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Investigation of Salt Uptake Kinetics in White Cheese Using Mass Transfer Models and Numerical Simulation

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ABSTRACT

Salting is one of the most important stages in cheese production, significantly influencing the rheological, microbiological, and sensory properties of the final product. In cheese, controlling salt uptake and distribution is particularly important because its porous structure and high moisture content make it highly sensitive to osmotic changes. To analyze the kinetics of salt uptake, six mathematical models were applied in this study, including the diffusion model, semi-infinite model, Azuara model, Peleg model, Zugarramurdi–Lupín model, and Weibull model. The salt diffusion experiments were designed under one-dimensional conditions in order to be consistent with the assumptions of analytical models, particularly the semi-infinite diffusion model. Salt concentration was measured at 4-hour intervals using the Volhard titration method. The results indicated that the semi-infinite model provided the highest accuracy among the theoretical models (R^2 = 0.999), while the Weibull model showed the best performance among the empirical models (R^2 = 0.996). The classical diffusion model exhibited the lowest accuracy due to the assumption of a constant diffusion coefficient and its limited compatibility with the experimental geometry. In addition, numerical simulation based on the solution of Fick's second law using COMSOL software demonstrated that the salt diffusion front gradually progresses from the surface toward the interior over time, leading to a more uniform concentration distribution within the cheese. These findings indicate that appropriate modeling can serve as an effective tool for predicting salt mass transfer behavior and optimizing the cheese brining process.

1-Introduction

Salting is one of the key stages in the cheese manufacturing process and plays a decisive role in the physicochemical, microbiological, and sensory characteristics of the final product. The presence of sodium chloride not only contributes to the development of desirable flavor but also enhances product stability and regulates the fermentation process by reducing water activity and inhibiting the growth of undesirable microorganisms. Moreover, salt directly influences the structure, texture, and ripening of cheese through the regulation of enzymatic activity, its effect on pH, and its impact on the electrical charge and solubility of casein micelles. Sodium and chloride ions interact with the protein network and the aqueous phase, affecting matrix swelling, final texture, and flavor development. Consequently, precise control over the concentration and distribution pattern of salt is essential for achieving consistent and stable quality in industrial-scale production. The importance of this stage becomes particularly pronounced in white, semi-hard, and brined cheeses, whose structures are highly sensitive to osmotic and moisture variations [1–2].

Various methods are employed for cheese salting, including dry salting, surface salting, curd salting, and brining. Among these techniques, brining is more widely applied in industrial production due to its operational simplicity, improved process controllability, and ability to achieve relatively uniform salt distribution. In this method, cheese blocks are immersed for a specified period in a brine solution of known concentration, allowing mass transfer to occur between the external medium and the internal cheese matrix. Owing to its variable and dynamic nature, this process cannot be regarded as a simple diffusion phenomenon; rather, it involves the simultaneous bidirectional transfer of salt from the surrounding medium into the cheese and water and soluble compounds from the cheese into the brine solution [3–4]. During this process, the salt concentration gradient between the brine solution and the aqueous phase of the cheese provides the primary driving force for NaCl diffusion, whereas the osmotic pressure gradient resulting from differences in moisture content promotes water migration from the cheese matrix. In the initial stages, water loss generally occurs more rapidly than salt uptake, and this asymmetry leads to displacement of the surface layers, alterations in the effective mass transfer area, and the formation of complex diffusion patterns. These continuous changes affect the chemical composition, moisture content, density, and even the textural structure of the cheese throughout the brining period, making the theoretical prediction of system behavior considerably more difficult than in simple solution systems [5–6].

Salt transport in cheese occurs predominantly through the aqueous phase of the matrix; however, the complex structure of the casein network substantially reduces salt diffusion compared with that in pure water. This behavior is described in the scientific literature as impeded diffusion and results from a combination of limiting mechanisms. First, the dense and interconnected casein network forms pores of very small dimensions that restrict the movement of hydrated Na^+ and Cl^- ions. Second, the presence of fat globules, protein particles, and colloidal structures partially obstructs diffusion pathways and increases tortuosity, thereby extending the effective diffusion path length. Third, the higher viscosity of the aqueous phase relative to pure water, according to the Stokes–Einstein relationship, reduces ionic mobility. Fourth, the presence of bound water within the protein network, which constitutes a significant fraction of the matrix water, decreases the effective pore volume available for salt transport because it does not participate in mass transfer. Fifth, the rapid moisture loss from the cheese surface during the early stages of brining leads to the formation of denser surface layers, displacing the effective diffusion interface inward and creating a dynamic barrier to salt penetration. The combined effects of these factors cause the effective diffusion coefficient of NaCl in cheese to be several times lower than its value in water. Therefore, accurate evaluation of diffusion kinetics is only possible when these factors are taken into consideration [7–9].

In addition to microstructural characteristics, processing conditions also exert a significant influence on salt uptake kinetics. Brine concentration represents the principal driving force for diffusion; however, at high concentrations, the formation of a dense surface layer may occur, thereby restricting further penetration. Temperature is another key factor governing the diffusion coefficient through its effects on molecular kinetic energy, the viscosity of the aqueous phase, and the flexibility of the casein network. Sample geometry and the surface-to-volume ratio influence the effective diffusion path length, such that smaller samples with larger relative surface areas exhibit faster salt uptake rates. The pH of both the brine and the cheese can alter the swelling behavior of the protein matrix and the electrical charge of casein micelles, consequently modifying diffusion pathways. Variables such as initial moisture content, fat content, and technological treatments applied prior to brining, including pre-salting, also affect diffusion behavior. Therefore, accurate analysis of the process requires simultaneous consideration of a wide range of structural, chemical, and operational factors. For this reason, the salt absorption process must be investigated individually for each cheese variety [3,10,11].

To mathematically describe this process, the application of mass transfer models is essential, and Fick's second law is the most commonly used theoretical framework in studies of cheese salting. This law describes the temporal and spatial variations in concentration as a function of the effective diffusion coefficient and can be solved analytically or numerically for simple geometries such as slabs, cylinders, and cubes [12–15].

Salt concentration and distribution play a decisive role in microbial growth, fermentation intensity, rheological properties, and the final sensory quality of cheese. Therefore, accurate prediction of salt transport behavior is essential for effective quality control of the product. The novelty of the present study lies in the application of a multi-model approach that integrates empirical models, analysis based on fundamental transport models, and two-dimensional numerical simulation to describe and predict salt transfer in Iranian white cheese.

Despite extensive research on European cheese varieties, relatively limited studies have addressed the physical modeling of salt transport in Iranian white cheese, particularly considering its distinctive structural characteristics. Accordingly, the development of an integrated modeling framework can provide a valuable scientific tool for the design, control, and optimization of the brining process in the Iranian cheese industry. The objective of this study is to investigate the kinetics of salt uptake in white cheese and to develop a multi-level modeling framework for predicting salt transport behavior during the brining process. In this regard, the performance of a set of fundamental and empirical models is first evaluated in describing the experimental data in order to identify the most suitable model in terms of both physical consistency and statistical accuracy. Subsequently, a numerical model based on the solution of Fick's second law is developed in the COMSOL environment to enable prediction of the spatial–temporal distribution of salt concentration throughout the entire cheese matrix during brining. This modeling framework can contribute to a better understanding of the mechanisms governing salt transport and ultimately support the optimization of processing conditions and the improvement of uniformity and final quality in Iranian white cheese.

2- Materials and Methods

2.1. Sample Preparation and Salt Diffusion Experiments

To investigate the kinetics of salt uptake and transport in cheese, rectangular prism samples with dimensions of 20 × 10 cm were obtained from the production line of Pegah Dairy Company. Each sample was placed inside a plastic holder in such a way that only one surface was exposed to the brine solution. To prevent mass transfer from other directions, the upper surface of the sample was coated with a layer of paraffin, while the lateral sides were protected using a plastic rectangular enclosure. Consequently, salt transfer occurred exclusively through a single surface, resulting in one-dimensional diffusion. This experimental arrangement was consistent with the assumptions of the one-sided mass transfer model and enabled more accurate analysis of the diffusion phenomenon (Figure 1).

The experiments were conducted in a tank containing the brine solution. The cheese sample was positioned on a supporting stand such that its lower surface was in direct contact with the solution. To avoid the formation of concentration gradients in the solution and to minimize mass transfer resistance in the liquid phase, a magnetic stirrer was placed at the bottom of the tank to ensure uniform mixing of the brine and to maintain an approximately constant salt concentration in the vicinity of the sample [16].

Experimental conditions, including temperature, brine concentration, and the ratio of brine volume to sample volume, were carefully controlled. The experiments were carried out at 5–6 °C, and the brine concentration was set at 0.27 kg salt per kg brine. In addition, a brine-to-sample volume ratio of 10:1 was selected to ensure that the solution concentration remained approximately constant throughout the diffusion process. All experiments were performed under identical conditions and in triplicate to ensure the accuracy and reproducibility of the results.

To determine salt uptake over time, samples were removed from the solution at regular 4-h intervals, and their salt content was measured. Salt concentration was determined using the Volhard method, which is one of the conventional precipitation titration techniques for chloride ion determination. In this method, chloride ions present in the sample first react with a known quantity of standard silver nitrate solution to form a silver chloride precipitate. The excess silver ions are then titrated using a standard potassium thiocyanate solution. In the presence of ferric ammonium sulfate indicator, the endpoint of the reaction is identified by the formation of a red-colored complex between ferric ions and thiocyanate ions. Based on the amount of thiocyanate consumed, the chloride ion concentration and, consequently, the salt content of the sample were calculated [17].

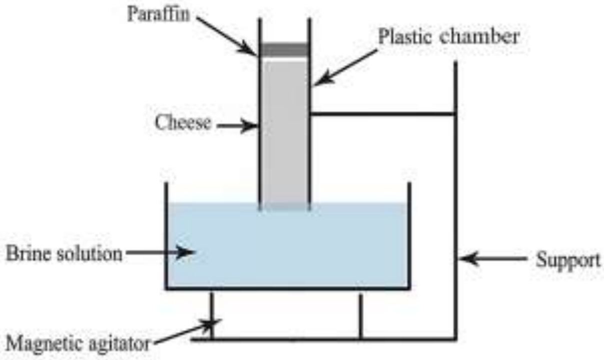

Figure 1. Schematic representation of the experimental setup used for cheese brining experiments

2.2. Mathematical Modeling of Salt Uptake in Cheese

In order to describe the kinetics of salt uptake in cheese during the brining process and to determine the diffusion coefficient, six mathematical models were applied, including the diffusion model, the semi-infinite diffusion model, the Azuara model, the Peleg model, the Zugarramurdi–Lupin model, and the Weibull model. These models were used to predict the temporal variation of salt concentration in cheese, and their performance in describing mass transfer behavior during the brining process was evaluated [5,18].

2.2.1. Diffusion Model

To determine the effective diffusion coefficient of salt in cheese, a diffusion model based on Fick's second law was employed, which is widely used to describe mass transfer phenomena in food systems. In this model, the cheese samples were considered as slabs with a defined thickness, and salt transport was assumed to occur primarily through the aqueous phase of the cheese matrix. The analytical solution of Fick's second law for slab geometry is expressed as follows:

$$\frac{C_{S,0}-C_{S,t}}{C_{S,0}-C_{S,\infty}} = 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2\pi^2} e^{\frac{-D_S(2n+1)^2\pi^2 t}{L^2}} \quad [1]$$

where $C_{s,0}$ is the initial salt concentration in the cheese (g salt/kg cheese), $C_{s,\infty}$ is the equilibrium salt concentration (g salt/kg cheese), Ds is the effective diffusion coefficient of salt in cheese (m²/s), t is the brining time (s), and L is the thickness of the cheese sample (m).

2.2.2. Semi-Infinite One-Directional Mass Transfer Model

$$\frac{C_{S,\infty}-C_{S,t}}{C_{S,\infty}-C_{S,0}} = erf\left(\frac{x}{2\sqrt{Dt}}\right) \quad [2]$$

where $C_{s,0}$ is the initial salt concentration in the cheese (g salt/kg cheese), $C_{s,\infty}$ is the equilibrium salt concentration (g salt/kg cheese), D_s is the effective diffusion coefficient of salt in cheese (m²/s), erf denotes the error function, t is the brining time (s), and L is the thickness of the cheese sample (m) [5].

2.2.3. Azuara Model

The Azuara model is a semi-empirical model used to describe mass transfer kinetics in osmotic processes and was applied in this study to predict salt uptake in cheese. The equation of this model is expressed as follows:

$$C_s = \frac{k_S t C_{S,\infty}}{1 + k_S t} \quad [3]$$

where C_s is the salt concentration in cheese, $C_{s,\infty}$ is the equilibrium salt concentration, k_s is the model constant (1/h), and t is the brining time (h).

2.2.4. Peleg Model

The Peleg model is a widely used empirical model for describing mass transfer in food materials and was employed in this study for modeling salt uptake in cheese. The equation of this model is expressed as follows:

$$C_s = \frac{t}{k_{S,1} + k_{S,2} t} \quad [4]$$

where C_s is the salt concentration in cheese, k_{s1} and k_{s2} are the kinetic constants of the model, and t is the brining time.

2.2.5. Zugarramurdi–Lupin Model

This model was also used to predict changes in salt concentration during the brining process. The equation of the model is given as follows:

$$C_S = C_{S,\infty}[1 - \exp(-k_S t)] + C_{S,0}[\exp(-k_S t)] \quad [5]$$

where C_s is the salt concentration in cheese, $C_{s,\infty}$ is the equilibrium salt concentration, k_s is the model constant (1/h), and t is the brining time (h).

2.2.6. Weibull Model

The Weibull model was employed to describe the nonlinear behavior of salt diffusion kinetics in cheese during the brining process. This model is expressed as follows:

$$\frac{C_{S,t} - C_{S,t}}{C_{S,0} - C_{S,\infty}} = exp\left[-\left(\frac{t}{\alpha_S}\right)^{\beta_S}\right] \quad [6]$$

where $C_{s,0}$ is the initial salt concentration in cheese, $C_{s,\infty}$ is the equilibrium salt concentration, α_s and β_s are the model parameters, and t is the brining time.

2.3. Developed Numerical Model

During the brining process, salt transport from the brine solution into the cheese matrix occurs mainly through molecular diffusion. Due to the concentration gradient between the cheese surface, which is in direct contact with the brine solution, and the inner regions of the cheese, salt gradually penetrates the porous and moist structure of the cheese and becomes distributed throughout its volume over time. This process plays an important role in determining the physicochemical, textural, and sensory characteristics of cheese. To mathematically describe this phenomenon, Fick's second law of mass transfer in a two-dimensional form was applied, which relates the temporal and spatial variations of salt concentration to the effective diffusion coefficient of salt within the cheese matrix [6,19]. This equation enables the prediction of salt distribution within the cheese matrix during the brining process. For numerical simulation and solution of the governing equations, COMSOL Multiphysics software (version 6.0) was used. In this approach, the geometry of the cheese sample was defined and the computational domain was discretized using the finite element method. To improve computational accuracy, a mesh consisting of 2054 triangular elements was employed, allowing appropriate analysis of the spatial distribution of salt concentration within the cheese. The general form of the governing equation is expressed as follows:

$$\frac{dC_S}{dt} = D_S\left(\frac{d^2C_S}{dx^2} + \frac{d^2C_S}{dy^2}\right) \quad [7]$$

where C is the salt concentration in cheese, t is time, and D is the effective salt diffusion coefficient in the cheese. In this model, the following assumptions were considered:

1. Salt transport within the cheese occurs predominantly through molecular diffusion.
2. The temperature remains approximately constant throughout the process.
3. The diffusion coefficient of salt in the cheese was determined based on the results obtained in the first phase of the study, using the model with the highest coefficient of determination and the lowest root mean square error, and it was assumed to remain constant within the considered time interval.
4. Mass transfer at the cheese surface is faster than within the cheese matrix; therefore, the main resistance to mass transfer is attributed to diffusion within the cheese structure.

Boundary and Initial Conditions

$$t = 0 \quad C_S(x, y, 0) = C_{S,0} \quad [8]$$

$$t > 0 \;\; at\; x = 0 - n.J_S = k_S\left(C_{S,\infty} - C_{S,t}\right) \quad [9]$$

$$t > 0 \;\; at\; x = L \;\; \left.\frac{\partial C(x, y, t)}{\partial x}\right| = 0 \quad [10]$$

1. At the beginning of the process, the salt concentration within the cheese is assumed to be approximately zero or equal to a specified initial value.
2. At the cheese surface, the salt concentration is assumed to be equal to the equilibrium concentration with the brine solution.

By solving this model, it is possible to predict the salt distribution profile within the cheese over time, the time required to reach the desired salt concentration, as well as the effects of cheese size and geometry.

3. The convective mass transfer coefficient k_s was determined through an optimization procedure using the Levenberg–Marquardt algorithm, whereby the parameter values were automatically adjusted to achieve the best agreement between the simulation results and the experimental data.

2.4. Model Performance Evaluation

To evaluate the accuracy of the models in predicting the experimental data, the coefficient of determination R^2 and the root mean square error (RMSE) were used [19].

$$R^2 = 1 - \frac{SSE}{SST} \quad [11]$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(C_{Predicted} - C_{Observed})} \quad [12]$$

In the coefficient of determination equation, SSE and SST represent the sum of squares due to error and the total sum of squares, respectively. In the root mean square error equation, \(n\) is the number of experimental data points, while $C_{predicted}$ and $C_{observed}$ represent the values predicted by the model and the experimental values, respectively.

3- Results and Discussion

The results obtained from fitting the different models indicate that the accuracy of analytical and empirical models in describing salt transfer in cheese differs significantly. This difference can be interpreted based on the fundamental or empirical nature of the models (Figure 2).

The diffusion model and the semi-infinite model are analytical and fundamental models that are directly derived from the physical equations of mass transfer (Fick's second law) and therefore have the capability to describe the real behavior of the system based on physical principles. Among these models, the semi-infinite model, with a diffusion coefficient of 5×10^{-7} m²/h, demonstrated considerably better performance than the classical diffusion model. The experimental conditions—where one surface of the sample was in contact with the brine while the opposite side was insulated—are fully consistent with the assumptions of the semi-infinite model. Therefore, its very high accuracy was expected and indicates that this model can realistically describe the diffusion behavior of the system. In contrast, the classical diffusion model showed weaker agreement with the experimental data, with a lower coefficient of determination and a higher root mean square error (0.96 and 0.011, respectively). This discrepancy may be attributed to geometric limitations and the assumption of a constant diffusion coefficient within the heterogeneous structure of cheese [3].

On the other hand, the Azuara, Peleg, Weibull, and Zugarramurdi–Lupin models are empirical–kinetic models which, unlike fundamental models, are not based on explicit physical equations and are mainly used for data fitting. Among these models, the Weibull model showed the highest accuracy, with a coefficient of determination (R^2) of 0.996 and a root mean square error (RMSE) of 0.0004, indicating its high flexibility and strong capability in describing the nonlinear behavior of salt absorption. The Peleg model also demonstrated very satisfactory performance and was able to effectively model the initial stages of diffusion and the approach to equilibrium. Although the Azuara model showed good agreement with the experimental data (R^2 = 0.994), its accuracy was lower than that of the Weibull and Peleg models. In contrast, the Zugarramurdi–Lupin model exhibited the lowest accuracy among the empirical models and showed the weakest agreement with the experimental data.

From an applied perspective, fundamental models such as the semi-infinite model possess greater scientific value because they allow the extraction of physical parameters such as the diffusion coefficient and have higher generalizability. In contrast, although empirical models often provide better statistical fitting, they are dependent on specific experimental conditions and therefore have limitations in predicting behavior under different conditions. Considering the nature of salt transfer in this experiment—diffusion from one surface while the opposite surface remained impermeable—the good performance of the semi-infinite model was not only expected but also physically justifiable. This makes the model, in addition to its high accuracy, the most reliable option for explaining the transfer mechanism. Overall, if the objective is to analyze the physical behavior and extract fundamental parameters, the semi-infinite model is the best choice; however, if the goal is the accurate prediction of experimental data, the Weibull and Peleg models provide higher predictive accuracy [20].

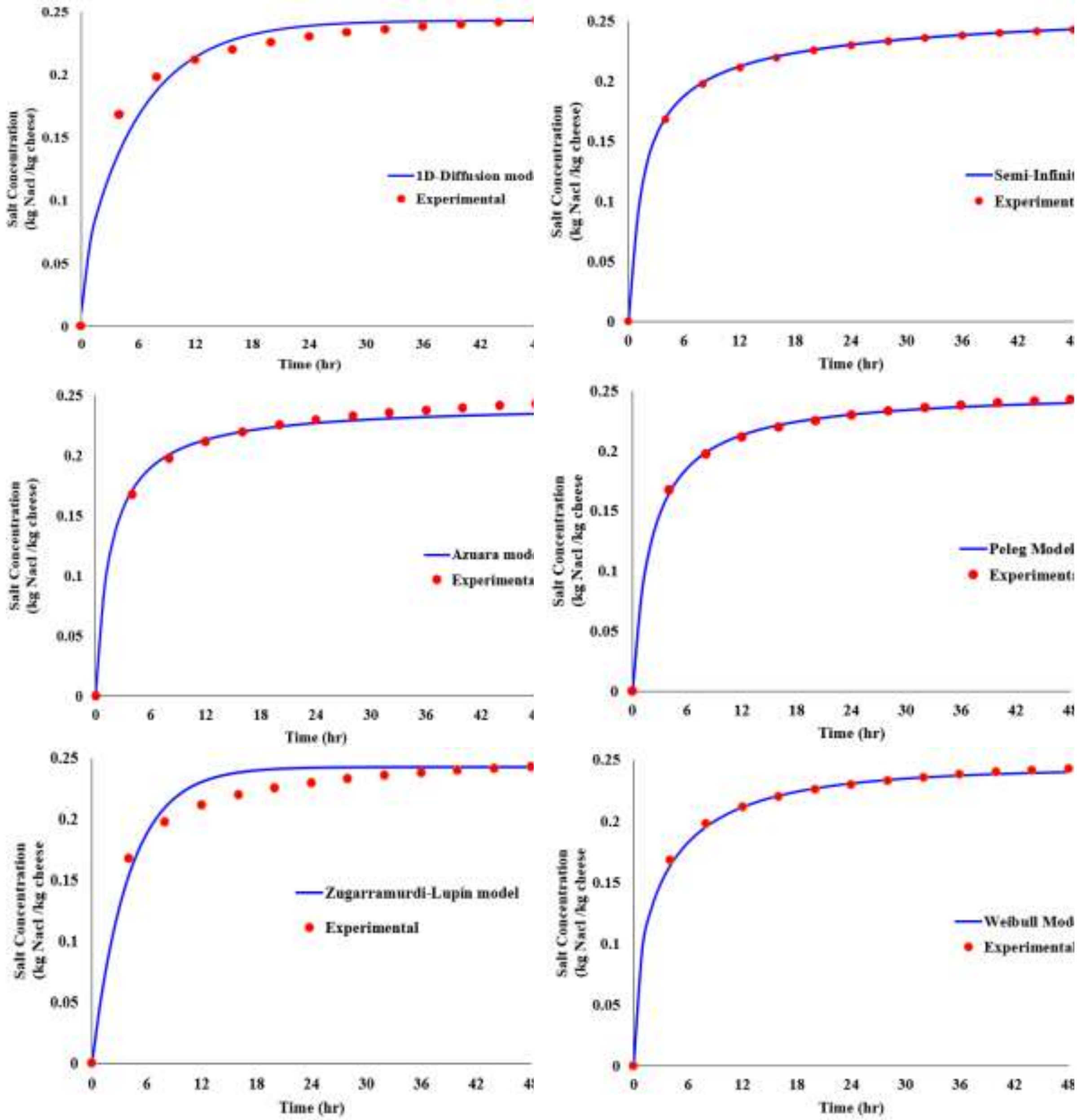

Figure 2. Comparison between experimental salt concentration and model-predicted values during cheese brining using different mass transfer models (Diffusion, Semi-infinite, Azuara, Peleg, Zugarramurdi–Lupín, and Weibull).

Table 1. Estimated parameters and goodness-of-fit statistics of mass transfer models for salt uptake in cheese during brining.

Model	**Parameter**	**Value**
Diffusion Model	D (m^2/h)	1.8×10^{-7}
	R^2	0.960
	RMSE	0.011
Semi-infinite Model	D (m^2/h)	5.0×10^{-7}
	R^2	0.999
	RMSE	0.001
Azuara Model	k_S	0.009
	R^2	0.994
	RMSE	0.004
Peleg Model	$k_{S,1}$	500.5
	$k_{S,2}$	3.95
	R^2	0.998
	RMSE	0.002
Zugarramurdi-Lupín Model	k_S	0.004
	R^2	0.979
	RMSE	0.0133
Weibull Model	α	3.31
	β	0.55
	R^2	0.996
	RMSE	0.0004

The salt concentration distribution profile across the cheese thickness at different times was simulated by solving Fick's second law using the finite element method in COMSOL software. The simulation results, presented in Figure 3, demonstrate that at all time intervals, the highest salt concentration occurs at the surface in contact with the brine solution (x = 0), where it remains constant. From this boundary, the salt concentration gradually decreases with increasing distance into the cheese matrix, confirming that salt transport is a diffusion-controlled process driven by the concentration gradient between the brine and the internal regions. At the early stages of the process, specifically at 6 and 14 days, the salt penetration is confined to the peripheral layers, and the concentration profiles exhibit steep gradients, indicating that the salt has not yet reached the deeper regions of the cheese. As the process time increases to 22 and 30 days, the diffusion front moves further into the inner layers and the slope of the curves decreases, representing a more gradual transition of mass. At the longest simulated durations of 38 and 46 days, the salt concentration in the inner regions increases significantly, though it remains low at depths beyond 10 centimeters. These numerical results show that salt diffusion in cheese is a slow, time-dependent process where the concentration gradient decreases as the salt penetrates deeper over several weeks. This corrected profile is consistent with the expected physical behavior of cheese salting and provides a realistic prediction of salt distribution during long-term brining.

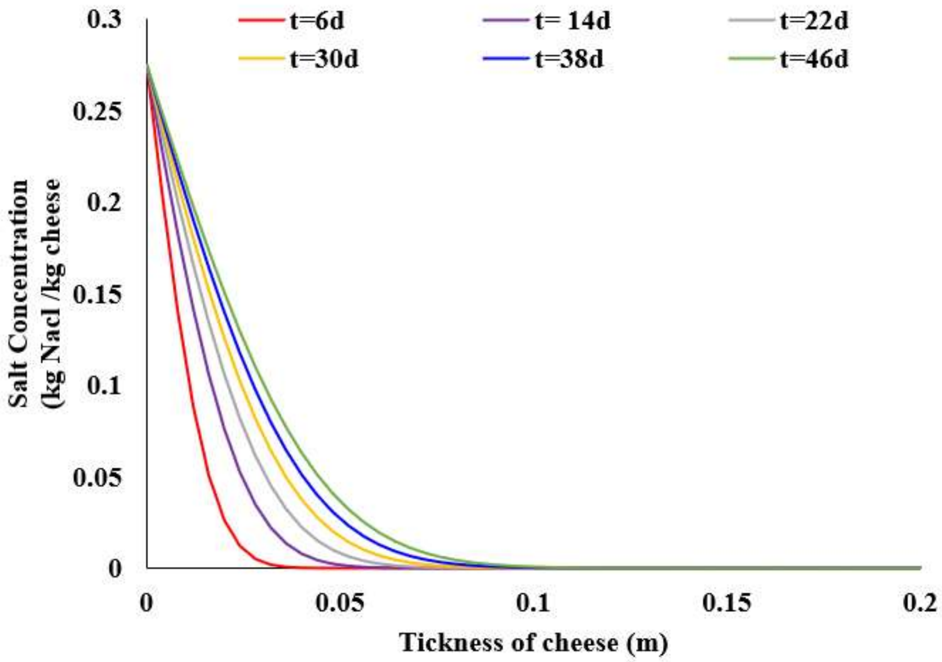

Figure 3. Predicted salt concentration profiles across the cheese thickness at different brining times based on the diffusion model developed by COMSOL Software

Figure 4 presents the results of the two-dimensional numerical simulation of Fick's second law in COMSOL software, illustrating the salt concentration distribution in the cheese at four selected times: 1, 5, 20, and 48 days. As shown in the contour plots, during the early stages of the process (1 and 5 days), salt diffusion is strictly confined to the thin boundary layers near the surface in contact with the brine solution, leaving the vast majority of the sample thickness at a zero or near-zero concentration. This highlights a very steep concentration gradient and underscores that molecular diffusion is a slow transport mechanism in the initial stages. As time progresses to 20 days, the salt front visibly advances deeper into the cheese matrix, with the penetration depth reaching approximately 4 to 5 centimeters. By the end of the simulated period (48 days), the salt distribution has reached nearly half of the total sample thickness. While the salt concentration in the inner regions has increased, a significant gradient still exists compared to the surface, indicating that even after several weeks, the system has not yet reached full diffusion equilibrium. This observed pattern clearly reflects the slow progression of the salt diffusion front toward the interior of the sample and is fully consistent with the expected physical behavior of a mass transfer process driven by concentration gradients in a dense food matrix.

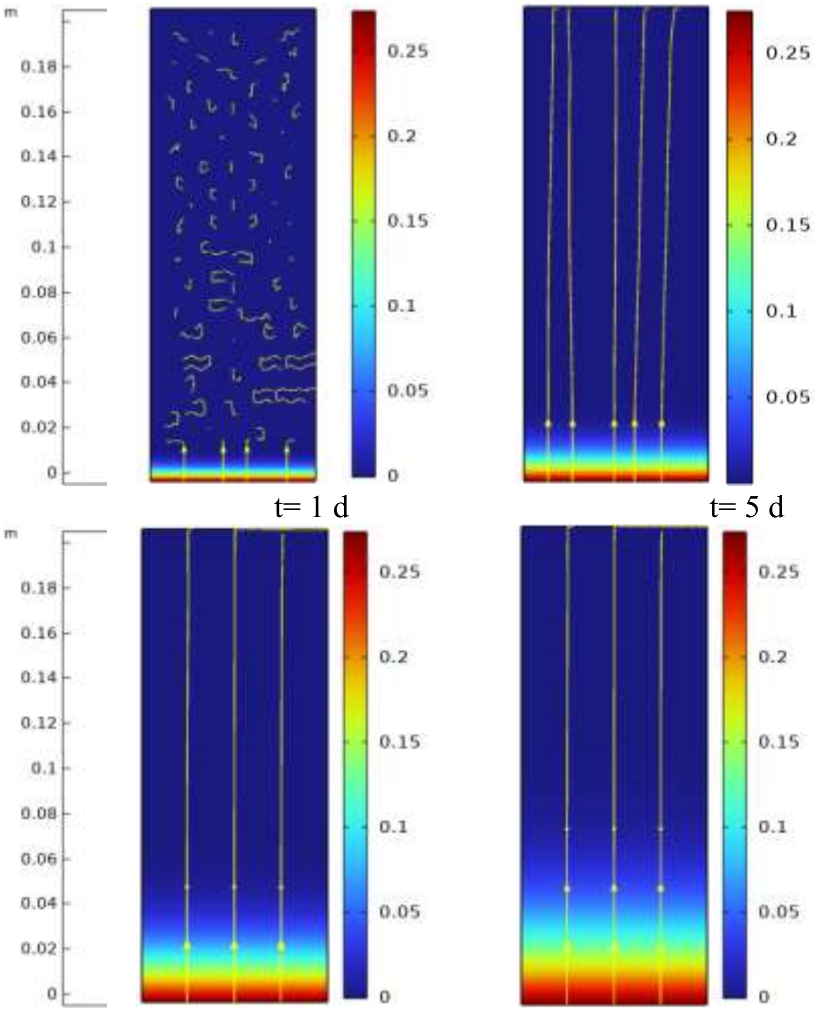

Figure 4. Two-dimensional numerical simulation of salt diffusion in cheese at four brining times.

Figure 5 presents a three-dimensional surface plot illustrating the variation of salt concentration in cheese as a dual function of brining time (days) and distance from the surface (thickness). The color gradient effectively maps the evolution of the diffusion process over a 48-day period. At the onset of the process, a sharp elevation in salt concentration is strictly localized at the surface interface (x=0), while the vast majority of the 3D surface remains at the baseline (purple/dark blue zone), representing the unsalted core. This stark contrast between the saturated surface and the pristine interior creates the primary concentration gradient that drives the mass transfer. As the process time increases from 1 to 48 days, the “slope” of the concentration profile visibly extends toward the interior, signifying the gradual advancement of the diffusion front. However, even at the 48-day mark, the salt concentration only begins to rise significantly within the first 10 centimeters of the thickness, leaving the deeper regions largely unaffected. This behavior highlights the high mass transfer resistance within the dense cheese matrix and confirms that while time is a decisive factor, the molecular diffusion of salt is a remarkably slow process. The three-dimensional pattern demonstrates that salt transport is predominantly governed by Fickian molecular diffusion, and a uniform salt distribution would require a significantly longer duration than the simulated 48-day window.

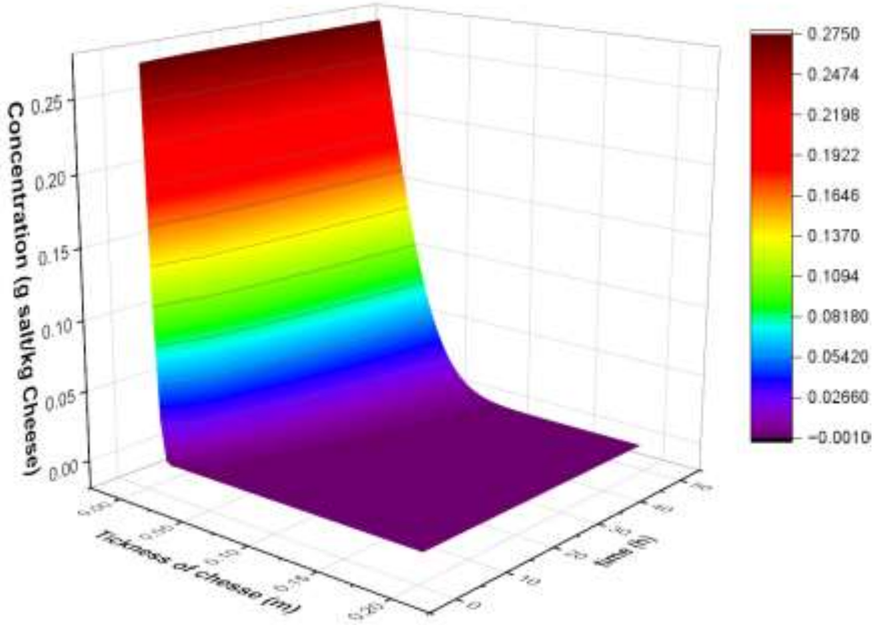

Figure 5. Three-dimensional surface plot illustrating the variation of salt concentration in cheese as a function of brining time and sample thickness

4- Conclusion

In this study, the kinetics of salt uptake in white cheese during the brining process were investigated using a set of fundamental and empirical models. In addition, a numerical model based on Fick's second law was developed to simulate salt distribution within the cheese matrix. The results showed that the different models exhibited varying capabilities in describing salt transfer behavior. Among the fundamental models, the semi-infinite model provided the best fit to the experimental data due to its good agreement with the experimental conditions and the assumption of one-dimensional diffusion. This model was also able to estimate the effective salt diffusion coefficient with high accuracy. Among the empirical models, the Weibull and Peleg models showed the highest statistical accuracy in predicting changes in salt concentration over time, indicating their high flexibility in describing the nonlinear behavior of the salt absorption process.

The numerical simulations performed in COMSOL software further demonstrated that salt distribution in cheese is strongly time-dependent, with salt diffusion progressing gradually from the surface in contact with the brine solution toward the inner layers over a period of several weeks. During the initial stages of the process, the concentration gradient between the cheese surface and the center was exceptionally high; however, as time progressed toward 48 days, this gradient began to moderate as the salt front advanced deeper into the matrix. The patterns obtained from the two-dimensional and three-dimensional simulations clearly illustrated the slow progression of the salt diffusion front, which is consistent with the expected physical behavior of a diffusion-controlled process in a dense protein matrix. Overall, the findings of this study indicate that the integration of fundamental laws, empirical models, and numerical simulations provides a comprehensive framework for analyzing and predicting salt transfer in cheese. Such an approach not only contributes to a better understanding of mass transfer mechanisms within the complex cheese matrix but also serves as an effective tool for designing and optimizing industrial brining protocols. By accurately predicting penetration depths over extended periods, this model can help the white cheese industry improve salt distribution uniformity and enhance final product quality.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Mohsen Dalvi-Isfahan: Project administration, conceptualization, methodology, data collection, validation, writing – review and editing.

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چکیده

نمک‌زنی یکی از مهم‌ترین مراحل تولید پنیر است که بر ویژگی‌های رئولوژیک، میکروبی و کیفیت حسی محصول نهایی اثر می‌گذارد. در پنیر کنترل جذب و توزیع نمک اهمیت ویژه‌ای دارد، زیرا ساختار متخلخل و رطوبت بالا موجب حساسیت زیاد این محصول به تغییرات اسمزی می‌شود. برای تحلیل سینتیک جذب نمک، در این پژوهش از شش مدل ریاضی شامل مدل نفوذ، مدل نیمه‌بی‌نهایت، آزوارا، پلگ، زوگاراموردی- لوپین و ویبال استفاده شد. آزمایش‌های نفوذ نمک به‌صورت یک‌بعدی طراحی گردید تا با فرضیات مدل‌های تحلیلی به‌ویژه مدل نیمه‌بی‌نهایت سازگار باشد. اندازه‌گیری غلظت نمک با روش تیتراسیون ولهارد انجام گرفت. نتایج نشان داد مدل نیمه‌بی‌نهایت بالاترین دقت را در بین مدل‌های بنیادی ارائه می‌دهد (R^2=0.999)، در حالی‌که مدل ویبال دقیق‌ترین مدل تجربی بود (R^2=0.996). مدل نفوذ کلاسیک، به دلیل فرض ضریب نفوذ ثابت و عدم انطباق کامل با هندسه آزمایش، کمترین دقت را داشت. علاوه بر این، شبیه‌سازی عددی بر پایه حل قانون دوم فیک با استفاده از نرم‌افزار کامسول نشان داد که جبهه نفوذ نمک در طول یک دوره زمانی طولانی، به‌تدریج از سطح به سمت بخش‌های داخلی پیشروی کرده و منجر به افزایش قابل‌توجه عمق نفوذ نمک می‌گردد. این یافته‌ها بیانگر آن است که مدل‌سازی عددی مناسب می‌تواند به عنوان ابزاری کارآمد برای پیش‌بینی رفتار انتقال جرم نمک در بلندمدت و بهینه‌سازی زمان فرآیند آب نمک گذاری پنیر جهت دستیابی به سطوح نمک مطلوب، مورد استفاده قرار گیرد.