Journal of Food Science and Technology (Iran)

Homepage: www.fsct.modares.ir

Scientific Research

Development and Simulation of a Coupled Salt and Moisture Transfer Model in Cheese Considering the Effects of Temperature and Osmotic Forces

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ARTICLE INFO

Article History:

Received: 2026/04/19

Review: 2026/06/05

Accepted: 2026/06/06

Keywords:
Brining,
Cheese,
Diffusivity,
Temperature,
Osmotic force,
Numerical simulation

DOI: **10.48311/fsct.2026.119858.83108**

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ABSTRACT

Salting is a critical step in cheese production, contributing to microbial safety, shelf life, texture, and flavor development. In this study, salt uptake during the brining process was investigated using both experimental measurements and modeling approaches. The chemical composition of cheese samples was first determined. The effective diffusion coefficient of salt at different temperatures was then calculated using Fick's second law. To more accurately describe the brining process, an extended numerical model incorporating simultaneous salt and water transport as well as osmotic effects was developed and simulated. Results showed that salt concentration in cheese increases over time, with the highest rate of uptake occurring in the early stages due to strong concentration gradients. As brining progresses, the rate of diffusion decreases. Temperature had a significant impact: increasing the temperature from 6 to 20 °C led to higher effective diffusion coefficients and greater overall salt uptake. The temperature dependence of diffusivity followed the Arrhenius relationship, yielding an activation energy of 53.32 kJ/mol. Numerical simulations demonstrated that incorporating osmotic forces provides a more realistic prediction of moisture loss and the coupled spatial distribution of salt and water within the cheese matrix. Two-dimensional concentration maps further confirmed that higher temperatures promote deeper salt penetration over a fixed brining duration.

1-Introduction

Salt is one of the essential components in the production and processing of many food products, and it plays an important role in microbial safety, flavor development, and improvement of product texture. By reducing water activity (*aw*), salt addition limits the growth of undesirable microorganisms and consequently increases product shelf life. In addition, the phenomenon of salt penetration and uptake is one of the important mass transfer processes in products such as meat, fish, and cheese, and it has a significant effect on their quality characteristics, stability, and microbial safety [1].

In the cheese-making industry, besides its general functions, salt also has specific and determining effects. By influencing the activity of starter bacteria and the enzymes involved in ripening, salt regulates the rate of biochemical reactions such as proteolysis and lipolysis and contributes to the development of cheese flavor, aroma, and body/texture. From a structural point of view, the presence of salt also causes changes in the casein protein network, reduces moisture, and increases the firmness of cheese texture [2].

In general, there are three main methods for salting cheese: dry salting, surface dry salting, and brine salting. In dry salting, salt is mixed with the milled curd during the final stages of production and, after dissolving in the surface moisture, gradually penetrates into the curd. In the surface dry salting method, salt or a salt slurry is rubbed onto the surface of the cheese block and diffuses inward from the surface. In the brine-salting method, cheese blocks are immersed in a brine solution, and due to concentration differences and osmotic pressure, sodium and chloride ions penetrate into the cheese while, at the same time, part of the cheese water is transferred to the brine environment.

The mechanism of salt uptake in cheese is mainly based on mass transfer and diffusion phenomena within the protein matrix. When cheese is placed in a salty environment, Na^+ and Cl^- ions diffuse from the surface toward the center of the cheese, while part of the internal moisture of the cheese moves in the opposite direction toward the external environment. This process creates salt and moisture concentration gradients from the surface to the center of the cheese, and over time, salt distribution within the tissue gradually becomes more uniform. The extent of salt uptake is influenced by several factors, such as brine concentration, salting time, the size and geometry of the cheese, and its surface conditions. In general, increasing salt solution concentration and prolonging contact time with the brine increase salt absorption, although this increase occurs at a decreasing rate over time. In addition, cheeses with a higher surface-to-volume ratio absorb salt more rapidly, and surface drying can reduce the rate of ion penetration. Subsequently, during storage or ripening, the gradual diffusion of salt within the cheese matrix continues, and its distribution moves toward a relative equilibrium [3–4].

In recent years, numerous studies have been conducted to better understand mass transfer mechanisms and to develop mathematical models for predicting salt behavior in food matrices. For example, Marchetti et al. (2021) investigated mass transfer kinetics in hake fillets under three salting methods, including dry salting, mixed salting, and brining. In this study, changes in salt and water content, water activity, and sample weight variations were evaluated. The results showed that weight loss occurred in all methods; however, brining caused the lowest weight loss and therefore resulted in higher yield, whereas dry salting led to the greatest dehydration and the highest salt content. In addition, the kinetics of mass transfer were modeled using various empirical models, among which the Weibull model showed the best fit with the experimental data [5].

In the field of meat curing, Graiver et al. (2009) presented a mathematical model to predict the uptake of curing salts, including $NaNO_2$, KNO_3, and NaCl in pork meat cuts. This model was based on the numerical solution of partial differential equations for mass transfer under unsteady-state conditions within a finite three-dimensional cylindrical geometry. Within this framework, in addition to molecular diffusion, the effect of convective transport caused by water absorption by the tissue was considered, and the dependence of the salts' diffusion coefficients on sodium chloride concentration was taken into account. The results indicated that the NaCl concentration gradient can cause microstructural changes in the tissue, thereby increasing salt penetration [6].

In another study, Torres-Baix (2024) modeled salt absorption during the production process of dry-cured ham. This research utilized non-destructive magnetic induction technology to measure the textural characteristics of low-fat and high-fat hams, subsequently developing salt absorption prediction models using various statistical methods. The results showed that increasing the salting time leads to an increase in salt content following an asymptotic behavior, while salt absorption is lower in high-fat hams. The best model performance was achieved when salting time, weight, and fat content were considered as independent variables [7].

Pajonk (2003) investigated the kinetics of salt diffusion in Emmental cheese during the brining process. In this study, salt concentration profiles were measured in cylindrical samples over a temperature range of 4 to 18°C, and three modeling approaches were evaluated: Fick's second law with a constant diffusion coefficient, the Boltzmann method with a concentration-dependent diffusion coefficient, and numerical identification of the diffusion equation with a variable diffusion coefficient. The results showed that considering the dependence of the diffusion coefficient on concentration and temperature provided better agreement with the experimental data. The effective salt diffusion coefficient decreased with increasing salt concentration and increased with rising temperature [8].

In addition to mass transfer approaches based on the classical Fick equations, some studies have used thermodynamic models to describe mass transfer. Velázquez-Varela (2014) modeled the simultaneous transport of water and ions during the cheese salting process using a nonlinear and irreversible thermodynamic framework in a three-phase system consisting of protein, fat, and aqueous phases. The results showed that various driving forces, including chemical, mechanical, and electrical potentials, play a role in mass transfer, and that the complex interactions among the components of the cheese matrix, as well as microstructural changes, can significantly affect diffusion behavior [9].

Santapaola (2013) also investigated the dry salting process of goat cheese from a diffusion perspective. In this study, by determining the temporal and spatial concentration profiles of salt and water at sample depth, Fick's second law was applied in the form of a semi-infinite model to describe mass transfer. The results showed that after 24 hours, salt penetrated only to a depth of about 2 cm into the sample, with the highest concentration observed at the surface in contact with the salt. In addition, the reduction in the effective diffusion coefficient over time was attributed to structural changes in proteins and tissue shrinkage during the early stages of the process [10].

Overall, the studies conducted indicate that the modeling of salt diffusion and uptake in foods has been carried out using various approaches, including empirical kinetic models, Fick's law-based models, multidimensional numerical models, and thermodynamic frameworks. The results of these studies show that factors such as tissue structure, chemical composition, temperature, processing time, and microstructural changes can significantly affect diffusion coefficients and mass transfer behavior. Therefore, the development of more accurate models to describe salt uptake in processes such as cheese brining can help optimize process conditions, control the uniformity of salt distribution, and improve the final product quality on an industrial scale. Accordingly, the aim of this study is to investigate the process of salt uptake in cheese during brining using an experimental and modeling approach.

2- Materials and Methods

2.1 Chemical analysis and evaluation of the salt diffusion coefficient in cheese

Chemical analysis of the cheese samples, including ash, salt, moisture, fat, and protein, was performed two weeks after production. The fat content of the samples was determined using the Gerber method, and moisture content was measured by the oven-drying method. Protein content was determined using the macro-Kjeldahl method. To determine ash content, the samples were first dried in an oven at 105 °C, and then placed in an electric furnace at 550 °C until white or light gray ash was obtained. Afterward, the sodium chloride (NaCl) content was measured using the Volhard method. All chemical analyses were performed in triplicate. The results of the chemical analysis of the cheese samples are presented as weight percentages in Table 1 [11].

Table 1. Chemical composition of cheese samples before brining

Cheese	**Moisture**	**Protein**	**Fat**	**Carbohydrate***	**Ash**
Non-salted	67.35±0.23	11.20±0.11	17.12±0.38	3.12	1.48±0.36

*Carbohydrate percentage was calculated as 100 – (moisture%+fat%+protein%+ash%)

In this study, in order to consider cheese as a semi-infinite medium, the Fourier number criterion was evaluated. According to the relation $F_o = \frac{D_t}{L^2}$, a medium can be assumed to be semi-infinite when the Fourier number is less than 0.05. By considering the salt diffusion coefficient in cheese and a brining time of 48 h, the minimum required thickness in the direction of diffusion was calculated to be approximately 3.1 cm. Since the thickness of the samples used in this experiment was 5 cm, the Fourier number obtained was less than 0.05; therefore, the necessary condition for assuming the medium to be semi-infinite was satisfied. Thus, it may be assumed that during the experimental period, the diffusion front did not reach the end of the sample, and the conditions of the diffusion model used remained valid and stable.

Under these conditions, the diffusion coefficient was determined using a one-dimensional mass transfer model for a semi-infinite medium, assuming one-sided diffusion. The analytical solution of Fick's diffusion equation for these conditions is expressed as Equation (1) [12]. To investigate the mass transfer kinetics and determine the salt diffusion coefficient, samples were taken from the central part of the cheese and equilibrated at the experimental temperature for 24 h in order to achieve thermal stability. To ensure one-dimensional diffusion conditions and to prevent moisture loss or structural changes, the lateral surfaces of the samples were sealed with a layer of paraffin and a protective covering (Parafilm), so that mass transfer occurred only through the end cross-sectional surface in contact with the solution.

The salt uptake process was carried out in a tank containing brine solution, together with the addition of 300 mg/L calcium chloride and adjustment of pH to 5.4 (using lactic acid). In this method, a magnetic stirrer operating at a gentle and continuous speed was used to eliminate mass transfer resistance in the liquid-phase boundary layer and to maintain a constant concentration at the contact surface, thereby providing the boundary conditions required for agreement with mathematical diffusion models and for the accurate extraction of kinetic parameters [8].

$$\frac{C_{S,\infty} - C_{S,t}}{C_{S,\infty} - C_{S,0}} = erf\left(\frac{x}{2\sqrt{Dt}}\right) \quad [1]$$

where: $C_{s,0}$ is the initial salt concentration in cheese (g salt per g cheese), $C_{s,\infty}$ is the equilibrium salt concentration (g salt per g cheese), Ds is the effective diffusion coefficient of salt in cheese (m²/s), *erf* is the error function, t is the brining time (s), and L is the thickness of the cheese sample (m). To determine the effect of temperature on the salt diffusion coefficient, the Arrhenius equation (2) was used. In this equation, D0 is the pre-exponential factor or the diffusion coefficient at a very high temperature, Ea is the activation energy of diffusion (kJ/mol), R is the universal gas constant (8.314 $J \cdot mol^{-1} \cdot K^{-1}$), and T is the absolute temperature (K).

$$D(T) = D_0 e^{-E_a/RT} \quad [2]$$

2.2 Developed numerical model considering the effect of osmotic force

During the brining process, the transfer of salt from the brine solution into the cheese matrix mainly occurs through molecular diffusion. However, due to the concentration difference between the brine solution and the internal moisture of the cheese, osmotic pressure is generated, causing water to leave the cheese tissue and move toward the surrounding solution. This phenomenon not only changes the moisture content of the cheese but can also influence salt transport by introducing a convective component to the mass transfer process. Therefore, to describe the brining process more accurately, the classical diffusion model was extended by considering the effect of osmotic force.

In addition, during the brining process, salt diffusion and moisture loss occur simultaneously and are interdependent phenomena. To accurately describe these kinetics, a clear distinction between "osmosis within the internal tissue" and "mass exchange at the contact surface" was incorporated into the model. The details are described as follows:

a) Osmosis phenomenon within the internal tissue:

Changes in salt concentration (cs) and the mass fraction of water (cw) at all points within the internal tissue are described by coupled differential equations (Equation 3):

$$\frac{\partial C_S}{\partial t} = \nabla.(D_S \nabla C_S)$$

$$\frac{\partial C_w}{\partial t} = \nabla.(D_w \nabla c_w) - k_{osm}(c_s - C_{S,eq}) \quad [3]$$

In this relation, c_w is the mass fraction of water in cheese, D_w is the effective diffusion coefficient of water in the cheese matrix, c_s is the salt concentration in cheese, $C_{s,eq}$ is the equilibrium salt concentration, and k_{osm} is the transfer coefficient associated with the osmotic phenomenon. The greater the difference in salt concentration between the inside of the cheese and the equilibrium state, the stronger the osmotic force becomes, and the greater the water loss from the tissue. At this level, the term $-k_{osm}(c_s - C_{s,eq})$ acts as a sink term, representing the exit of moisture from the internal layers of the cheese. In fact, the local presence of salt at any point in the tissue (c_s) changes the chemical potential of moisture and creates the osmotic driving force for water movement toward the outside [13–14].

b) Mass exchange at the contact surface:

Unlike the internal process, mass exchange at the cheese-solution interface (x = 0) is subject to convective boundary conditions (Equations 6 and 7). At this boundary, the equilibrium values of salt ($C_{s,eq}$) and moisture ($C_{w,eq}$) are not independent of each other and are determined based on the thermodynamic properties of the brine solution at the contact surface. The high concentration of salt in the external solution, by reducing the water potential at the surface, provides the concentration gradient necessary to initiate diffusion and moisture loss. Therefore, the salt concentration affects moisture transport kinetics not only at the boundary (to determine $C_{w,eq}$), but also throughout the internal points (as the driving variable in the osmotic term). To simulate this complex behavior, COMSOL Multiphysics software version 6.0 based on the finite element method was used. The model geometry was defined according to the laboratory dimensions, and for the insulated surfaces (walls and the sample center at x=L), a no-flux boundary condition was applied in accordance with Equations 8 and 9.

Initial and boundary conditions

The initial and boundary conditions of the model were considered as follows:

Initial condition:

$t = 0 \quad C_S(x, y, 0) = 0$ [4]

$t = 0 \quad C_w(x, y, 0) = C_{w,0}$ [5]

Boundary conditions:

$t > 0 \quad at\ x = 0 - n.J_S = k_S(C_{S,eq} - C_{S,t})$	[6]
$t > 0 \quad at\ x = 0 - n.J_w = k_w(C_{w,eq} - C_{w,t})$	[7]
$t > 0 \quad at\ x = L \quad \left.\frac{\partial C_S(x,y,t)}{\partial x}\right\vert = 0$	[8]
$t > 0 \quad at\ x = L \quad \left.\frac{\partial C_w(x,y,t)}{\partial x}\right\vert = 0$	[9]

where k_s and k_w are the convective mass transfer coefficients for salt and water, and $C_{s,eq}$ and $C_{w,eq}$ are the equilibrium concentrations of salt and water at the cheese surface. The amount of salt over the entire surface of the sample over time was determined using Equation (4).

$M(t)=\int C_s(x,y,t)\, dA$ [10]

where $C_s(x,y,t)$ is the salt concentration at spatial coordinates and time, and dA is an elemental area of the sample cross-section. This relation represents the cumulative amount of salt over the entire surface under consideration at time t. The parameters used in the model are presented in Table 2.

Table 2. Model parameters used in COMSOL Multiphysics simulations

Parameter	**Value**
Salt diffusivity at 6 ºC	9.2E-11 [m²/s]
Salt diffusivity at 13 ºC	1.5E-10 [m²/s]
Salt diffusivity at 20 ºC	2.8E-10 [m²/s]
Water diffusivity at 6 ºC	3.4E-10 [m²/s]
Water diffusivity at 13 ºC	5.6E-10 [m²/s]
Water diffusivity at 20 ºC	7.8E-10 [m²/s]
Initial moisture content of unsalted cheese	0.672
Molecular weight of water	0.018 [kg/mol]
Equilibrium salt concentration	5179.79 [mol/m³]
Convective mass transfer coefficient (salt)	5e-6 [m/s]
Molecular weight of sodium chloride	0.05844 [kg/mol]
Density of cheese	1100 [kg/m³]
Convective mass transfer coefficient (water)	1e-6 [m/s]
Equilibrium water	38500.00 [mol/m³]
Osmotic rate constant	1.89e-6 [1/s]

3- Results and Discussion

Figure 1 shows the changes in salt concentration in cheese as a function of time at three different temperatures (6, 13, and 20°C). The results indicate that the salt diffusion process increases over time and occurs more rapidly during the initial hours. At the beginning of the brining process, due to the large difference in salt concentration between the brine solution and the cheese surface, the slope of the curves is steep and salt mass transfer occurs at a high rate. As time passes and the concentration gradient decreases, the diffusion rate declines and the curves gradually approach a nearly steady state.

The results also show that increasing temperature leads to greater salt uptake in cheese. At 20°C, the highest salt concentration is observed at all times, whereas the lowest values correspond to 6°C. This behavior can be attributed to the increase in the salt diffusion coefficient and the decrease in solution viscosity with increasing temperature, which facilitates mass transfer. In general, the results indicate that temperature is an important factor in controlling the rate and extent of salt diffusion during the cheese brining process, and increasing temperature accelerates salt uptake and allows higher salt concentrations in cheese to be reached more quickly [2–15].

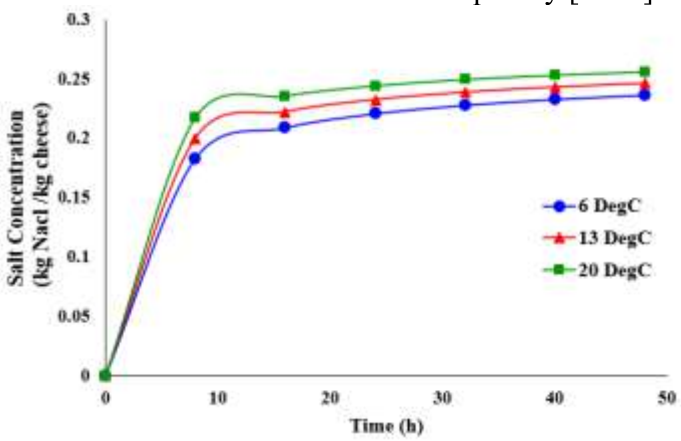
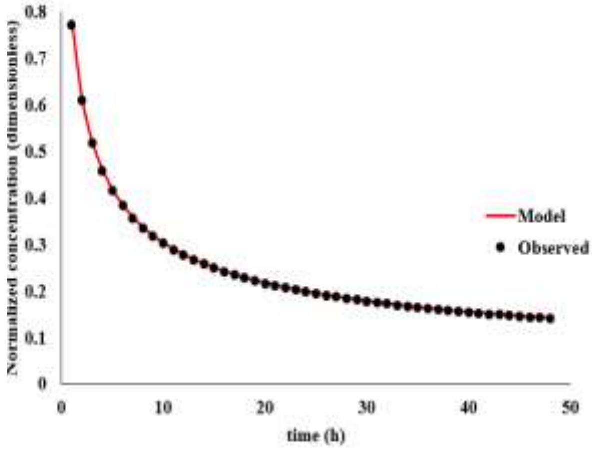


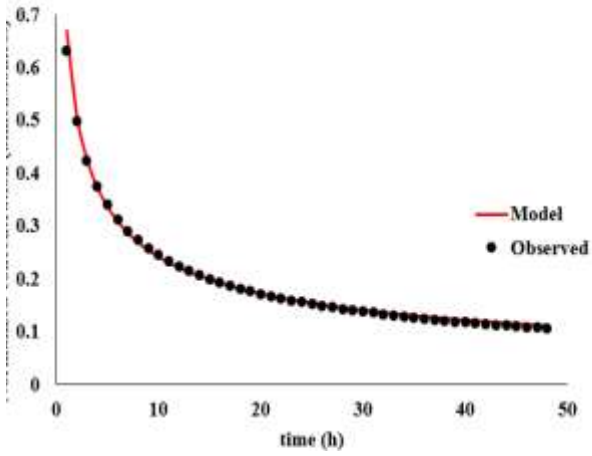
Fig. 1. Salt concentration in cheese as a function of brining time at three temperatures (6, 13, and 20 °C)

In the next step, the effective diffusion coefficient of sodium chloride (NaCl) within the cheese samples was determined. For this purpose, the analytical solution of Fick's second law for one-dimensional diffusion in a semi-infinite medium was applied. The normalized concentration values obtained from the experimental data were then fitted to the results of the analytical model (Figure 2), and the effective diffusion coefficient was calculated by minimizing the difference between the observed data and the values predicted by the model.

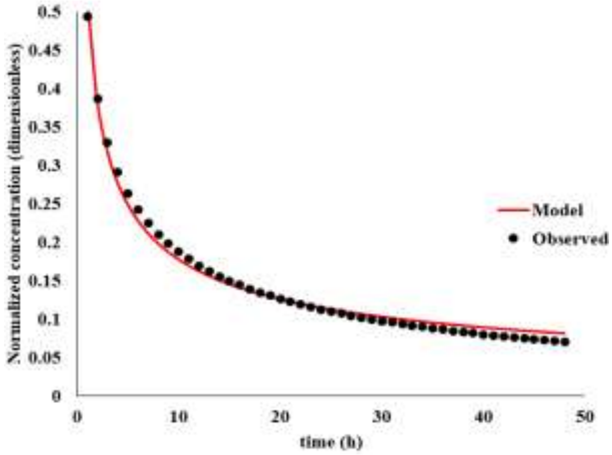
The results showed a good agreement between the experimental data and the model curves at the different temperatures studied (6, 13, and 20°C), indicating that the semi-infinite diffusion model is suitable for describing salt transport during the cheese brining process. Accordingly, the effective diffusion coefficients at these three temperatures were obtained as 9.2×10^{-11}, 1.5×10^{-10}, and 2.8×10^{-10} m^2/s, respectively, demonstrating an increase with temperature [12–16].



a=6 ºC



b=13 ºC



c=20 ºC

Fig. 2 Experimental and simulated normalized concentration for estimation of the effective diffusion coefficient at three different brining temperatures

Using the effective salt diffusion coefficients obtained at three temperatures (6, 13, and 20°C), the temperature dependence of the diffusion coefficient was evaluated based on the Arrhenius equation (Equation 2). For this purpose, a plot of ln(D) versus the inverse of temperature (K) was constructed, and the results are shown in Figure 3. According to this plot, the Arrhenius relationship for the salt diffusion coefficient in cheese was obtained as LnD = -6413.1(1/T) + 8.0207, indicating a significant dependence of the diffusion coefficient on temperature. The slope of the obtained line made it possible to calculate the activation energy of the diffusion process, and the activation energy was determined to be 53.32 kJ/mol. This value indicates that with increasing temperature, the diffusion coefficient of salt in the cheese matrix increases, and consequently the diffusion and transport of salt during the brining process occur at a faster rate.

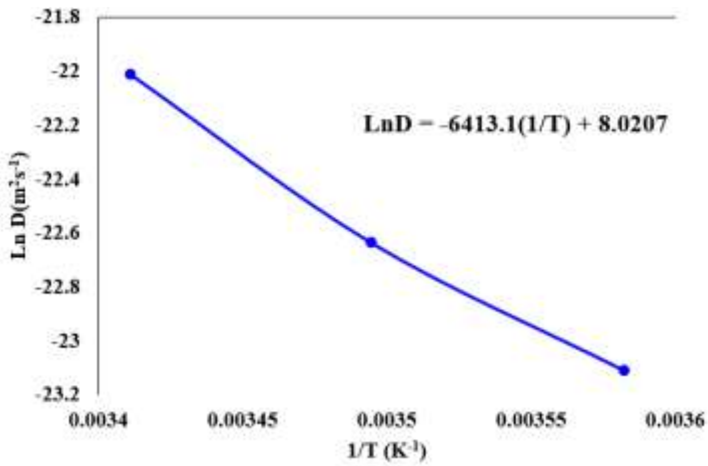


Fig. 3. Temperature Dependence of Salt Diffusivity Predicted by the Arrhenius Equation

Figure 4 shows the changes in cheese moisture during the brining process for two modeling approaches: the model with a constant diffusion coefficient (black curves) and the coupled model including simultaneous diffusion of salt and water together with the osmotic effect (red curves). The results are presented for three points within the sample, covering regions from near the surface to deeper parts of the cheese.

In both models, moisture decreases over time as a result of mass transfer and the migration of water from the cheese matrix to the brine environment. The reduction in moisture is faster during the initial hours, which is due to the large concentration gradient and the difference in chemical potential between the cheese and the brine solution. As time passes and these gradients decrease, the rate of moisture reduction gradually declines.

Comparison of the two models shows that when the coupling between salt and water diffusion is considered (red curves), the moisture content at all locations and times is lower than that predicted by the constant diffusion model. This behavior indicates that including the osmotic term in the mass transfer equations intensifies water loss from the cheese. In this situation, the diffusion of salt from the brine into the cheese creates an osmotic pressure difference between the cheese surface and the surrounding environment. This osmotic pressure difference generates a driving force for the movement of water from inside the cheese matrix toward the brine solution, thereby increasing moisture loss. Therefore, in the coupled model, in addition to the moisture diffusion mechanism, osmosis acts as an additional driving force that accelerates moisture reduction in the sample. As a result, the predicted moisture decrease in the osmotic model is greater than that obtained from the simple diffusion model, and the real physical behavior of the cheese brining process is better represented [17].

To evaluate the predictive accuracy of the models compared with the experimental data, statistical indices were calculated. The results showed that the coupled osmotic model, with an average coefficient of determination R^2 = 0.98 and an average RMSE = 0.38, had a higher agreement with the experimental data than the simple diffusion model (R^2 = 0.92 and RMSE = 1.24). This improvement in statistical indices confirms that considering osmotic pressure as an additional driving force is necessary for accurately predicting the dynamic behavior of mass transfer in cheese.

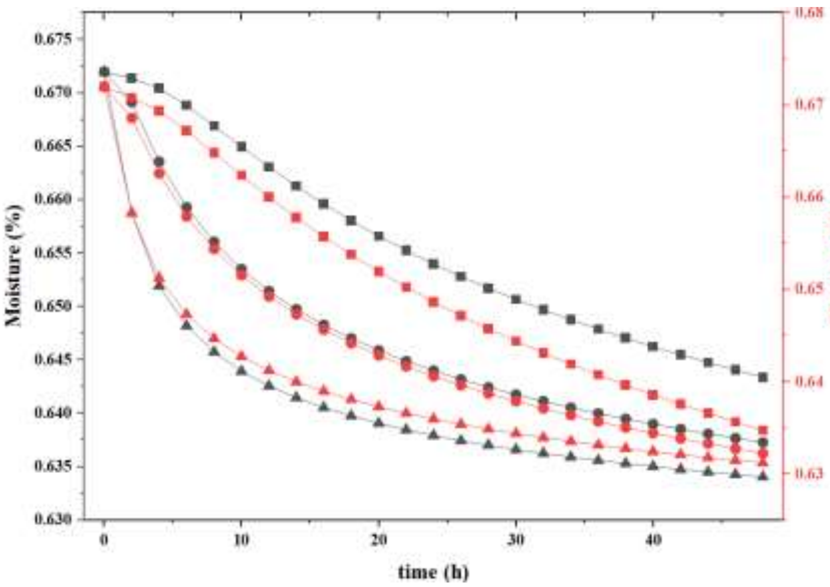


Fig. 4 Moisture content evolution during cheese brining predicted by constant diffusion model and coupled salt–water diffusion model including osmotic effects at different internal positions at 13 ºC (▲(0.025 m, 0.0025 m)●(0.025 m, 0.005 m)■(0.025 m, 0.01 m)).

Figure 5 shows the changes in salt concentration and moisture at three different positions inside the cheese sample during the brining process. In this figure, the black curves represent salt diffusion within the cheese, and the red curves indicate the moisture changes of the sample. The results are presented for three different points inside the sample. As observed, the salt concentration increases over time at all points; however, the rate of increase is higher at locations closer to the surface. At the point near the surface, salt uptake occurs more rapidly during the initial hours, whereas at deeper points the increase in salt concentration occurs with a delay and more gradually, indicating that the process is controlled by molecular diffusion within the cheese matrix.

In contrast, the moisture changes show a decreasing trend, and the red curves indicate the exit of water from the cheese tissue due to the osmotic gradient between the cheese and the brine solution. The moisture reduction is more pronounced at points close to the surface, and with increasing distance from the surface this decrease occurs with a gentler slope. Based on the confirmation of the one-dimensional model and the validation results, the effective diffusion coefficient of salt was determined for the three temperatures and used in the developed model. In this developed model, in addition to the effect of temperature, the osmotic force was also included in the mass transfer equations (Materials and Methods section), which makes it possible to simultaneously predict salt diffusion and moisture loss at different points of the sample and to describe the real behavior of the cheese brining process with reasonable accuracy [18].

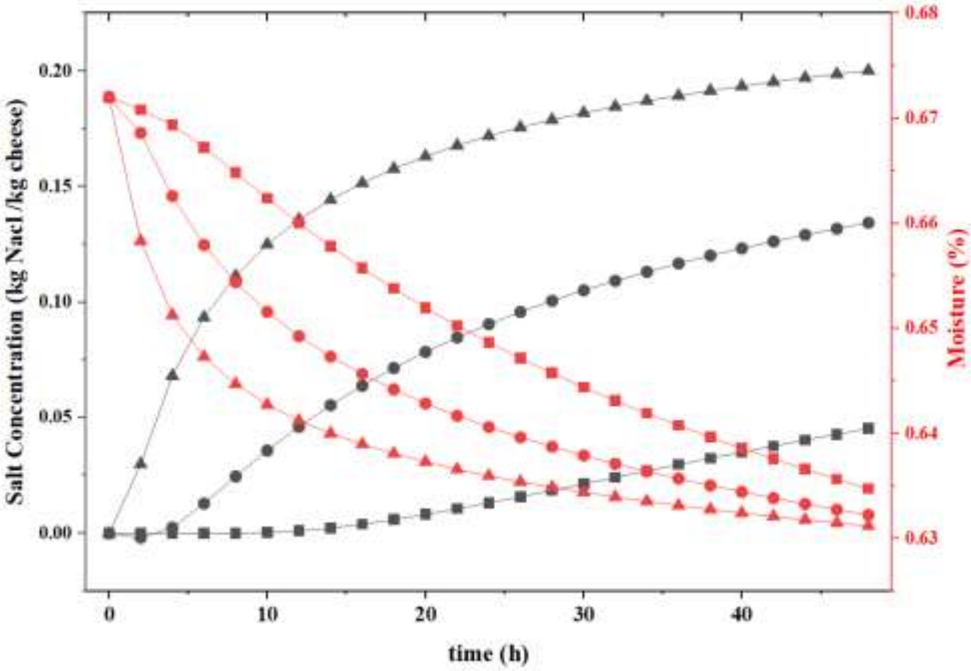


Fig. 5 Salt concentration (black) and moisture content (red) at different internal positions in cheese during brining at 13 ºC (▲(0.025 m, 0.0025 m)●(0.025 m, 0.005 m)■(0.025 m, 0.01 m)).

Figure 6 shows the changes in the total amount of salt absorbed in the cheese as a function of time at three different temperatures: 6, 13, and 20°C. The total amount of salt at each moment was calculated by integrating the salt concentration distribution over the entire cross-sectional area of the sample. As observed in the figure, the total amount of absorbed salt increases continuously over time at all three temperatures, indicating the ongoing diffusion of salt within the cheese matrix. During the initial hours, the rate of salt increase is higher, but as time progresses the slope of the curves gradually decreases. This behavior results from the gradual reduction of the concentration gradient between the brine solution and the interior of the cheese, which acts as the main driving force for mass transfer. The effect of temperature is also clearly visible in the figure; the highest salt uptake occurs at 20°C, while the lowest occurs at 6°C. Increasing temperature leads to an increase in the effective diffusion coefficient of salt and consequently accelerates mass transfer within the cheese matrix. Therefore, at higher temperatures the cumulative amount of salt across the entire sample surface becomes greater over the same period of time. These results indicate that temperature is one of the key factors controlling the rate of salt diffusion and the overall amount of salt uptake during the cheese brining process [13–16].

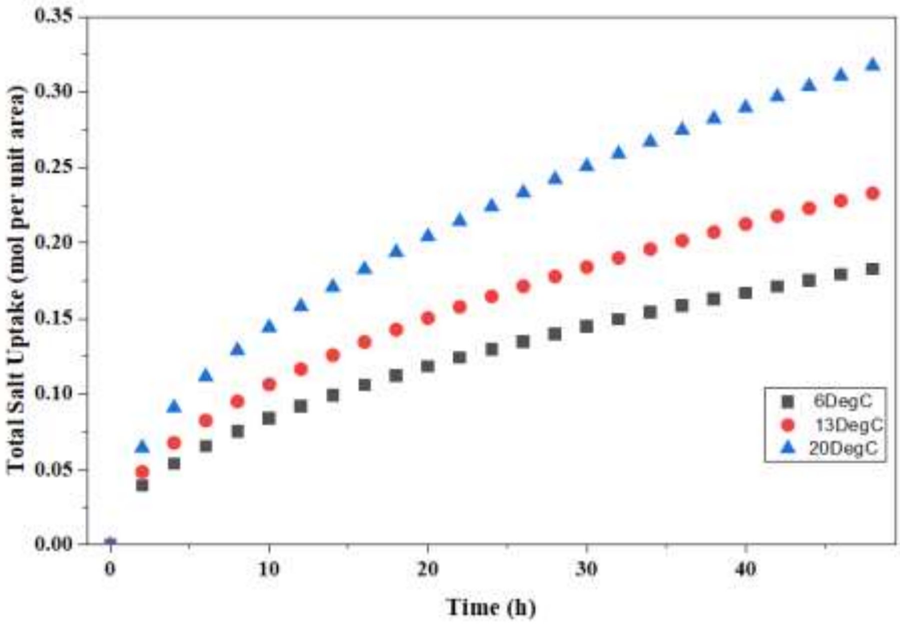
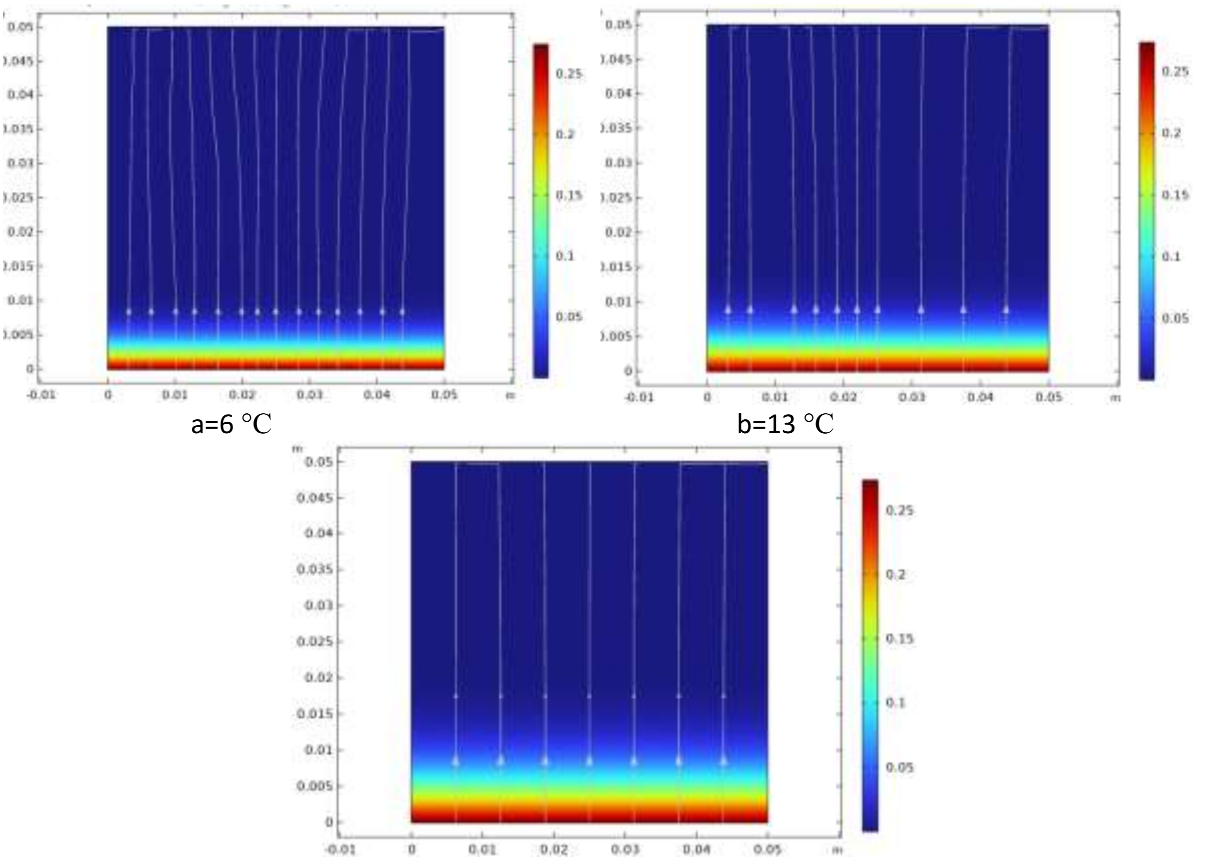


Fig. 6 Total Salt Uptake in Cheese During Brining at Different Temperatures

Figure 7 shows the two-dimensional distribution of salt concentration in the cheese cross-section after 24 hours of the brining process at three temperatures of 6, 13, and 20°C. These images provide a comprehensive view of how the salt front progresses from the surface toward the interior of the cheese. Based on this, 1) concentration distribution and penetration depth: at all temperatures, the highest salt concentration (red region) is observed at the lower boundary (the contact point with the brine). Moving toward the inner layers (along the y-axis), the colors change from red to yellow, green, and finally blue, indicating a gradual decrease in salt concentration. Comparison of the three images shows that at 20°C the colored band has a greater thickness; this means that salt has traveled a longer distance toward the center of the cheese and the penetration depth is clearly greater than at 6 and 13°C. 2) flux lines: the white lines accompanied by arrows indicate the direction of salt diffusion flux. The vertical orientation of these lines indicates that in this modeling the mass transfer occurs mainly in the vertical direction and perpendicular to the contact surface. This is consistent with the assumption of one-dimensional diffusion in a semi-infinite medium and shows that lateral diffusion is negligible or limited due to specific boundary conditions. 3) effect of temperature on diffusion kinetics: increasing temperature increases the kinetic energy of molecules and consequently increases the effective diffusion coefficient (D) according to the Arrhenius relationship. The visual results obtained from the simulation confirm that with increasing process temperature, the rate of mass transfer increases and within a fixed time period (24 hours) more effective penetration occurs in the cheese matrix. These two-dimensional maps clearly demonstrate the ability of the model to predict the spatial and temporal distribution of salt concentration and provide a useful tool for better understanding the process kinetics and for optimal design of brining time in the cheese industry [18–19].



a=6 °C b=13 °C

c=20 °C

Figure 7. Two-dimensional salt concentration distribution in cheese during brining at different temperatures (6 °C, 13 °C, and 20 °C) after 24 h brining.

4- Conclusion

The findings of this study showed that the cheese brining process is a time-dependent mass transfer phenomenon influenced by temperature and osmotic conditions, and temperature is one of the most important factors affecting the rate and extent of salt uptake in the cheese matrix. Increasing temperature leads to an increase in the effective diffusion coefficient of salt, accelerates its penetration into the cheese matrix, and consequently increases the amount of salt absorbed within a given time. On the other hand, moisture loss from the cheese occurs simultaneously with salt diffusion, and when the osmotic effect is taken into account, the intensity of moisture reduction is greater and the description of the real process becomes more accurate. The results also showed that the one-dimensional diffusion model based on Fick’s second law, under semi-infinite conditions, has good capability in estimating the effective diffusion coefficient of salt. Moreover, the developed numerical model, which simultaneously considers salt diffusion, water transport, and the osmotic effect, can simulate the real behavior of the brining process with satisfactory accuracy. Therefore, the use of such models can be an effective tool for optimizing brining conditions, controlling the uniformity of salt distribution, adjusting moisture content, and ultimately improving the final quality of cheese at the industrial scale.

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 influenced the work reported in this paper.

Author contributions

Mohsen Dalvi-Isfahan: Supervision, project administration, conceptualization, validation, writing – review and editing.
Hamid Khafaje: Methodology, formal analysis, data curation, writing – original draft.

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مقاله علمی_پژوهشی

توسعه و شبیه‌سازی مدل انتقال همزمان نمک و رطوبت در پنیر با بررسی اثر دما و نیروهای اسمزی

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اطلاعات مقاله

تاریخ های مقاله :

تاریخ دریافت: ۱۴۰۵/۰۱/۳۰

تاریخ داوری: ۱۴۰۵/۰۳/۱۵

تاریخ پذیرش: ۱۴۰۵/۰۳/۱٦

کلمات کلیدی:

آب‌نمک‌گذاری پنیر،

ضریب نفوذ،

دما،

نیروهای اسمزی،

شبیه‌سازی عددی

DOI: 10.48311/fsct.2026.119858.83108

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چکیده

نمک‌زنی یکی از مراحل کلیدی در تولید پنیر است که نقش مهمی در ایمنی میکروبی، ماندگاری، بافت و توسعه طعم محصول دارد. در این پژوهش، فرایند جذب نمک در پنیر طی آب‌نمک‌گذاری با رویکردی تجربی و مدل‌سازی مورد بررسی قرار گرفت. ابتدا ترکیب شیمیایی نمونه‌های پنیر تعیین شد و سپس با استفاده از قانون دوم فیک، ضریب نفوذ مؤثر نمک در دماهای مختلف محاسبه گردید. همچنین برای توصیف دقیق‌تر فرایند، یک مدل عددی توسعه‌یافته با در نظر گرفتن انتقال همزمان نمک و آب و اثر نیروی اسمزی شبیه‌سازی شد. نتایج نشان داد که غلظت نمک در پنیر با گذشت زمان افزایش یافته و این افزایش در ساعات ابتدایی سریع‌تر است، اما به‌تدریج با کاهش گرادیان غلظت، آهنگ جذب نمک کاهش می‌یابد. همچنین دما تأثیر قابل‌توجهی بر فرایند نفوذ داشت؛ به‌طوری‌که با افزایش دما از ٦ به ۲۰ درجه سانتی‌گراد، ضریب نفوذ مؤثر نمک افزایش یافت و میزان جذب نمک بیشتر شد. بررسی وابستگی دمایی ضریب نفوذ با استفاده از رابطه آرنیوس نشان داد که انرژی فعال‌سازی فرایند نفوذ نمک برابر با ۵۳/۳۲ کیلوژول بر مول است. نتایج شبیه‌سازی عددی نیز نشان داد که در نظر گرفتن اثر اسمزی، پیش‌بینی واقع‌بینانه‌تری از کاهش رطوبت و توزیع همزمان نمک و آب در بافت پنیر ارائه می‌دهد. نقشه‌های دوبعدی توزیع غلظت نمک نیز بیانگر آن بودند که در دماهای بالاتر، عمق نفوذ نمک در مدت‌زمان ثابت بیشتر است.