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Nanometric modeling of migration of α-Tocopherol from whey protein-based films on the cheese surface

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ABSTRACT

Nanotechnology has enabled the development of active food packaging with enhanced barrier properties and increased food protection. However, reducing the size of the compounds incorporated into the material to the nanoscale alters their properties. Such interaction requires understand their migration nanoscale mechanisms to release from the material to the food. The objective of this study was to model the migration process of α-Tocopherol on a nanoscale from whey protein-based films to cheese surfaces and compare the findings with experimental data obtained from double cream cheese samples. For the experimental analyses, the whey protein-based films loaded with α-Tocopherol were stored at 4, 14, and 25 °C. The system (film and double cream cheese) was sampled at different time intervals for extraction, quantification of migrant, and the migration process was studied by solving the general diffusion equation of Fick's second law. The migration of α-Tocopherol was modeled using a random walk scheme and a simplified one-dimensional model. A specific algorithm was developed for this study and utilized to model the migration process. The results confirmed the experimental migration of α-Tocopherol from the film to the cheese, yielding the respective experimental partition and diffusion coefficients at different temperatures for the active compound. Likewise, the modeling for the migration phenomenon allowed estimating the respective diffusion coefficients using the model based on Fick's second law and special a nanometric scale through the Brownian movement. The models accurately adjusted to the experimental data, depicting the concentration of the migrant as a function of time.

1. Introduction

Packaging has traditionally been used to contain and protect food, extending its shelf-life (Ashfaq et al., 2022), and there has been a growing interest in developing environmentally friendly packaging materials that can effectively protect food without negatively impacts on the environment (Flórez et al., 2022). Natural raw materials such as starches, proteins, and lipids have been studied to develop food packaging (Almasi et al., 2021), and whey proteins gaining significant attention because they made edible films, biodegradable, flexible, transparent, colorless, and odorless, and exhibit mechanical properties and moisture and oxygen barrier properties (Agudelo-Cuartas et al., 2021; Song et al., 2022). Like other synthetic and natural materials, protein-based packaging even allows the incorporation of compounds of interest that can enhance the shelf life of food products.

Active packaging has emerged to improve the protective properties of food packaging through interactions between the packaging material and the food product. Migration, which involves the transfer of compounds from the packaging material to the food surface or headspace, is one mechanism of interaction (Li et al., 2021). When compounds are incorporated into the packaging material with the intention of gradually releasing them to protect the product, it is known as positive migration, aiming to have antioxidant or antimicrobial compounds positively impacting the shelf-life extension of the food product (Ahmed et al., 2022; Sivakanthan et al., 2020).

Recent studies have focused on evaluating the migration processes

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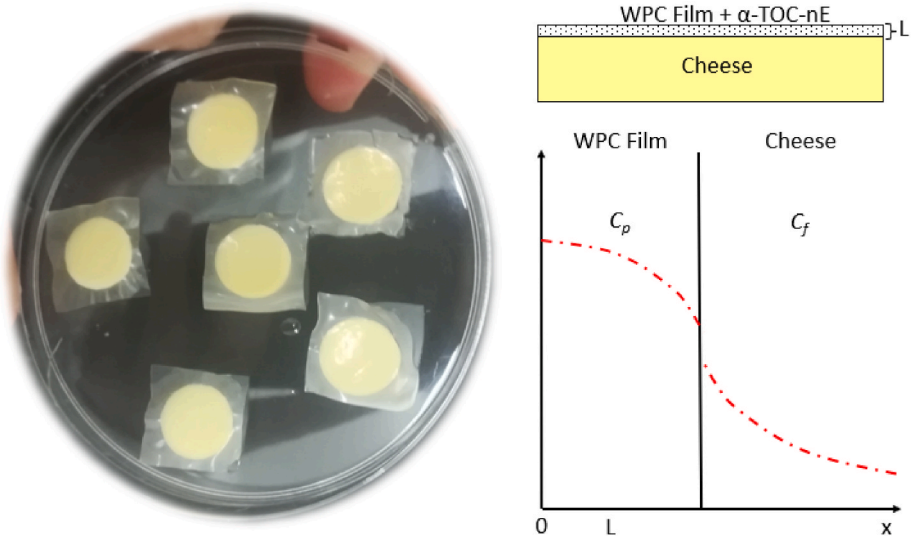


Fig. 1. Migration experiment (left) and graphical representation (right) of the kinetics of migration on cheese. L is film thickness, C_p and C_f are the concentration of migrants in film and cheese, respectively.

with experimental analyses conducted to quantify the compounds released into food simulants or foods from the polymer (i.e., plastic additives, antioxidant or antimicrobial activity) (Sanchez et al., 2022; Zhu et al., 2023). Nevertheless, migration processes involve complex physical and chemical phenomena that can be challenging to determine experimentally, and the presence of multiple components in food products requires robust technology for quantifying small quantities, making the overall design costly. Mathematical models, such as Fick's second law (Eq. (1))(Crank, 1979), have been commonly used for modeling migration in food packaging, particularly in situations where concentrations are measured or needed as a function of position and time (i.e., in the transient state).

Nanotechnology has also enabled the development of food packaging incorporating nanoparticles, which exhibit improved barrier properties and enhanced protection for food products (Ashfaq et al., 2022). However, understanding the migration mechanisms and the interaction of the compound with the polymer matrix necessitates the utilization of nanoscale modeling approaches. One such approach is the application of a mathematical method known as Random Walk (Wu et al., 2019). This technique has proven to be both precise and user-friendly, as evidenced by numerous studies conducted on various systems within the packaging field (Fayazi and Ghazanfari, 2015); the aggregation of colloidal particles in polymeric dispersions (Hernández, 2008); a particle into a heterogeneous porous media (Huang et al., 2019; Wernert et al., 2022); in the adsorption of a non-ionic surfactant on organoclays; it is then that in the process of diffusion (Kania et al., 2021).

In recent years more attention has been paid to evaluating the migration processes of compounds from packaging to food; however, published studies provide very little information on the release kinetics and the behavior of nano-scale compounds from biodegradable materials, in this context, this study aimed to model the migration process of α-Tocopherol on a nanometric scale from whey protein-based films to cheese surfaces and compare these results with the data obtained experimentally for double cream cheese samples.

2. Materials and methods

2.1. Materials

The active compound α-Tocopherol (α-T, 97% purity) was purchased from Sigma-Aldrich, USA; whey protein concentrate (WPC, 80% *w/w* protein) was supplied by Ingredients y Productos Funcionales (IPF, Colombia); water grade HPLC, glycerol (Gly) were obtained from J.T Baker, Germany; surfactants as polysorbate 80 (Tween 80) and sorbitan monoester (Span 60) were purchased from Sigma-Aldrich, USA; methanol and acetonitrile grade HPLC were purchased from Panreac, Italia, and double cream cheese (26.7% *w/w* fat) was buy in a local market.

2.2. Nanoemulsion preparation

The ingredients concentration for nanoemulsion of α-Tocopherol (α-T-nE) was determined in preliminary studies (Agudelo-Cuartas et al., 2020).The oil-in-water (O/W) α-T-nE was prepared by the mechanical size reduction method (Agudelo-Cuartas et al., 2020). The aqueous phase was prepared with 1.54% (*w/w*) of Tween 80 (HLB = 15) mixture with 96.03% (*w/w*) distilled water under continuous stirring at room temperature. The organic phase was prepared with 1.46% *(w/w)* of α-T, 0.97% (*w/w*) Span 60 (HLB = 4.7), and ethanol and stirred at 35 °C for 10 min. Thereupon these phases were mixed and homogenized at 20000 rpm for 5 min (5 periods with 3 min of rest) using a MicroDisTech homogenizer (MDT100, Kinematica, Switzerland), achieving a hydrophilic-lipophilic balance (HLB = 11) to obtain a nanoemulsion.

2.2.1. Polydispersity index and droplet size

At room temperature, the polydispersity indexes (PDI) and particle mean droplet size for α-T-nE were measured using a Zetasizer Nano ZS (Malvern Instruments Ltd., UK). The data were obtained with the average of three measurements.

2.3. Film preparation

The film-forming solution (FFS) with active compounds was prepared at room temperature dissolving 5% (*w/w*) Gly and 10% (*w/w*) WPC powder in 81.4% (*w/w*) of α-T-nE under continuous magnetic stirring, and the pH was reached to 7.0 using 0.1 M NaOH. The heat treatment of the film-forming solution was to 90 °C using a water bath (Lauda Alpha, Germany) for approximately 20 min and cooled until ambient temperature. Films were made by casting in polystyrene petri dishes (35 mm) and dried at 30 °C for 12 h in an oven (Binder FD 56, Germany).

2.4. Film thickness determination

At ten random positions, film thickness was measured using a digital

micrometer (Mitutoyo IP65 Quantumike, Japan).

2.5. Migration experiments

Films squares pieces (2 × 2 cm) were placed on circular pieces of cheese (15 mm diameter and 3 mm thickness) and placed on petri dishes (Fig. 1). These samples were stored at 4, 14, and 25 °C and were exposed to incandescent lamp bulb light (110V, 7W, 300–625 lux). The system (film + cheese) (triplicates) was taken out at different time intervals to determine the amount of α-T released from the films.

2.6. Extraction and quantification of α-Tocopherol in films

The active compound extraction from the film was carried out according to the procedures described by Molognoni et al. (2016) and Paseiro-Cerrato et al. (2013) with slight modifications and was analyzed by HPLC Shimadzu (Tokyo, Japan) with a pump (LC-20AD), a diode array detector (SPD-M20A), an autosampler (SIL-20A/HT), a communication module (CBM-20A), and a C18 column, 250 × 4 mm, 5 μm (Knauer, Germany).

The conditions to quantify α-T corresponded to a flow of 1.0 mL min^{-1} for 15 min, 5 μL injection, 285 nm wavelength, and the mobile phase was methanol and acetonitrile (50:50) (Granda-Restrepo et al., 2009). The calibration curve for α-Tocopherol was constructed with seven levels, including zero in 100–1000 mg kg^{-1}. Linearity was evaluated using three replicates per level on three different days.

2.7. Migration modeling

The migration process is described by the kinetic diffusion of the active compound (migrant) in the film for release to cheese (Fig. 1), and it is expressed by diffusion coefficient (D). The solution for this case (one-dimensional system) can be obtained by solving Eq (1), a general diffusion partial differential equation Fick's second law of diffusion.

$$\frac{\partial C_p}{\partial t} = D\frac{\partial^2 C_p}{\partial x^2} \tag{1}$$

where Cp is the concentration of migrants in WPC film at time t and x dimension. To find the concentration of migrant as a function of time in the film, the following assumptions were made to resolve Eq (1).

- This system assumes a piece of film is in contact with a piece of cheese on one surface.
- The system is closed.
- The migrants are uniformly distributed inside the film at $t = 0$.
- No interaction occurs between the film and the cheese.
- The concentration profile of migrants in the films is one dimensional.
- The partition ($K_{p,f}$) and diffusion (D) coefficients are constants, and D does not depend on the concentration of migrant.

The initial conditions when the film is added with initial concentration Co of migrant are:

$$C_p(x,0) = C_o \tag{2}$$

$$C_f(x,0) = 0 \tag{3}$$

where, C_f is the concentration of migrant in food, and the boundary conditions are:

$$\left.\frac{\partial C_p}{\partial x}\right|_{x=0} = 0 \tag{4}$$

$$-D\left.\frac{\partial C_p}{\partial x}\right|_{x=L} = \frac{V_f}{A}\left.\frac{\partial C_f}{\partial t}\right|_{x=L} \tag{5}$$

where, V_f and A are the volume of food and area the film, respectively. One analytic solution for Fick's second law equation for diffusion in one dimension assuming that volume of the cheese are infinite compared to the film is Eq (6) (Samsudin et al., 2018a,b).

$$\frac{M_{f,t}}{M_{f,\infty}} = 1 - \sum_{n=0}^{\infty}\frac{8}{(2n+1)^2\pi^2}exp\left[-\frac{D(2n+1)^2\pi^2\, t}{L^2}\right] \tag{6}$$

where $M_{f,t}$ represents the amount of the α-T released at time t (s); $M_{f,\infty}$ is the corresponding amount at equilibrium; D is the diffusion coefficient ($cm^2\ s^{-1}$) through the WPC film; and L is the thickness (cm) of film.

And, the partition coefficient ($K_{p,f}$) can be calculated from the ratio of the concentration of α-T in film ($C_{p,\infty}$) and the cheese ($C_{f,\infty}$) at equilibrium using equation (7) (Khan et al., 2022).

$$K_{p,f} = \frac{C_{p,\infty}}{C_{f,\infty}} \tag{7}$$

To determine the effect of temperature on the diffusion of α-T loaded into the WPC film the Arrhenius Model (Eq. (8)) was used (Granda-Restrepo et al., 2009; Manzanarez-López et al., 2011).

$$D = D_o\, exp\left(-E_a/_{RT}\right) \tag{8}$$

where D is the diffusion coefficient, D_o is a pre-exponential factor of the diffusion coefficient, Ea is the activation energy of diffusion (J mol^{-1}), R is the ideal gas constant (8.3145 J $mol^{-1}K^{-1}$), and T is the temperature in K. Ea was determined using the slope of the line obtained by plotting the logarithm of D versus the reciprocal of temperature (1/T) determined at each temperature.

2.8. Nanometric modeling of migration

The matter is transported from one part of the system to another part as a result of the random movement of the molecules. In developing the theory of Brownian motion, Einstein and Smoluchowski pioneered the description of the microscopic Brownian motion observed in colloidal particles through the macroscopic diffusion coefficient of Fickian diffusion (Eq. (1)). In the context of packaging migration, the molecules of the migrating substance behave in a similar way to particles in Brownian motion. Due to the thermal energy present in the system, the molecules move randomly and diffuse through the packaging material. Eq. (9) defines the constant diffusion and is known as the Einstein's diffusion equation (Hernández, 2008; Honary et al., 2019; Wernert et al., 2022).

$$\langle r^2\rangle = 2n_d D_j t \tag{9}$$

Where $<r^2>$ is the average square distance traveled by the particle in a time t, n_d is the number of dimensions, and D_j is the diffusion coefficient of compound j ($cm^2\ s^{-1}$).

The method of random tracking of particles in time and one-dimensional space is described by the stochastic expression (Eq. (10)); this method is widely used in dispersion and diffusion analysis (Fayazi and Ghazanfari, 2015; Huang et al., 2019; Nordam et al., 2019).

$$x(t+\Delta t) = x(t) + \xi\sqrt{2D_{ij}\Delta t} \tag{10}$$

where D_{ij} is the initial diffusion coefficient i of compound j ($cm^2\ s^{-1}$), ξ is a random number with a normal distribution (mean = 0 and variance = 1), and Δt is the change of time (s). The most significant possible displacement of the particles during a time step should satisfy the condition regarding the spatial resolution discretization Δx for the following expression:

$$\xi\sqrt{2D_i\Delta t} \le \Delta x \tag{11}$$

These techniques are adapted to simulate the displacement of

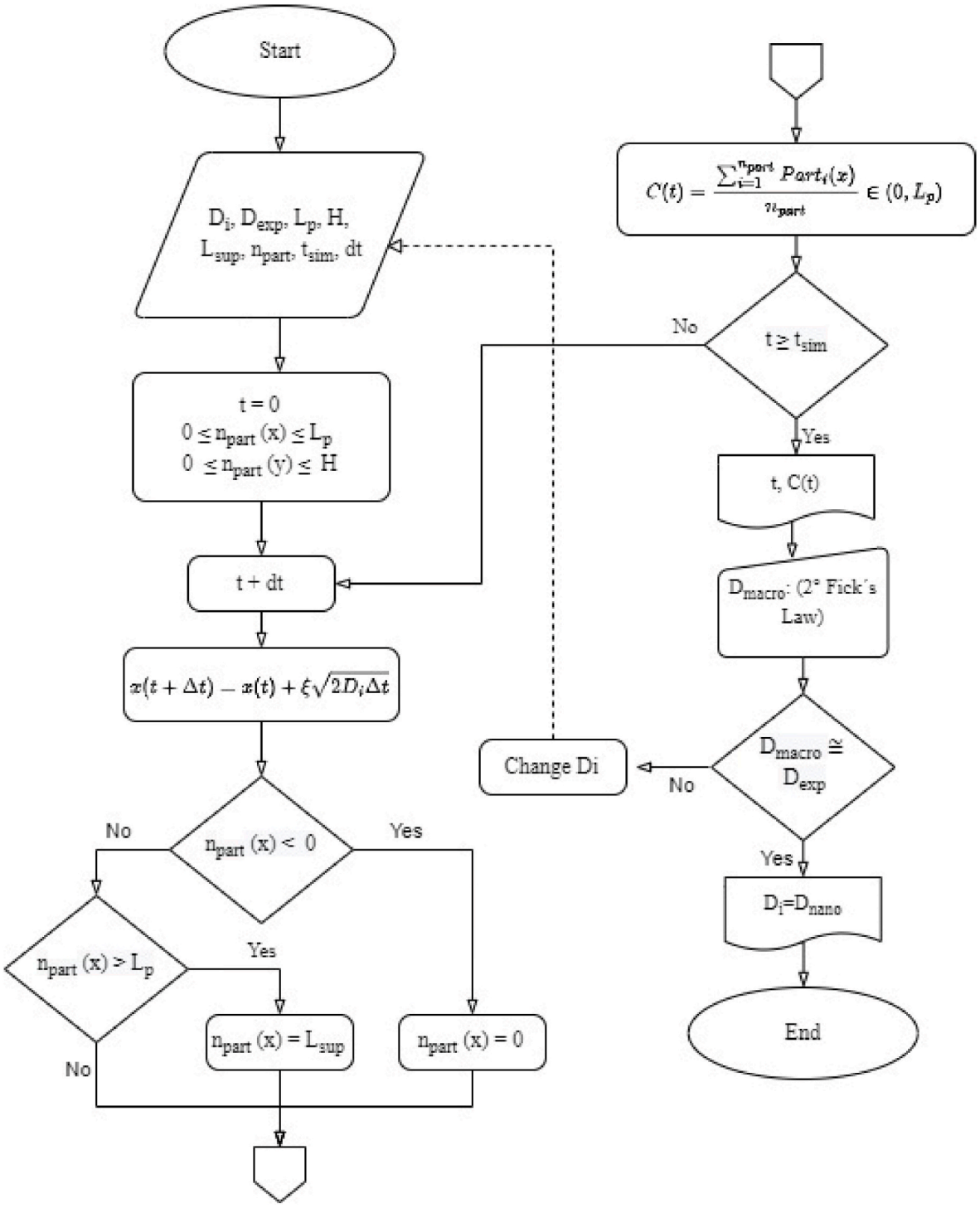


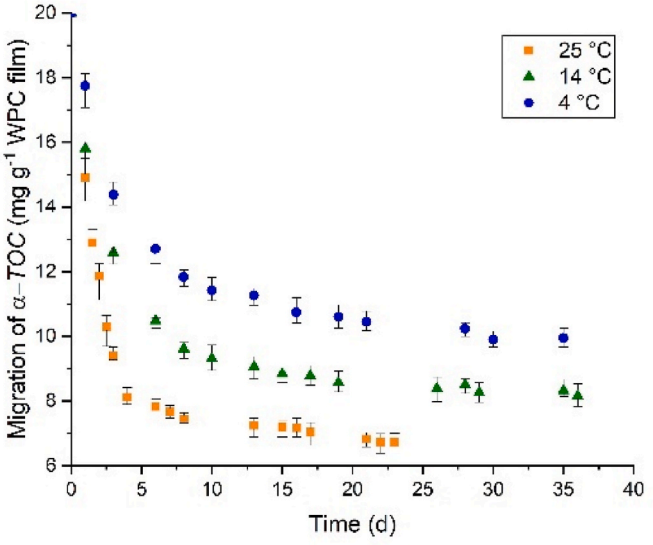
Fig. 2. Algorithm of the Brownian motion of α-T droplets into the WPC film.

particles in different media, the diffusion coefficient is obtained by fitting the predicted concentration profile of the random walk model to the experimental data (Fayazi and Ghazanfari, 2015; Wu et al., 2019), and the assumptions used in this study for the application of Einstein's equation for Brownian motion are.

- The α-T particles are homogeneously distributed within the WPC film. This has been confirmed by previous studies using the SEM method (Agudelo-Cuartas et al., 2020).
- Each particle represents a part of the total mass of the solute and executes a movement independent of the movements of all other particles.
- The movements of a given particle in different time intervals are independent, one-dimensional processes, and these intervals determine the evolution of the system.

The nanometric migration of α-T was made using the random walk scheme modeling using Eq (10) as a simplified one-dimensional model and Fig. 2 show the algorithm used to model the migration process.

Then, $M_{f,t}/M_{f,\infty}$ was plotted vs time t, and the diffusion and partition



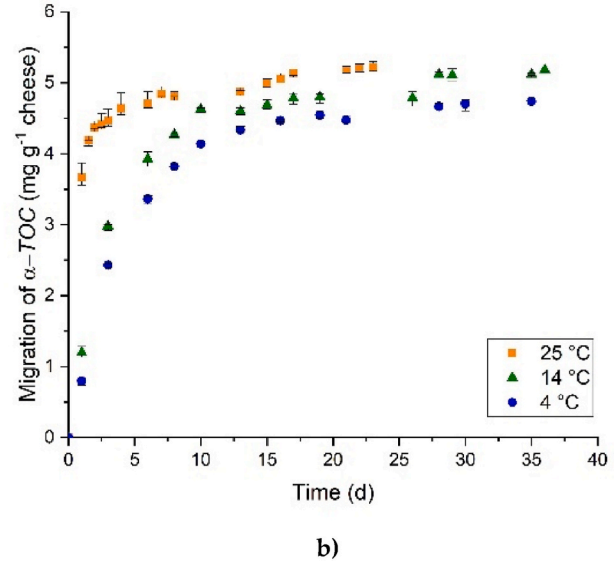


Fig. 3. Migration curves of α-T in film (a) and cheese (b) at different temperatures.

coefficients were calculated for each temperature. The value of D was determined by minimizing the sum of the squares error (SSE) of the measured ($M_{f,t}/M_{f,\infty}$) by fitting Eq (6) to experimental data by non-linear regression using the MATLAB ® R2018 (MathWork, USA).

Statistical analyses of data were performed through a variance analysis (ANOVA) employment of the Statgraphics® centurion XV software. The differences were tested using Duncan's multiple range test at $p < 0.05$.

3. Results and discussion

Guaranteeing the success in the manufacture of the nanoemulsion before determining its effect on mass transfer in the WPC film is necessary; therefore, the evaluation of the PDI and especially the droplet diameter of the nanoemulsion encapsulating α-Tocopherol was essential; the result of PDI was 0.16 ± 0.02 less than 0.5, describing a stable nanoemulsion (Dammak et al., 2017) and the drop diameter obtained was 35.4 ± 0.6 nm maintaining the nanometric range, less than 100 nm.

Table 1
Partition and diffusion coefficient of α-Tocopherol in the film-cheese system.

T (°C)	$K_{p,f}$	$D \times 10^{11}$ ($cm^2\ s^{-1}$)	R^2
4	2.02 ± 0.08 [a]	3.67 ± 0.49 [a]	0.987
14	1.60 ± 0.10 [b]	5.09 ± 0.78 [b]	0.990
25	1.30 ± 0.09 [c]	9.17 ± 2.07 [c]	0.983
Ea (kJ mol^{-1})	–	30.04	0.975

Mean values ± standard deviation. Different letters in the same column indicate significant differences ($p < 0.05$) among the average values obtained by application of Duncan's test.

These results were according for mean droplets of α-T-nE obtaining values of 79 nm (Pérez and Sobral, 2017), and 139 nm (Maldonado et al., 2023).

The WPC film made was transparent, without visual defects such as bubbles, scratches, phase separation, or cracks. The average thickness of the active film was 0.126 ± 0.021 mm, which was used in the migration models.

3.1. Migration modeling from film to cheese

The diffusion process in the film-cheese system can obtain a more realistic evaluation of this phenomenon than an in vitro study. Fig. 3 shows the concentration of α-T in the film and double cream cheese stored at 4, 14, and 25 °C respectively; different α-T equilibriums were obtained in the film as follows: 7.17 mg g^{-1} reached at 15 days, 8.50 mg g^{-1} at 26 days, and 9.90 mg g^{-1} at 30 days at 25, 14, and 4 °C, respectively, the high temperature could give rise to high α-T migration velocity. These results demonstrate the ability of α-T to migrate from the WPC film into cheese.

The final concentrations of α-T in the cheese were 4.73, 5.18, and 5.22 mg g^{-1} at 4, 14, and 25 °C, respectively, corresponding at 35, 36, and 23 days in the same order of temperature.

The final concentrations become a percentage release of α-T from the films to the cheese equal at 23.5, 25.9, and 26.1% for 4, 14, and 25 °C, respectively, based on the initial concentration incorporated in the film. This low percentage can be attributed to the effective barrier properties of the packaging material, which restrict the diffusion of α-T molecules through the film. Additionally, the interactions between the nanometric α-T and the polymer matrix may play a role in reducing migration, as the molecules may be partially trapped or bound within the film structure. Over the time of the experiment, the α-T concentration in the cheese did not decreased, perhaps due to the high availability in the film, the gradual migration and the high antioxidant capacity of the film (data not shown), in contrast, Granda-Restrepo et al. (2009) identified the difficulty to follow the behavior of α-Tocopherol that migrated from the active film to whole milk powder after 40 days of storage at 30 °C because the antioxidant was consumed by components of the food subjected to oxidation.

3.1.1. Partition coefficient

The $K_{p,f}$ values decreased with the temperature (Table 1); according to Hwang et al. (2013), this can be explained by the affinity and molecular interaction of α-T with the fat and protein present in the cheese, which influenced its solubility; therefore, the antioxidant presents a faster migration. The calculated $K_{p,f}$ presented significant differences ($p < 0.05$) for 4, 14, and 25 °C with average values of 2.02, 7.41, and 6.05, respectively. This is confirmed with the order of α-T release (Fig. 3). Similarly, a study of an active packaging with α-Tocopherol in contact with milk powder, found $K_{p,f}$ values higher and close to unity, indicating the affinity of α-T is mainly for the film, there is also affinity for the food (Granda-Restrepo et al., 2009).

3.1.2. Diffusion coefficient

The diffusion coefficient for α-T is shown in Table 1; all presented

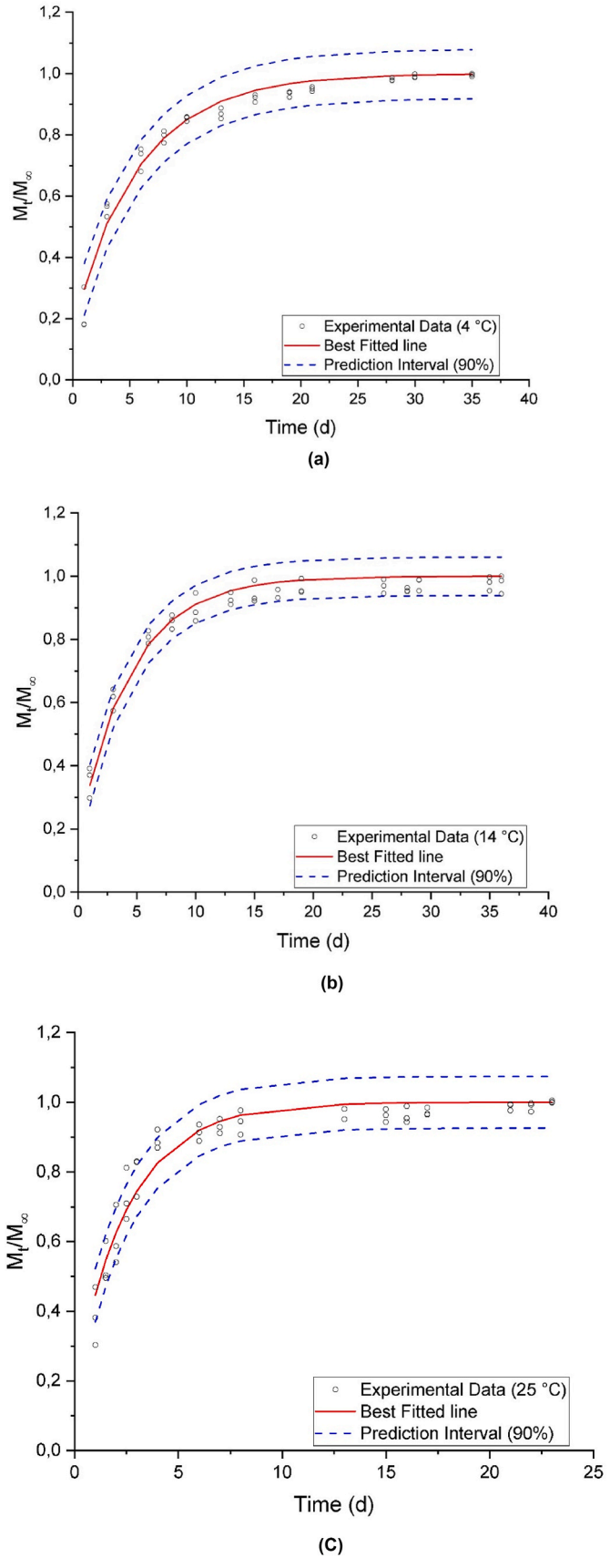


Fig. 4. Diffusion in the film-cheese system of α-Tocopherol in different temperatures according to Fick's second law.

Table 2
Parameters used in the nanoscale simulation.

Parameter	Value	Description
D_{nanoi} ($cm^2\ s^{-1}$)	4.30 x 10^{-10}	Initial nanometric diffusion coefficient
L_{film} (cm)[a]	0.0126	Film thickness
n_{part}[b]	500000	Representative α-T particles
Ci ($mg\ g^{-1}$)[a]	20	Initial concentration
dt (s)	1200	Time change for simulation
t_{fin} (d)	38	Total simulation time

[a] Values of the packaging system are constant in the simulation.
[b] Represents the α-T droplets on the film, as a calculation base representing the α-T concentration.

significant differences ($p < 0.05$). The D value at 4 °C was 3.67 x 10^{-11} $cm^2\ s^{-1}$, for this condition of temperature, the migration is comparable with the various macroscopic studies that calculated the diffusion coefficient at higher temperatures. Showing that the nanometric scale of Tocopherol can influence migration. Granda-Restrepo et al. (2009) obtained values of 3.14 x 10^{-11} $cm^2\ s^{-1}$ at 40 °C for a synthetic polymer (LDPE) in contact with whole milk powder. Also, in vitro studies report values of 3.16 x 10^{-11} $cm^2\ s^{-1}$ at 23 °C in poly(lactic acid) films (PLA) (Manzanarez-López et al., 2011), 4.63 x 10^{-11} $cm^2\ s^{-1}$ at 13 °C in PLA/starch films (Hwang et al., 2013), and 3.50 x 10^{-11} $cm^2\ s^{-1}$ at 9 °C in PLA (Samsudin et al., 2018a,b); the latter explains that the value of diffusion coefficient and release of α-T depends on the polymer matrix structure, where an increase in formed matrix bonds decreases the free space, at the same time as the movement of the antioxidant in the structure, another influencing factor, is the solubility of α-T in fatty media as in heavy cream cheese, and possibly the nanometer size of the α-T incorporated in the whey film.

The activation energy for α-T was 30.04 kJ mol^{-1}, it was shown that less energy is needed for diffusion of a-T from WPC film to cheese compared to values reported in in vitro systems using PLA films (96.2 and 140.6 kJ mol^{-1})(Hwang et al., 2013; Manzanarez-López et al., 2011). The nanometric scale of α-T can allow more movement into the WPC film since higher diffusion and lower energy barrier, these results are coincident with the values of $K_{p,f} > 1$ (Table 1), where the α-T presented higher affinity for the packaging material presenting in a certain way a gradual migration and propitiating protection for and from the polymer.

The plots of the migration of α-T from WPC film into cheese at different temperatures (Fig. 4.) demonstrated that Fick's second law equation for diffusion fits the experimental data whit values $R^2 > 0.9827$; these results demonstrate that the estimated values of diffusion coefficient explain the migration of α-Tocopherol (Table 1).

3.2. Nanometric modeling of migration

Simulation of the α-T nanodroplets inside the film in contact with the cheese was performed following the flow diagram (Fig. 2); a similar process was used by Hernandez to describe the Brownian dynamics of polymeric particles (Hernández, 2008);

The parameters and the algorithm used to simulate the migration process are shown in Table 2 and Fig. 2, these used to find the D_{nano}, note that the iteration starts with an arbitrary initial diffusion coefficient (D_i), which allows obtaining simulated data of the α-T concentration over time, these data were adjusted to the second Fick's law to estimate a macro diffusion coefficient, which is compared with the D_{exp}, if they are different a new iteration starts, changing D_i, otherwise, D_i is considered as D_{nano}. The methodology used was that of least squares minimizing the error between predicted and experimental data at the three temperatures; the number of particles is a parameter that is necessary to control because a higher number concerns an increase of the calculation time; similarly, small values of dt affects the simulation time, the ranges presented were used in the simulation of the Brownian motion of each migrant inside the film, further on the results obtained will be discussed.

Table 3
Diffusion coefficient for the α-T estimated at the nanometer scale.

T (°C)	$D_{macro\ (exp)}$ [c a]	D_{nano} [b]	R^2
4	3.67 ± 0.49	1.47	0.999
14	5.09 ± 0.78	2.03	0.999
25	9.17 ± 2.07	3.72	0.997

[a] x 10^{11} ($cm^2\ s^{-1}$).
[b] x 10^{10} ($cm^2\ s^{-1}$).
[c] : Experimental diffusion coefficient.

The values of the diffusion coefficient of the α-T nanodroplets obtained by simulating the Brownian motion are presented in Table 3. Note that the values of D_{nano} were higher than the experimental values that were estimated according to the second Fick's Law, which is denominated as D_{macro} (or D_{exp}) (macrometric and experimental diffusion coefficient). This behavior occurred because the net movement of each of the particles within the film has been described with a sufficiently small size (35.4 d nm), allowing greater mobility within the film and the estimation of the concentration of the active compounds in time was coincident with the experimental data (Fig. 5), hence the value of R^2 obtained greater than 0.99. These results indicate that the Brownian motion simulated at the nanometer scale is an accurate method to predict the behavior of the α-T at the three temperatures evaluated.

4. Conclusions

The migration of α-Tocopherol from the film to the double cream cheese was confirmed experimentally, obtaining the respective experimental partition and diffusion coefficients at different temperatures for each of the active compounds. Likewise, the modeling for the migration phenomenon allowed estimating the respective diffusion coefficients using the model based on Fick's second law and special a nanometric scale through the Brownian movement of each α-Tocopherol particle, faithfully adjusting to the experimental data (concentration of each migrant as a function of the time), since the character of the stochastic model allows a better variation of the movement of the particles within the film.

The results of this study provide detailed information on the migration behavior of nanoscale compounds when they are on biodegradable material and in direct contact with the surface of real foods and provide tools for engineers to model theoretically the effect of possible temperature changes during the storage process, with the confidence of having results very close to those obtained experimentally.

Credit author statement

Camilo Agudelo Cuartas: Conceptualization, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Diana María Granda Restrepo**: Resources, Supervision, Conceptualization, Methodology, Writing – review & editing. **Paulo J.A Sobral**: Resources, Writing – review & editing. **Hugo Hernandez**: Software, Writing – review & editing.

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Declaration of competing 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.

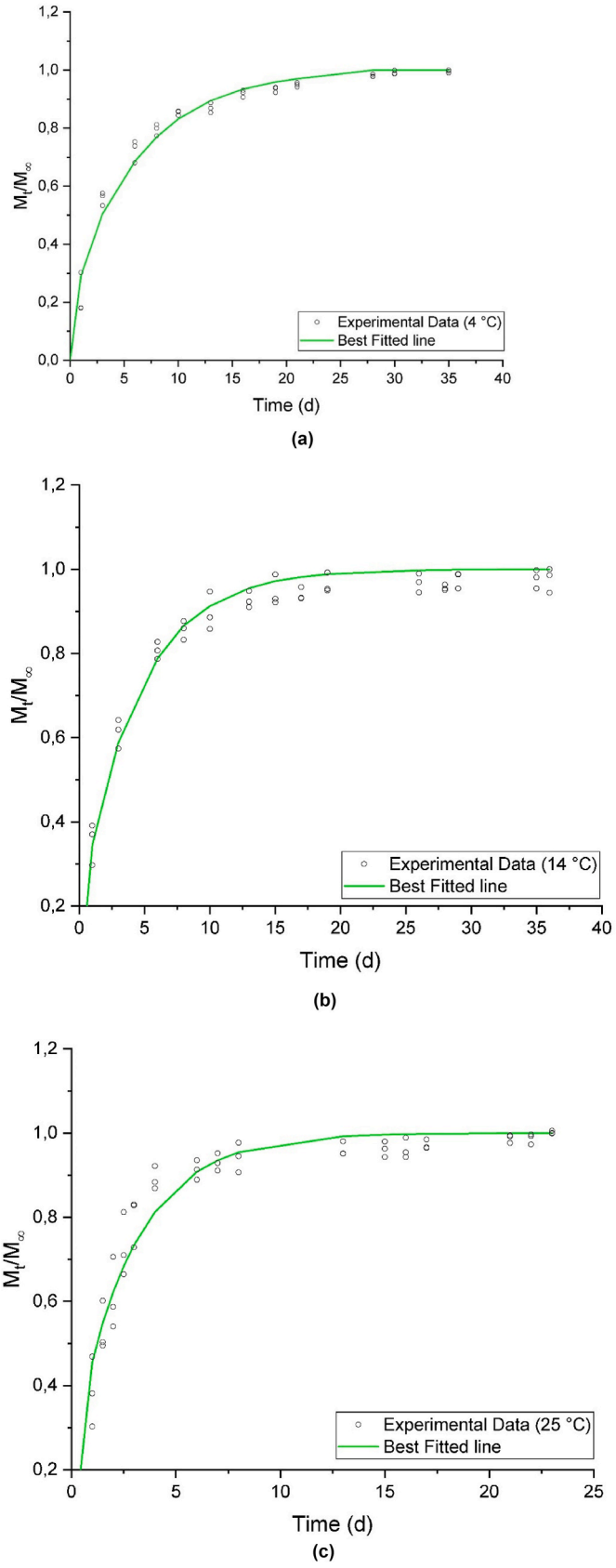

Fig. 5. Nanometric diffusion of α-Tocopherol in the film-cheese system in different temperatures.

Data availability

Data will be made available on request.

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