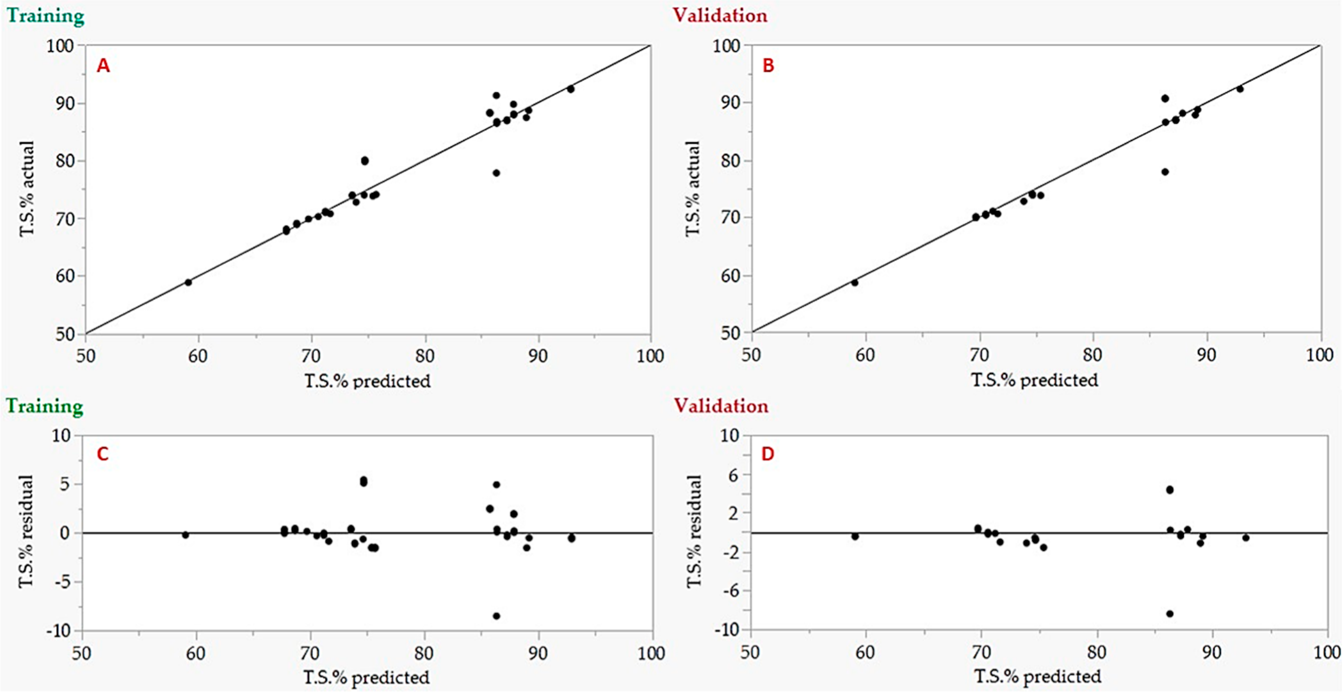

Figure 3. Plots of predicted values against the actual (A,B) and the residual (C,D) values for both training and validation processes for ANN modeling T.S. recovery from sesame seeds.

(X1−X5), and only one output layer with one neuron which represents the total solids, and the output neuron is connected to all the neurons in the hidden layers.

The ANN model employed a common activation function called NTanH in its hidden layers. This function can handle any real number as input and outputs a value between −1 and 1. The specific architecture of the model, 5-NTanH(3)-NTanH2(5), utilized two hidden layers with different numbers of neurons (3 and 5). This complex structure suggests a nonlinear relationship between the input variables (X1−X5, representing sesame seed extraction conditions) and the target T.S. This design effectively captured the underlying data patterns, enabling accurate prediction of T.S. values close to experimental results. This highlights the strength of ANNs in modeling complex relationships. Moreover, the success of this two-layered model demonstrates the potential of ANNs in food technology, a field ripe for further exploration with AI techniques.

3.3.3. Performance and Statistical Parameters of the ANN Model. The ANN model's effectiveness is corroborated by its close agreement between predicted and experimental T.S. values (Table 7). Figure 3 further strengthens this, where both training and validation data for the actual and predicted (Figure 3A,B) plots show a tight clustering around the diagonal line. This signifies a strong correlation between predicted and actual T.S. recovery. To validate the model's generalizability, residual analysis (Figure 3C,D) was performed. The randomness and even distribution of residuals around zero for both training (Figure 3A,C) and validation (Figure 3B,D) processes confirm the model's low error and lack of bias. In essence, the model effectively learns the relationships within the training data and generalizes well to predict T.S. recovery for unseen data, demonstrating its robustness and applicability.

To assess the ANN model's performance and generalizability, several statistical parameters were calculated for both training and validation data (Table 8). The high R^2 values (0.92 for training and 0.95 for validation) indicate a strong correlation between predicted and actual T.S. recovery, signifying that the model effectively captures the underlying relationships. Similarly, low RMSE (2.14 for validation and 2.42 for training) and MAD (1.12 for validation and 1.43 for training) values point toward good model accuracy and generalization. Lower SSE (118.65 for validation and 305.48 for training) further reinforces this. Finally, the low-Loglikelihood values (119.82 for training and 56.63 for validation) suggest a good fit and minimal overfitting, ensuring the model's validity and generalizability. Overall, these metrics demonstrate the model's effectiveness in accurately predicting T.S. recovery from sesame seeds based on the input variables.

Table 8. Statistical Parameters of the ANN Model for Both Training and Validation Data for Maximization of T.S. Recovery from Sesame Seeds[a]

model parameter	training	validation
coefficient of determination	0.9202	0.9514
root average squared error	2.424	2.136
mean absolute deviation	1.426	1.123
−loglikelihood	119.82	56.63
the sum of squared errors	305.475	118.650
sum frequency	52	26

[a] Sum frequency is the count of the observations in each data set, 52 for training and 26 for validation, reflecting data distribution.

3.3.4. Optimum Extraction Conditions and Model Validation. The ANN model not only predicted T.S. recovery accurately but also identified the optimal conditions for maximizing it from sesame seeds. Figure 4 depicts these optimal settings for the five key factors: soaking time (11.24

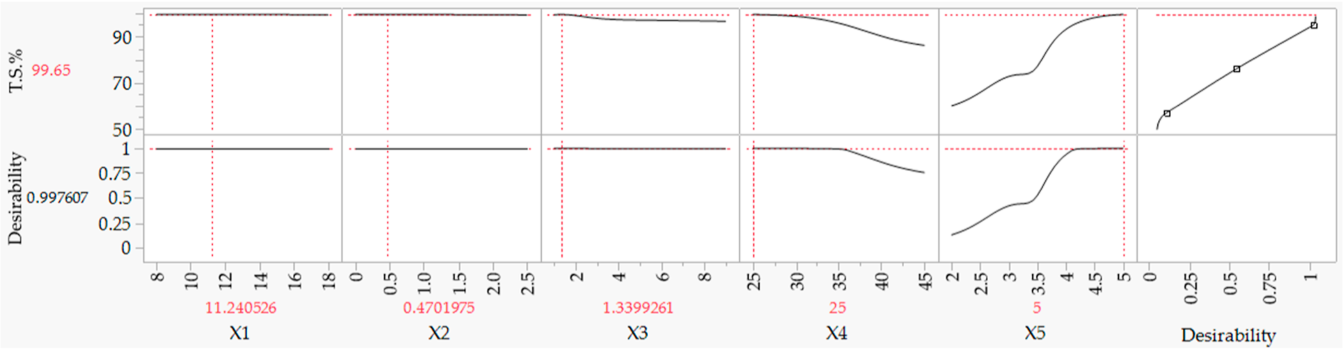

Figure 4. Optimum levels of the five tested factors obtained in the ANN mode maximize T.S. recovery from sesame seeds. X1; soaking time (h), X2; $NaHCO_3$ (%), X3; blending time (min), X4; temperature (°C), and X5; water: sesame seeds ratio. Each factor is represented on an individual axis with the predicted. The optimum levels for each factor are marked with red dots on the respective axes.

Table 9. Expected Conditions of the Five Investigated Parameters as Predicted by the ANN Model in Comparison to OVAT for T.S. Yield from Sesame Seeds[a]

	investigated parameters					T.S. yield (%)	
model	X1	X2	X3	X4	X5	predicted	actual
OVAT	16.00	0.5	5.00	35	5:1		92.37 + 0.08
ANN	11.24	0.47	1.34	25	5:1	99.65	95.18 + 0.13
	16.00	0.5	5.00	35	5:1	92.92	92.37 + 0.08
	16.00	0.5	5.00	35	3:1	86.34	77.86 + 0.05

[a]VAT; one variable at a time, X1; soaking time (h), X2; $NaHCO_3$ (%), X3; blending time (min), X4; temperature (°C), and X5; water: sesame seeds ratio.

Table 10. Recovery Ratio of Sesame Seeds Compounds in Sesame Milk Using Water or Permeate as Extractants at a Mixing Ratio of 5:1, Soaked Seeds: Water or Permeate[a]

	recovery, %						
milk type	T.S.	fat	protein	carbohydrate	ash	acidity	pH
WSM	95.18 ± 0.25	70.14 ± 0.15	81.03 ± 0.35	73.51 ± 1.82	71.10 ± 0.15	0.08 ± 0.03	6.81 ± 0.18
PSM	96.25 ± 0.17	72.22 ± 0.12	82.96 ± 0.57	81.21 ± 0.67	77.39 ± 1.02	0.12 ± 0.05	6.68 ± 0.20

[a]WSM; water-based sesame milk. PSM; permeate-based sesame milk.

h), NaHCO3 concentration (0.47%), blending time (1.34 min), temperature (25 °C), and extraction ratio (5:1 water: sesame seeds). Importantly, the model considers the complex, nonlinear interactions between these factors, which might be challenging for traditional methods. This allows it to predict T.S. recovery for untested factor combinations, offering a powerful tool for optimizing sesame seed extraction processes. Notably, exceeding the optimal soaking time, $NaHCO_3$ concentration, or blending time can lead to negative effects such as leaching, flavor alteration, or seed degradation. Similarly, excessively high temperatures can degrade sesame constituents.

The ANN model's predictive power was validated under laboratory conditions. Table 9 compares the optimal conditions predicted by the ANN model for maximizing T.S. recovery with those obtained by using the traditional OVAT method. Notably, the ANN model outperformed OVAT, predicting a maximum yield of 99.65% (experimentally validated at 95.18%) with a high desirability of 0.9976. This signifies the model's superiority in optimizing T.S. recovery.

Beyond the superior yield, the ANN-predicted settings offer economic benefits. Compared to OVAT, the optimal values for soaking time, $NaHCO_3$ concentration, blending time, and temperature are lower while maintaining a high extraction ratio (water: sesame). This translates to lower processing costs. It is important to remember that these optimal settings might vary depending on sesame seed type, desired T.S. composition, and other processing factors.

While the ANN model excelled in optimizing responses and delivering high predictive accuracy due to its ability to handle nonlinear relationships, it did come with some limitations. The iterative nature of ANN training can be computationally expensive, requiring a significant processing time. Additionally, due to the complex structure of the ANN, it can be challenging to pinpoint the specific contributions and importance of individual factors within the model. This lack of interpretability makes it difficult to identify and remove nonsignificant factors, potentially leading to an overly complex model.[22,25,26]

3.4. Sesame Seed Extract Using Milk Permeate.

This study proposes a novel approach for sesame milk extraction that utilizes milk permeate, a byproduct of the dairy industry, as a solvent. This strategy aligns with circular economy principles by minimizing waste and potentially enhancing the functional properties of the resulting sesame extract (sesame milk). Two types of sesame milk were prepared: water-based sesame milk (WSM) and permeate-based sesame milk (PSM), both produced with a 5:1 ratio (solvent: sesame seeds) under optimal conditions identified through modeling. The results (Table 10) revealed that PSM yielded a higher recovery of sesame seed components compared to WSM. This might be due to the inherent acidity of permeate compared to the neutral pH of water. The acidic nature of permeate potentially enhances its extractive activity,[36] leading to increased solubilization of sesame seed components. Consequently, permeate-based sesame milk exhibited a lower pH and higher acidity compared to that of water-based sesame milk.

Ultrafiltration, a cornerstone process in the dairy industry, generates significant volumes of milk permeate, a byproduct traditionally considered waste. However, permeate's composition, rich in lactose (65−85%), water-soluble vitamins, and minerals (sodium, potassium, magnesium, zinc, calcium), has garnered recent interest in its valorization within the dairy sector. Notably, permeate's electrolyte profile presents a unique approach to fortifying beverages and enhancing their overall nutritional content.[47,48]

Several studies support the concept of optimal mixing ratios for different plant-based milks. El-Shafie[36] found a 5:1 water-to-peanut ratio to be optimal for peanut milk, which aligns with the findings for sesame milk in this study. Similarly, oat milk and barley milk can be prepared using various water ratios, with a 5:1 ratio yielding the best results.[49] However, using a different ratio (12:88 sesame seeds: water) for maximum yield of sesame milk.[50]

Beyond its functional properties, permeate holds significant economic potential due to its rich nutritional composition, cost-effectiveness, and versatility in food and beverage applications, unlocking promising avenues for further research and development. Additionally, employing permeate as a plant-based milk extractant offers a compelling strategy. Its dairy origin is expected to contribute to a milky mouthfeel and flavor profile, potentially mitigating undesirable characteristics often associated with plant-based alternatives.

3.5. Features of Sesame Milk Formulations.

3.5.1. Supporting Probiotic Bacteria.

Fermentation is a cornerstone process in the dairy industry, particularly for producing fermented milk products containing probiotic LAB. However, there is a growing interest in exploring alternative growth media for these beneficial bacteria due to factors such as lactose intolerance and vegan dietary preferences. This study investigated the potential of sesame milk as a novel growth medium for LAB. The two types of WSM and PSM were evaluated. Both media were inoculated with probiotic ABT-5 culture. The growth of *B. bifidum*, *L. acidophilus*, and *S. thermophilus* and the acidification (changes in pH) over a 10 h fermentation period were monitored during incubation at 37 °C. Reconstituted skim milk (natural medium) served as a positive control (Table 11).

The results showed that all three LAB strains could grow in all three media. However, the final cell densities, measured in log cfu/mL, were consistently the highest in the reconstituted milk for all strains. This suggests that reconstituted milk provides the most favorable environment for LAB growth. Interestingly, PSM generally supported higher bacterial growth compared with WSM. The cell densities achieved in PSM were closer to those observed in reconstituted milk.

Lactic acid bacteria exhibited promising growth in both WSM and PSM, with levels comparable to those of reconstituted skim milk. This finding suggests that sesame milk holds promise as a viable alternative to LAB cultivation. Consistent with bacterial growth, the pH of all cultures decreased during incubation, reaching approximately 4.5 for reconstituted milk, 4.65 for WSM, and 4.61 for PSM after 10 h. The highest final cell density of LAB was observed in reconstituted skim milk, followed by PSM and then WSM. Throughout the fermentation process, the pH of all cultures decreased, indicating the production of lactic acid by the LAB. This is a characteristic feature of LAB fermentation. The rate of acidification, however, differed among the media. The pH dropped the fastest in the reconstituted skim milk cultures, followed by PSM and then WSM.

Table 11. Impact of Sesame Milk Formulations (Water-Based and Permeate-Based) on Lactic Acid Bacteria Count (Log cfu/mL) and pH during 10 h Fermentation[a]

time, h	pH	La	Bb	St
Natural Medium (Reconstituted Milk)				
0	6.48 ± 0.01^{a}	5.47 ± 0.06^{d}	4.25 ± 0.02^{f}	6.88 ± 0.12^{f}
2	6.21 ± 0.01^{b}	6.28 ± 0.10^{c}	4.42 ± 0.03^{e}	7.33 ± 0.15^{e}
4	5.42 ± 0.02^{c}	6.30 ± 0.11^{b}	4.78 ± 0.07^{d}	7.59 ± 0.11^{d}
6	5.11 ± 0.01^{d}	6.32 ± 0.06^{a}	4.91 ± 0.01^{c}	7.97 ± 0.17^{c}
8	4.82 ± 0.02^{e}	6.31 ± 0.18^{ab}	5.14 ± 0.05^{b}	8.27 ± 0.15^{b}
10	4.50 ± 0.03^{f}	6.32 ± 0.12^{a}	5.61 ± 0.04^{a}	8.63 ± 0.18^{a}
Water-Based Sesame Milk				
0	6.47 ± 0.02^{a}	5.41 ± 0.05^{e}	4.22 ± 0.02^{f}	6.83 ± 0.05^{f}
2	6.25 ± 0.03^{b}	5.90 ± 0.11^{d}	4.33 ± 0.03^{e}	7.01 ± 0.12^{e}
4	5.62 ± 0.02^{c}	6.05 ± 0.02^{c}	4.67 ± 0.07^{d}	7.29 ± 0.04^{d}
6	5.31 ± 0.01^{d}	6.11 ± 0.03^{b}	4.77 ± 0.01^{c}	7.52 ± 0.03^{c}
8	4.89 ± 0.05^{e}	6.19 ± 0.07^{a}	4.91 ± 0.05^{b}	7.83 ± 0.11^{b}
10	4.65 ± 0.02^{f}	6.21 ± 0.01^{a}	5.11 ± 0.04^{a}	8.10 ± 0.06^{a}
Permeate-Based Sesame Milk				
0	6.30 ± 0.03^{a}	5.50 ± 0.03^{e}	4.23 ± 0.02^{f}	6.85 ± 0.15^{f}
2	6.11 ± 0.01^{b}	6.02 ± 0.12^{d}	4.45 ± 0.03^{e}	7.23 ± 0.25^{e}
4	5.45 ± 0.02^{c}	6.22 ± 0.11^{c}	4.76 ± 0.05^{d}	7.37 ± 0.05^{d}
6	5.21 ± 0.05^{d}	6.35 ± 0.05^{b}	4.88 ± 0.01^{c}	8.13 ± 0.15^{c}
8	4.85 ± 0.01^{e}	6.41 ± 0.03^{a}	5.11 ± 0.03^{b}	8.21 ± 0.10^{b}
10	4.61 ± 0.02^{f}	6.44 ± 0.15^{a}	5.55 ± 0.05^{a}	8.45 ± 0.13^{a}

[a] Bp; *Bifidobacterium bifidum*. La; *Lactobacillus acidophilus*. St; *Streptococcus thermophilus*. For each milk type and period, the mean superscripted with different letters indicates significant differences based on Tukey's honest significant difference test, ($\alpha \leq 0.05$, $n = 3$).

These findings offer promising evidence for the potential use of sesame milk, particularly PSM, as a novel fermentation medium for the LAB. The presence of lactose in reconstituted skim milk appears to provide a readily available energy source for the LAB, leading to faster growth and acidification. Similarly, PSM supported LAB growth, potentially due to the presence of residual lactose and other growth factors in the permeate. Sesame milk of WSM, although lacking lactose, LAB could utilize components within the sesame seeds for energy and growth factors, and the absence of lactose likely resulted in slightly lower growth compared to PSM or skim milk, suggesting that sesame components are capable also of supporting LAB growth. In this connection, WSM (12:88 sesame seeds: water) was suitable for producing sesame fermented milk using *Lactobacillus plantarum* Dad 13 strain.[50]

3.5.2. Sensory Evaluation.

It is of great importance to perform sensory evaluation of the two patterns of sesame milk to ensure its acceptability. Table 12 presents the results of a sensory evaluation comparing WSM, PSM, and cow's milk (control). Panelists assessed the sensory properties of each sample across four categories: flavor (45 points), texture (35 points), acidity (10 points), and appearance (10 points), with a possible total score of 100 points possible.

The data reveal that cow's milk received the highest overall score (94.77 ± 0.68), followed by PSM (89.66 ± 0.57) and

Table 12. Sensory Evaluation of Sesame Milk Formulations (Water-Based and Permeate-Based) Compared to Cow's Milk[a]

sensory properties	control (cow's milk)	WSM	PSM
flavor (45 points)	43.55 ± 0.51^{a}	34.33 ± 0.57^{c}	40.44 ± 0.51^{b}
texture (35 points)	33.00 ± 1.00^{a}	29.89 ± 0.83^{c}	31.33 ± 0.57^{b}
acidity (10 points)	9.22 ± 0.38^{a}	8.00 ± 0.01^{b}	9.22 ± 0.38^{a}
appearance (10 points)	9.00 ± 0.01^{a}	7.22 ± 0.38^{c}	8.78 ± 0.69^{b}
total (100 points)	94.77 ± 0.68^{a}	79.44 ± 2.35^{c}	89.66 ± 0.57^{b}

[a] WSM; water-based sesame milk. PSM; permeate-based sesame milk. For column, mean superscripted with different letters indicates significant differences based on Tukey's honest significant difference test, ($\alpha \leq 0.05$, $n = 12$).

WSM (79.44 ± 2.35). This suggests that cow's milk was generally better accepted by the panelists in terms of sensory attributes. Looking at the individual categories, cow's milk and PSM achieved similar scores for flavor (43.55 ± 0.51 vs 40.44 ± 0.51) and acidity (9.22 ± 0.38 vs 9.22 ± 0.38). However, cow's milk received a higher score for texture (33.00 ± 1.00) compared to both sesame milk formulations (WSM: 29.89 ± 0.83; PSM: 31.33 ± 0.57). This suggests that the texture of cow's milk was perceived as more desirable by the panelists. For appearance, PSM scored closer to cow's milk (8.78 ± 0.69 vs 9.00 ± 0.01) compared to WSM (7.22 ± 0.38).

This might indicate that the visual characteristics of PSM, potentially due to the presence of milk permeate, were more like cow's milk than those of WSM. Permeate, with its milky origin, has been shown to contribute a milky taste and aroma to other plant-based milk alternatives.[51] This aligns with the sensory evaluation results for flavor, where PSM scored closer to cow's milk compared to WSM. These findings suggest that sesame milk formulations, particularly PSM, hold promise as alternatives to cow's milk based on sensory evaluation. Yet, sesame in dairy products can solve challenges like beany flavor and low dispersion stability found in legumes and other plant-based milk.[12] Sesame-based milk beverages with minimal beany taste can overcome consumption restrictions associated with soy-based and other plant milk options.

Building on the successful development of a novel sesame milk alternative using an ANN paradigm, this study further explored the development of a sesame milk alternative with enhanced functionality by incorporating milk permeate. The ANN model was used to optimize WSM extraction, maximizing T.S. recovery, which closely matched the actual T.S. value, demonstrating its potential as a tool for optimizing high-yield production. This approach effectively utilizes a previously underutilized byproduct and holds promise for future probiotic applications.

Sesame milk, while promising as a LAB growth medium for future probiotic applications, presents some limitations. Its nutrient composition might differ from that of dairy, potentially requiring fortification with essential elements for optimal LAB growth. Additionally, sesame's inherent antibacterial properties could hinder LAB functionality. Investigating LAB strains resistant to these properties is crucial. Finally, sesame milk lacks lactose, necessitating the identification and optimization of alternative carbon sources and fermentation conditions for efficient LAB growth and acid production.

Despite the limitations mentioned previously, sesame milk, particularly when prepared with milk permeate, offers several advantages as a LAB growth medium. Notably, it could be a suitable option for individuals with lactose intolerance who cannot consume traditional dairy-based probiotic products. Furthermore, incorporating milk permeate, a byproduct of cheese production, into sesame milk production presents economic and environmental benefits. Utilizing a waste stream in this way reduces the environmental impact and promotes resource recovery.

4. CONCLUSIONS

This study successfully developed a novel sesame seed-based milk alternative with enhanced probiotic viability and sensory appeal. We innovatively employed an ANN model to optimize the WSM extraction process, maximizing the T.S. recovery. Furthermore, incorporating milk permeate, a previously underutilized byproduct, during PSM preparation resulted in a product with superior nutritional value and sensory characteristics compared to WSM. Both WSM and PSM supported the growth of LAB, demonstrating their potential as LAB growth media for future probiotic applications. These findings highlight the promise of AI-powered optimization and milk permeate integration for creating innovative nondairy milk alternatives with enhanced functionality. Future research can explore additional AI applications to further optimize sesame milk production with permeate. Optimizing fermentation conditions for sesame milk-based probiotic products, investigating the potential health benefits associated with LAB fermentation in this medium (e.g., gut health and immune function) and evaluating consumer preferences for flavors and textures are crucial next steps. Selecting LAB strains specifically suited for sesame milk as a growth medium is also essential for enhancing the viability and consumer acceptance of these probiotic products. By addressing these aspects, sesame milk with permeate has the potential to become a commercially viable and attractive option for consumers seeking a plant-based, functional beverage with probiotic benefits and sensory appeal.

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Notes

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