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KINETICS OF MASS TRANSFER IN OSMOTIC DEHYDRATION OF ALOE VERA GEL (*ALOE VERA BARBADENSIS MILLER*)

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ABSTRACT

The mass transfer kinetics during the osmotic dehydration of sábila (*Aloe vera barbadensis Miller*) were analyzed. A gel-to-solution ratio of 3:1 was used over an 80-hour process. The Azuara and Peleg mathematical models were applied to describe the kinetics of moisture loss and solid gain at a constant temperature of 25 °C and fixed concentration. Although the experimental data fit both models, the Peleg model provided a better fit. Additionally, the effective diffusion coefficients were adjusted using the Arrhenius equation as a function of temperature.

Keywords: Azuara model, osmotic dehydration, Peleg model, sábila

1. INTRODUCTION

Aloe vera (*Aloe vera barbadensis Miller*) belongs to the Asphodelaceae or Liliaceae family (Domínguez et al., 2012). The name Aloe comes from the Arabic word alloeh, which means “bright and bitter substance”; the plant is also commonly known as sábila. Its thick, brittle leaves, lined with spines, grow in a spiral rosette around the stem. The aloe’s mucilage contains parenchyma tissue—a type of spongy plant tissue that stores water absorbed through the roots and leaves. Through a remarkable metabolic process, this water is transformed into the translucent, bitter gel that is highly prized for its medicinal properties (Schweizer, 1995). Today, Aloe vera is used worldwide to treat a variety of ailments and is especially important in the cosmetic, pharmaceutical and food industries.

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Researchers have described Aloe gel as “the most ingenious blend of antibiotic, astringent, and coagulant, while also functioning as a pain inhibitor, scar reducer, and growth stimulant.” It has even been called the “wound hormone” (Ferraro, 2009).

Two main products of significant interest to researchers are obtained from this plant genus: acíbar (a type of dried latex) and Aloe vera gel. Both are extracted from the leaves but differ completely in their chemical composition, pharmacological properties, and therapeutic applications. These substances provide the body with many essential nutrients and, although of plant origin, are recognized by the body as compatible, making them easily absorbed without causing unwanted side effects. Evidence also suggests that sábila gel contains a variety of compounds that, either individually or in combination, have therapeutic effects. A deeper understanding of these components and their actions is therefore essential for developing effective therapeutic products based on Aloe vera gel (Domínguez et al., 2012).

Monosaccharides and polysaccharides are responsible for many of aloe’s therapeutic effects. Monosaccharides are simple carbohydrates, such as glucose, mannose, and galactose, while polysaccharides are complex carbohydrates made up of long chains of simple sugars, such as glucomannan and acemannan. Among these, acemannan is particularly noteworthy for its strong germicidal, fungicidal, and bactericidal properties. Research has shown that it also boosts the immune system and has antitumor effects, playing a crucial role in the prevention and treatment of serious diseases such as certain types of cancer, Acquired Immunodeficiency Syndrome (AIDS), and multiple sclerosis (Escobar, 2016).

Three types of commercial products can be obtained from the leaves of the Aloe vera plant:

1. The mucilaginous gel of Aloe vera, thanks to the biological activity of its components, has been widely used in various applications. It serves as an ingredient in functional foods, ice creams, fruit-based beverages, and yogurts. In addition, it is extensively used in cosmetology and medicine for its antiviral, disinfectant, vermifuge, and fungicidal properties, among others (Aristizabal et al., 2010).
2. A dried exudate secreted by the aloin cells located in the vascular region, commonly known as Aloe. This natural substance is well known for its cathartic effect and is also used as a bittering agent in alcoholic beverages.
3. The oil, extracted using organic solvents, is the lipid fraction of the leaves and is used exclusively in the cosmetics industry as a pigment carrier and soothing agent (Izaguirre et al., 2013).

The main producers of this crop are the Dominican Republic, Venezuela, and Mexico (Rubio et al., 2018). Mexico is expected to become the leading producer of sabila, due to its favorable climate

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and the established cultivation in the states of Tamaulipas, San Luis Potosí, Querétaro, Yucatán, and Veracruz (Alvarez et al., 2015).

The potential applications of sabila products often involve some form of processing, such as heating, dehydration, or grinding. However, improper processing during the preparation and stabilization of the gel can lead to irreversible changes in bioactive components such as polysaccharides and antioxidant compounds. These changes alter the original structure and significantly affect the biochemical properties, resulting in products that contain little or almost no active ingredients.

For this reason, in recent decades, research has focused on identifying the key active chemical compounds responsible for the therapeutic effects of Aloe vera. At the same time, efforts have been made to develop effective and natural methods to preserve these compounds in the gel, with the aim of improving product quality (Domínguez et al., 2012).

Studies in laboratory animals have shown that Aloe can prevent and slow the progression of arthritis, promote wound healing, reduce pain and inflammation, stimulate bone growth, and act as a carrier for nutrients in the body (Gampel, 2002). For this reason, efforts have been made to enhance the bioactive potential of sábila gel by increasing its solid content and reducing its moisture, with the goal of producing it in powdered form.

The dehydration process reduces water activity (*Aw*), which refers to the amount of water available for chemical and biochemical reactions, as well as for microbial growth. Several dehydration methods exist, including exposing the food product to a stream of hot air. However, this and similar techniques have the drawback of subjecting the product to high temperatures, which can negatively affect its sensory and nutritional properties (Valera et al., 2005).

Introducing osmotic dehydration (OD) as an intermediate step in the drying process is a novel preservation method that can extend the shelf life of fruits and vegetables while reducing total processing time. This approach also enhances the organoleptic and nutritional qualities of the final product, helping to meet consumer demand for processed fruits with sensory characteristics similar to those of fresh produce (Bambicha et al., 2012).

The solutes commonly used in osmotic solutions are inexpensive and include substances such as sucrose, glucose, fructose, sodium chloride, glycerol, sorbitol, and combinations of these, which can produce a synergistic effect—for example, the sucrose–sodium chloride mixture. Generally, sucrose solutions are used for fruits, while sodium chloride solutions are preferred for vegetables. Several studies have analyzed the key variables that influence osmotic dehydration, particularly those affecting mass transfer kinetics. These include product-related factors such as composition, size, shape, presence of skin, and pre-treatments, as well as parameters of the osmotic solution,

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such as temperature, concentration, type of osmotic agent, working pressure, food-to-solution ratio, processing time, and agitation (Vega et al., 2007).

The objective of this study was to evaluate the osmotic dehydration kinetics of sabila gel using the Azuara and Peleg mathematical models under scaled drying conditions. The gel will also be characterized through physicochemical and bromatological analyses. Finally, weight loss will be compared between sliced sabila gel and whole gel samples.

2. MATERIALS AND METHODS

2.1 Selection of the raw material

The sabila used in this study was sourced from the town of Umán, Mérida, Yucatán (México). The leaves selected were those with the best size and color.

2.2 Cleaning and sanitization of plant material

The leaves were washed with potable water using detergent and commercial chlorine at a concentration of 50 ppm, then rinsed and immersed in a solution of water and citricidin (a disinfectant) for 20 minutes. They were then stored under refrigeration at 4 °C until use.

2.3 Gel extraction

To obtain pure sabila (*Aloe vera*) gel, approximately 5 cm were trimmed from both the base and tip of each leaf. The leaves were then placed in a strainer for 90 minutes to allow the acibar to drain completely. Once the acibar was fully removed, the gel was filleted. For the gel pieces, circular sections were cut with a diameter of 2.54 cm and a thickness of 1.02 cm.

2.4 Gel characterization

The physicochemical analyses included pH (measured with a Denver Instrument potentiometer, Ultrabasic model), titratable acidity, °Brix (using an Atago Pocket refractometer), water activity (AGUA-Lab CX-2), total sugars (Dubois, 1956), and reducing sugars (James, 1999). The bromatological analyses included moisture, ash, fat, nitrogen-based protein, fiber, and total carbohydrates—the latter calculated by difference—according to AOAC methodology (1998). All samples were analyzed in triplicate.

2.5 Blanching

To improve the dehydration of the gel samples, they were subjected to a blanching process aimed at preventing or minimizing deterioration during drying, as well as enhancing the quality and shelf life of the final product. The process consisted of immersing the gel for two minutes in a solution

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containing 3 liters of water, 90 g/ml of citric acid, and 3 g/ml of calcium chloride, at a temperature between 70 °C and 100 °C.

2.6 Preparation of the osmotic solution

An osmotic solution was prepared with a total weight of 250 g, composed of sucrose (87.977 %), maltodextrin (9.775 %), citric acid (1.955 %), and sodium benzoate (0.293 %). The mixture was applied at a ratio of 3 g of gel to 1 g of osmotic solution.

2.7 Analysis

Physicochemical analysis was performed every 20 hours over a total period of 80 hours. The weight of the gel and the osmotic solution was measured at 20-hour intervals using the following formula:

$$Gel\ weight = P_i - P_t$$

P_i= Initial weight

P_t= Weight at time *t*

The weight of the osmotic solution was calculated using the following formula:

$$Solution\ weight = P_t - P_i$$

2.8 Drying

After 80 hours of dehydration, the samples were washed and drained. They were then air-dried to remove any remaining moisture and finally subjected to a drying process in an oven at 50 °C for 48 hours.

2.9 Modeling of osmotic dehydration (OD) kinetics

The most important parameters of the OD process were determined, including the percentage of moisture loss (ML) and the percentage of soluble solids gain (SSG). These parameters were fitted as a function of time using an empirical penetration model proposed by Azuara (Arias et al., 2017).

$$ML(\%) = \frac{(X_{wi} - X_{wt})}{X_{wt}} * 100 \qquad (1)$$

$$SSG(\%) = \frac{(X_{st} - X_{si})}{X_{st}} * 100 \qquad (2)$$

Where: X_{wi} and X_{si} represent the initial moisture content (in percentage) and initial soluble solids (in °Brix), respectively. X_{wt} and X_{st} represent the moisture content (in percentage) and soluble solids (in °Brix) at time *t*, respectively.

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2.10 Azuara empirical model

The Azuara model is an empirical model based on fitting an equation to experimental data. Its main advantage is that it allows for the prediction of equilibrium without requiring the system to actually reach it. However, its primary limitation is that its validity is restricted to the experimental range from which the parameters were derived (Ochoa et al., 2005).

It is based on mass balance to predict the dehydration kinetics during the osmotic process and to determine the final equilibrium point.

$$\mathrm{MLt} = \frac{\beta_1 t(ML_\infty)}{1+\beta_1 t} \qquad (3)$$

$$\mathrm{SSGt} = \frac{\beta_2 t(SSG_\infty)}{1+\beta_2 t} \qquad (4)$$

The model is based on moisture loss over time (ML_t), where $ML\infty$ represents the moisture loss at infinite time (equilibrium), and β_1 is the diffusion rate constant for water moving out of the product. Similarly, solids gain is expressed as a function of time (SSG_t), with $SSG\infty$ representing the solids gain at infinite time (equilibrium), and β_2 being the diffusion rate constant for solutes entering the product (Arias et al., 2017).

2.11 Peleg model

The Peleg model (1988) is a simple and easy-to-use method that has been validated for modeling water absorption phenomena in a wide variety of plants, fruits, and vegetables (Agudelo et al., 2009). The Peleg equation is expressed as follows:

$$X_w = X_{w0} \pm \frac{t}{K_1+K_2 t} \qquad (5)$$

Where Xw is the moisture content on a dry basis (g/g db) at a given time t, Xw is the initial moisture content (g/g db), K_1 is the rate constant, and K_2 is the capacity constant. In the equation, the symbol "±" is interpreted as "+" for absorption processes and "–" for desorption or drying.

By linearizing equation (5), we obtain:

$$\frac{t}{X_{w0}-X_w} = K_1 + K_2 t \qquad (6)$$

The graphical representation is a straight line with an intercept equal to K_1 and a slope equal to K_2.

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$$\frac{t}{X_{w0} - X_w} = K_1 + K_2 t$$

$$Y = b + aX$$

Equation 6. Determination of constants K_1 and K_2 (Paredes et al., 2012).

Similarly, weight loss is described as:

$$\frac{M_0 t}{M_0 - M} = K_3 + K_4 t \qquad (7)$$

Where M is the weight (g) at time t, $M_0$is the initial weight (g), $K_3$is related to the initial rate of weight loss, and K_4 corresponds to the equilibrium weight (Corzo et al., 2008).

3. RESULTS AND DISCUSSION

3.1 Characterization of sabila gel

3.1.1 Physicochemical characteristics

Table 1 presents the results of the physicochemical analysis of untreated sabila gel samples. The sample had a water activity (Aw) of 0.98 and a pH of 5.03. The acidity, expressed as ascorbic acid, was 0.014 g/ml. Soluble solids were measured at 3.5 °Brix. Total sugars, in a sample diluted 500 times, were 0.0129 g/ml, while reducing sugars were 0.00013 g/ml.

Table 1: Results of the physicochemical analysis of untreated sabila gel

Analysis	Average
Aw	0.98
pH	5.03 ± 0.025
Acidity %	0.014 ± 0.010
°Brix %	3.5 ± 0.5
Total sugars, ppm.	0.012 ± 0.002
Reducing sugars, ppm	0.00013 ± 0.000005

Source: Own elaboration

The pH (5.03) and water activity (Aw) (0.98) of sabila gel are primarily attributed to its content of polysaccharides, vitamins, enzymes, and steroids (Efterpi et al., 2010). According to Calzada and Pedroza (2005), the polysaccharides present in the gel include glucose, mannose, galactose, xylose, arabinose, along with tannins, steroids, and organic acids such as glucuronic, citric, succinic, and malic acids. The gel also contains enzymes such as oxidase, cellulase, catalase, and amylase,

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among others. Additionally, it contains glucose, proteins, biogenic stimulators, saponins, magnesium, lactate, and various vitamins.

3.1.2 Bromatological characteristics

As shown in Table 2, the bromatological analysis indicates that *sabila* gel contains 98.8 % moisture. This high-water content is consistent with the fact that the gel accounts for 65 % to 80 % of the plant's total weight, which is primarily made up of water (Domínguez et al., 2012). The ash content suggests that the gel may serve as a source of minerals, with the untreated sample containing 0.55 % inorganic compounds. Total nitrogen content was determined using the Kjeldahl method (AOAC, 1998), resulting in a total protein content of 0.04 %. The gel also showed a lipid content of 0.24 %. *Aloe vera* contains several carbohydrate polymers, mainly glucomannans, along with other organic and inorganic components (Kojo and Qian, 2004). In this case, the carbohydrate content was calculated by difference and found to be 0.17 %. The fiber content was low, measured at 0.2 %.

Table 2: Results of the Bromatological Analysis of Untreated *Sábila* Gel

Analysis	Average (%)
Moisture	98.80 ± 0.00084299
Ash	0.55 ± 0.00058432
Fats	0.24 ± 0.00028904
Nitrogen-based proteins	0.04 ± 5.9326E-06
Total carbohydrates	0.17
Fiber	0.2
Total	100.00

Source: Own elaboration

3.2 Physicochemical analysis

3.2.1 Acidity evaluation

As shown in Figure 1, the gel reached its highest acidity at 20 hours into the process. In both the gel and the solution, acidity showed opposite trends—increasing in the gel while decreasing in the solution. This is due to the gain of solids (GS) and moisture loss (ML) during the process, influenced by the acids naturally present in the gel and the citric acid added to the osmotic solution.

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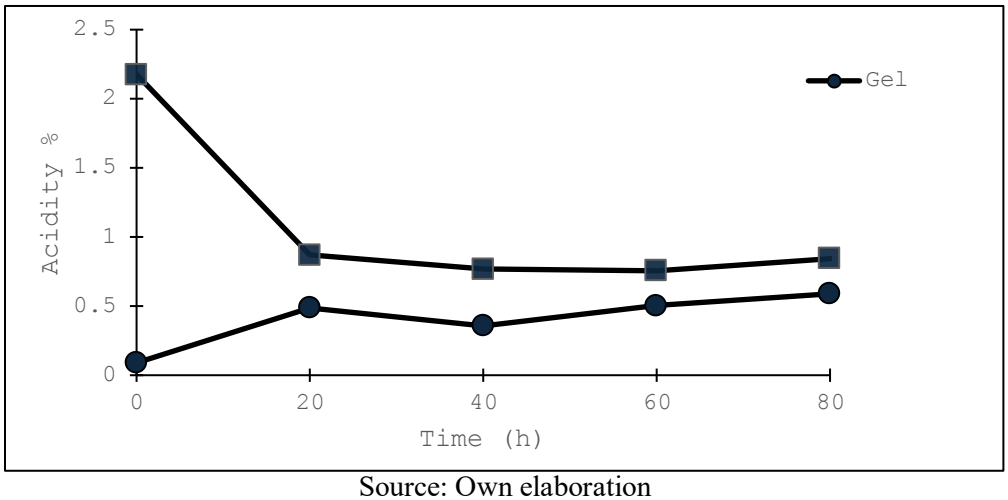

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Figure 1: Acidity kinetics of the gel and osmotic solution during the osmotic dehydration of sabila gel.

3.2.2 pH evaluation

As shown in Figure 2, the pH of the gel gradually decreases during the dehydration process, ranging from 4.5 to 3.32, while the pH of the osmotic solution increases, ranging from 2.54 to 3.28. This opposite behavior results from the diffusion of solids and liquids between the gel and solution until osmotic equilibrium is reached. The citric acid present in the solution contributes to the effective preservation of the gel by inhibiting the growth of pathogenic microorganisms.

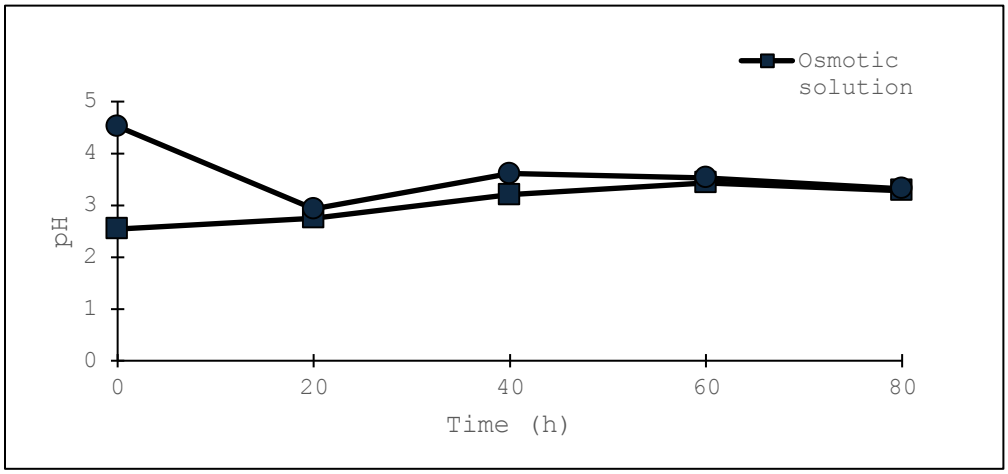

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Figure 2: pH kinetics of the gel and osmotic solution during the osmotic dehydration of sabila gel.

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3.2.3 Water activity evaluation

As shown in Figure 3, the water activity (Aw) of the gel at the end of the process was approximately 0.939. The decrease in Aw in the gel is due to water loss and solids gain, while the osmotic solution experienced an increase in water content from the gel's dehydration, reaching 0.969 by the end of the process.

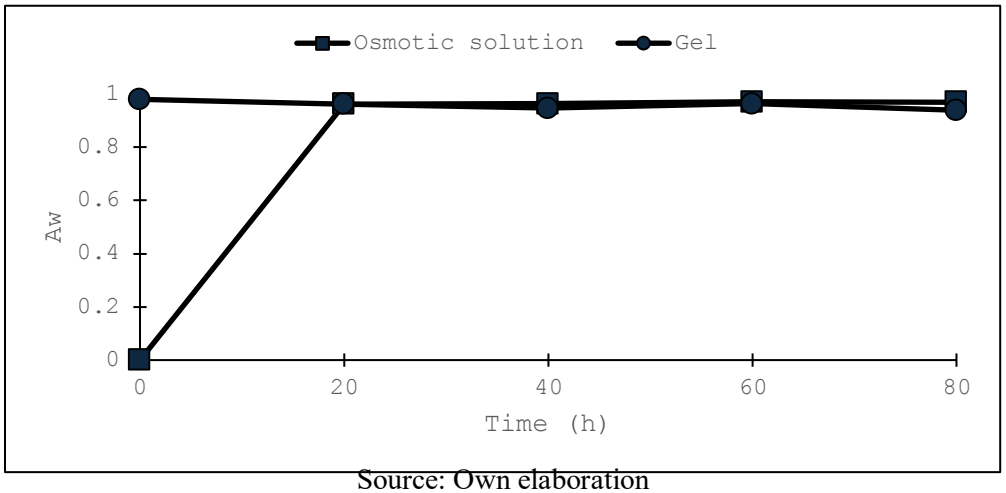

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Figure 3: Water activity kinetics of the gel and osmotic solution during the osmotic dehydration of sabila gel.

3.2.4 °Brix evaluation

Figure 4 shows that the gel reached its highest concentration of soluble solids at 80 hours, while the osmotic solution had its peak concentration at 20 hours. This occurs because, during osmosis, water is drawn out from the gel's membrane, causing solids to enter the cells. As a result, the osmotic solution gains water and loses solids. The system reached equilibrium in soluble solids concentration between 40 and 60 hours into the osmotic process.

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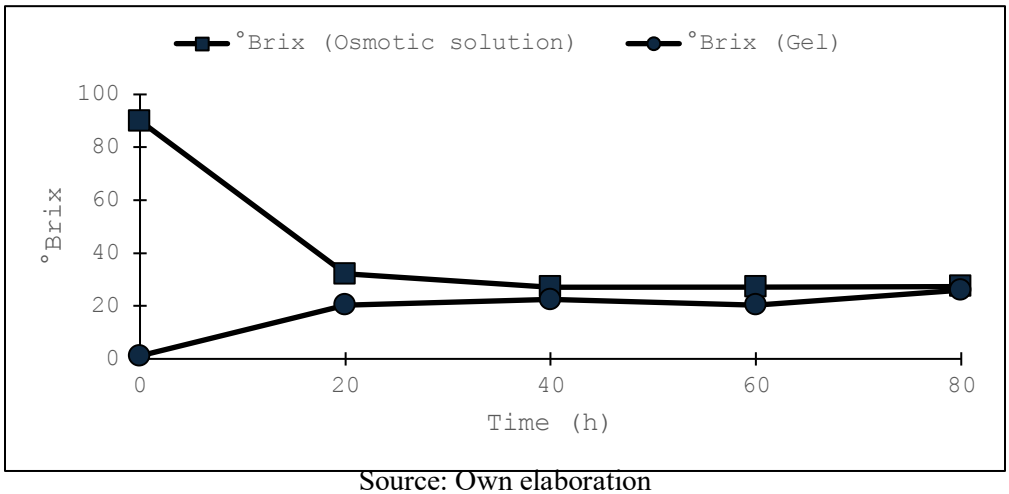

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Figure 4: Kinetics of soluble solids content during the osmotic dehydration of Aloe vera (*Aloe vera barbadensis* Miller).

3.2.5 Weight Loss in the Gel

Weight loss results for the whole sabila gel showed that 35 % of the weight was lost during the first 20 hours. In the following periods, weight loss increased to 43 %, 42 %, and 49 %, respectively. Correspondingly, the weight of the osmotic solution increased until equilibrium was reached, as shown in Figure 5.

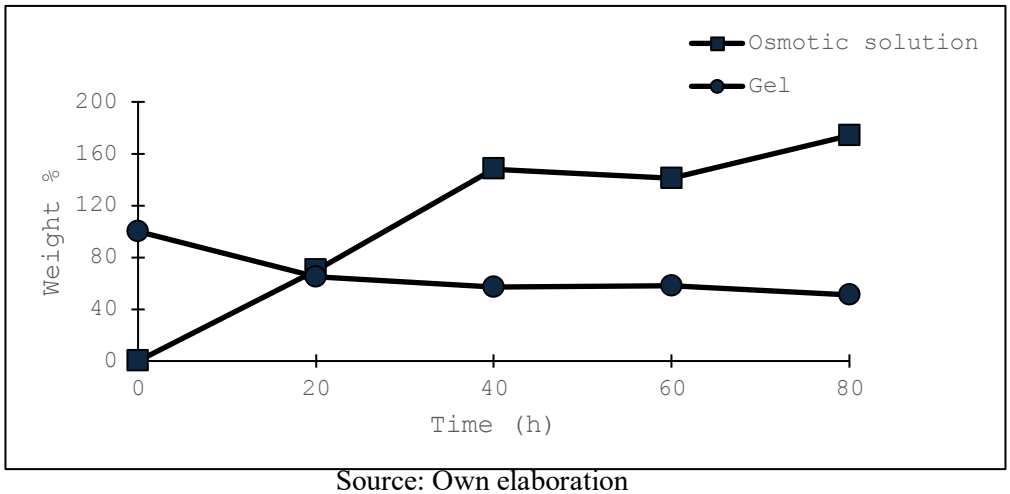

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Figure 5: Weight loss kinetics in whole sabila gel at a constant concentration.

The weight loss of the sabila gel pieces was 45 % during the first 20 hours, after which the weight stabilized, reaching a final value of 52 %.

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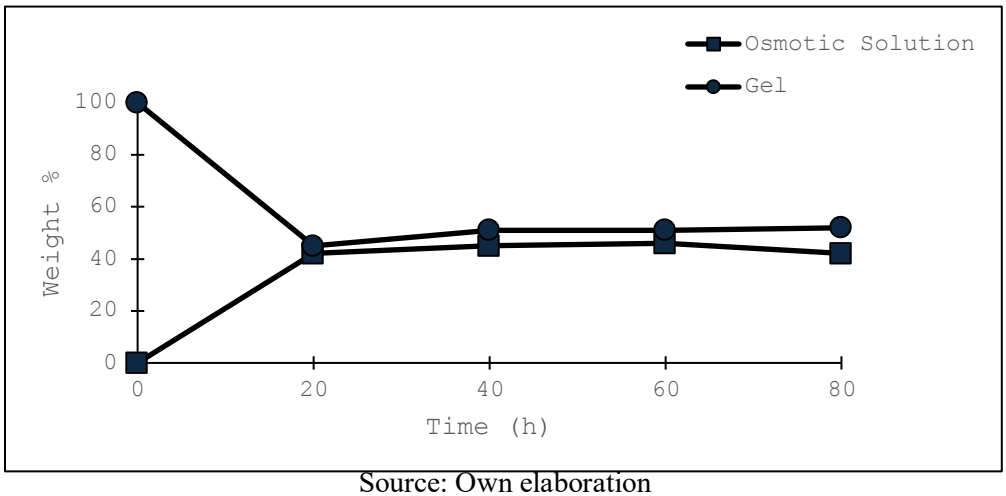

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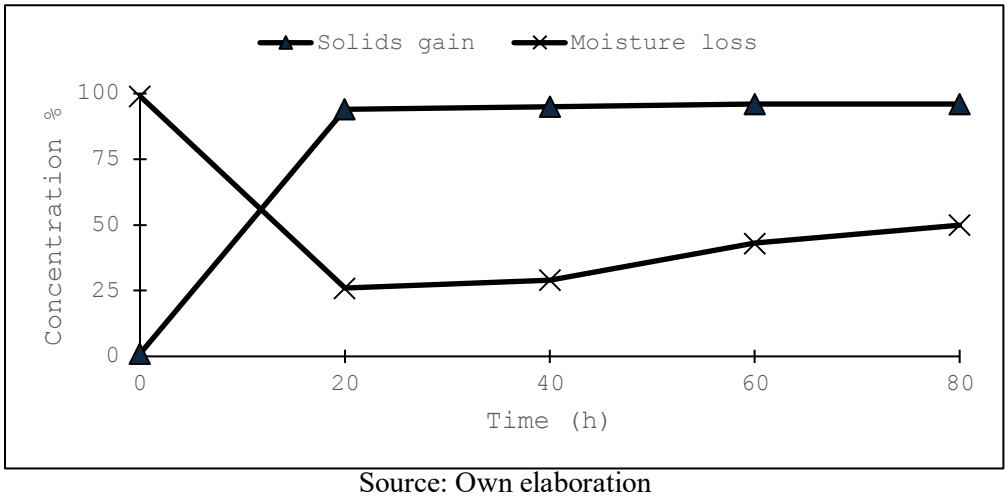
Figure 6: Weight loss kinetics in sabila gel pieces at a constant concentration.

3.3 Modeling of OD kinetics

In Figure 7, a decrease in moisture and an increase in solids are observable. Evaluating the pH results showed that the highest dehydration, a 72.68 % moisture loss, occurred within the first 20 hours. This was a notable difference compared to the other samples, which only showed moisture losses of 69.39 %, 55.71 %, and 48.67 %, respectively.



Source: Own elaboration

Figure 7: Modeling of OD kinetics over 80 hours for moisture loss (ML) and solids gain (SG).

This showed that the greatest solids gain occurred during the first 20 hours, reaching a value of 94.11 %. This is due to the osmotic process, where water exits the gel membrane, causing solids

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to enter the cells. Consequently, the Aloe vera gel loses water and gains solids. The dehydration process concludes upon reaching equilibrium, which, in this case, occurs between 0 and 20 hours.

3.4 Azuara empirical model

Table 6 presents the parameter values of the Azuara model fitted to the experimental data, along with the coefficient of determination and the mean relative percentage error (MRPE). The parameters ML and SG represent the rates of moisture loss (ML) and solids gain (SG), respectively, resulting from the osmoconvective diffusion mechanism (Kaur and Singh, 2013). Figures 7 and 8 display the graphical comparison between the experimental data and the model's predicted values.

The results of the R^2 and MRPE, along with the graphical behavior, indicate a good fit of the experimental data to the Azuara model.

Table 3: Parameters of the Azuara Model for Moisture Loss (ML) and Solids Gain (SG) in the Osmotic Dehydration of Aloe vera (*Aloe vera barbadensis Miller*) at 25 °C.

		SG Parameters				ML Parameters			
Hours	**T(°C)**	**SG∞(%)**	**β_2 (min^{-1})**	**MRPE**	**R^2**	**ML∞(%)**	**β_1 (min^{-1})**	**MRPE**	**R^2**
20	25	98.2398	1.0122	-0.2670	1	24.344	2.6828	1.0726	1
40	25	95.1144	1.1806	-0.1335	0.725	27.728	2.3639	0. 5363	0.714
60	25	96.2454	1.3332	-0.0890	0.582	40.943	2.0923	0.3575	0.401
80	25	96.5169	1.0000	-0.0667	0.489	47.613	1.9247	0.2681	0.203

Source: Own elaboration

The limiting factor for water removal from the gel is the penetration of water through the skin, as the dehydration kinetics are mainly governed by the skin's permeability (Moreira, 2000). This is why the moisture loss (ML) parameter is particularly relevant in this process. Solids gain (SG) is also an important parameter because, in some cases, its increase can be undesirable due to its association with changes in sensory properties. Additionally, a high solids gain can negatively affect water loss by forming a barrier on the product's surface. On the other hand, if the goal is to reduce weight loss to avoid significantly impacting product cost, a high solids gain may be desirable (Zapata et al., 2016).

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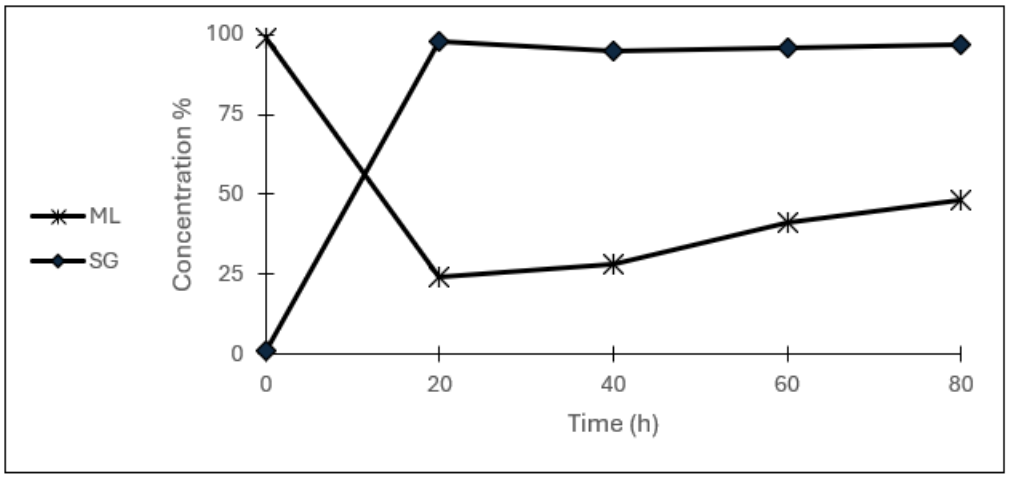

Source: Own elaboration

Figure 8: Azuara Model Prediction at 80 Hours for Moisture Loss (ML) and Solids Gain (SG).

The osmotic dehydration process was studied in terms of moisture loss and solids gain. The highest rates of water loss observed in the trials occurred at the beginning of the process, due to the greater osmotic dehydration force between the food and the hypertonic solution (Acevedo et al., 2014).

A strong effect of the osmotic solution concentration on water loss was observed. An increase in concentration results in a higher osmotic pressure gradient (and thus a decrease in water activity), which increases the driving force for water removal between the solution and the food. This leads to higher mass transfer rates and greater apparent diffusion coefficients for water (Moreira et al., 2000).

Figure 8 shows that the influx of solutes and the efflux of water occur at the highest rates during the first 10 hours, which is typical in osmotic dehydration. After this initial phase, the process rate gradually slows down. This can be explained by the chemical potential differences of the substances involved between the inside and outside of the fruit at the start. The fruit's interior has a higher chemical potential of water and a lower chemical potential of solutes compared to the external solution. These differences drive solutes into the fruit and water out of it.

Over time, the exchange of substances reduces these chemical potential differences, causing the system to move closer to equilibrium. As a result, the transfer of matter slows gradually and approaches zero as the driving force for mass transfer decreases (Arias et al., 2017).

3.5 Peleg empirical model

Table 4 shows the parameter values obtained from the Peleg model (Eq. 6), determined using the experimental data from the osmotic dehydration process. These parameters were also used to

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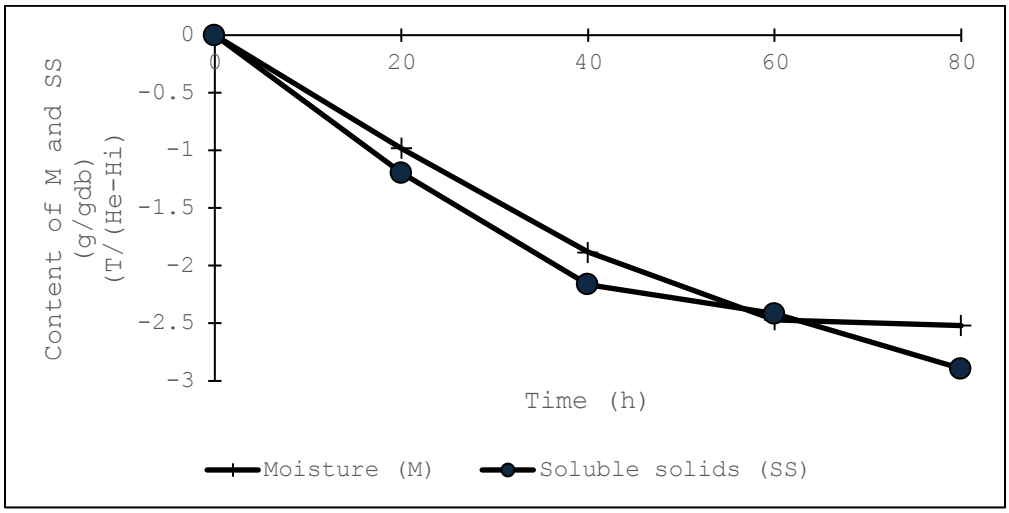
predict the behavior of soluble solids (SS) and moisture (M). The R^2 and MRPE values presented in the table indicate the goodness of fit achieved for these variables under the specified conditions. The Peleg equation provides a better overall fit for the entire process, as evidenced by higher R^2 values (Maldonado et al., 2008).

Table 4: Parameters of the Peleg Empirical Model for Moisture (H) and Soluble Solids (SS) in the Osmotic Dehydration of Aloe vera (*Aloe vera barbadensis Miller*) at 25 °C.

		Parameters SS				Parameters M			
Hours	**T(°C)**	**K_1**	**K_2**	**MRPE**	**Adjusted R^2**	**K_1**	**K_2**	**MRPE**	**Adjusted R^2**
20	25	0	-0.0597	15.4	1	0	-0.049	6.87	1
40	25	-0.0375	-0.0541	7.7	0.9964	-0.0123	-0.0472	3.43	0.9995
60	25	-0.211	-0.0411	5.13	0.9351	-0.087	-0.0416	2.29	0.9878
80	25	-0.3322	-0.035	3.85	0.928	-0.2656	-0.0326	1.71	0.9218

Source: Own elaboration

Figure 9 shows the variations in moisture (M) and soluble solids (SS) over time in sabila gel during osmotic dehydration at 25 °C. The data in the graph correspond to each mass transfer (equations 6 and 7) at a constant concentration and temperature. The correlation coefficient (R^2) values ranged from 1 to 0.928 for SS, and from 1 to 0.9218 for H, indicating that the Peleg model can effectively predict moisture and soluble solids in sabila gel under the specified conditions (Corzo et al., 2008).



Source: Own elaboration

Figure 9: Peleg model prediction at 80 hours, based on the fitted moisture (M) and soluble solids (SS) content of sabila gel (*Aloe barbadensis Miller*) osmotic dehydrated at 25 °C, according to the Peleg equation: $t/(X_{w0}-X_0) = K_1+K_2t$

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4. CONCLUSIONS

- The osmotic dehydration of sabila gel (*Aloe vera barbadensis Miller*) can be shortened to a total of 10 hours, thereby reducing costs.
- The characteristics of moisture loss, soluble solids gain, acidity, and weight loss in Aloe vera (*Aloe vera barbadensis Miller*) are improved by osmotic dehydration under the conditions of this study.
- The osmotic dehydration process under the conditions established in this study can be accurately modeled using empirical models, with the Peleg model providing the best fit.

5. SUGGESTIONS AND FUTURE PROSPECTS

This study has enabled the effective osmotic dehydration of sabila gel by successfully applying dehydration models to the process. The method uses simple, environmentally friendly conditions and does not require advanced technology. Therefore, it is recommended that this dehydration technology be scaled up for industrial use.

Dehydrating sabila gel offers several advantages, including easier transportation—since the gel is over ninety percent water—and the potential to concentrate and enhance its functional and medicinal properties.

The work would benefit from sensory and quality evaluations (texture, color, acceptability) of the dehydrated product to increase relevance for industry and consumers.

Long-term storage stability and retention of bioactive compounds after dehydration should be assessed to demonstrate practical usability.

Expanding the study to Aloe vera from diverse sources or varieties would improve generalizability and reliability of the findings.

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