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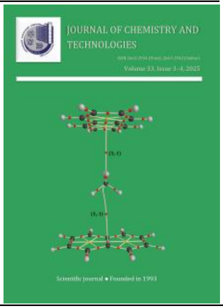

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WATER ABSORPTION KINETICS OF WHITE CHICKPEA SAMPLES IN OMAN: IMPLICATIONS FOR SUSTAINABLE FOOD PROCESSING

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Abstract

This study examines the water absorption kinetics of four samples of white chickpeas (A, B, C, and D) available in Oman, utilizing the Peleg model to evaluate their water absorption behavior. The experiments were conducted at room temperature, and the moisture content was measured at regular intervals until equilibrium was reached. The rate constant (k_1) and capacity constant (k_2) of water absorption for each sample were determined, and the model's fit was assessed using the coefficient of determination (R^2). Sample C demonstrated the highest rate of water absorption (k_1 = 0.0085) and reached equilibrium the fastest, with a near-perfect model fit (R^2 = 0.9999), making it the most efficient in terms of hydration. Sample D exhibited a similar absorption rate but with a slightly less accurate model fit (R^2 = 0.9409). Sample A showed a moderate absorption rate with a strong model fit (R^2 = 0.9911), while Sample B had the slowest absorption rate and the longest time to reach equilibrium, reflected in a lower model fit (R^2 = 0.9559). These findings provide insights into the water absorption dynamics of white chickpeas in Oman, with implications for food processing and optimization of soaking processes.

Keywords: White chickpeas; Water absorption kinetics; Soaking behavior; Peleg's model.

КІНЕТИКА ВОДОПОГЛИНАННЯ ЗРАЗКІВ ОМАНСЬКОГО БІЛОГО НУТУ: НАСЛІДКИ ДЛЯ СТАЛОГО ХАРЧОВОГО ВИРОБНИЦТВА

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Анотація

У цьому дослідженні вивчається кінетика водопоглинання чотирьох зразків білого нуту (A, B, C і D), доступних в Омані, з використанням моделі Пелега. Експерименти проводили за кімнатної температури, а вміст вологи вимірювали через рівні проміжки часу до досягнення рівноваги. Для кожного зразка були визначені константа швидкості (k_1) і константу ємності (k_2) водопоглинання, а відповідність моделі оцінювали за допомогою коефіцієнта детермінації (R^2). Зразок C продемонстрував найвищу швидкість поглинання води (k_1 = 0.0085) і найшвидше досяг рівноваги з майже ідеальною відповідністю моделі (R^2 = 0.9999), що робить його найефективнішим з точки зору гідратації. Зразок D продемонстрував схожу швидкість поглинання, але з дещо менш точною відповідністю моделі (R^2 = 0.9409). Зразок A показав помірну швидкість поглинання з точною відповідністю моделі (R^2 = 0.9911), тоді як зразок B мав найменшу швидкість поглинання й найдовший час для досягнення рівноваги, що відображено в гіршій відповідності моделі (R^2 = 0.9559). Ці результати дають уявлення про динаміку водопоглинання білого нуту в Омані, що має значення для харчової промисловості та оптимізації процесів замочування.

Ключові слова: білий нут; кінетика водопоглинання; поведінка при замочуванні; модель Пелега.

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Introduction

Chickpeas (*Cicer arietinum*) are among the oldest cultivated legumes, with a history spanning over 7,000 years [1]. Renowned for their high protein content and nutritional benefits, chickpeas are a staple in various global cuisines. They are rich in essential nutrients such as fiber, vitamins, and minerals, making them an excellent dietary choice for promoting overall health [2]. Chickpeas are typically classified into two main types: Desi and Kabuli. Desi chickpeas are smaller, darker, and have a rough seed coat, while Kabuli chickpeas are larger, lighter in color, and have a smoother texture [3]. Both varieties offer unique flavors and are used in a wide range of dishes, from salads and soups to stews and snacks. Their high protein content makes them an ideal meat substitute in vegetarian and vegan diets [4]. When paired with grains, they provide a complete protein, containing all essential amino acids. Additionally, chickpeas are a good source of dietary fiber, which aids digestion and helps maintain stable blood sugar levels. They also provide important vitamins and minerals, including folate, iron, magnesium, and zinc [5]. In Oman, chickpeas are increasingly recognized for their potential as a sustainable crop, contributing to both food security and economic growth. Although the arid climate and limited water resources in the country pose challenges for agriculture, chickpeas have proven to be resilient. They are well-suited to dry conditions and grow in various soil types, making them a valuable addition to Oman's agricultural landscape. Their resilience and increasing market demand position chickpeas as an essential crop for both local consumption and export [6–8]. As Oman continues to invest in agricultural development, chickpeas will likely play a central role in promoting food security and enhancing the livelihoods of Omani farmers [9; 10].

Structurally, chickpeas consist of several key components. The outermost layer is the seed coat (testa), a tough, fibrous layer that protects the internal seed and regulates water entry during soaking [11]. Beneath the seed coat lie the cotyledons, which are two large seed leaves that store nutrients like proteins, starches, and lipids, comprising most of the chickpea's mass. These cotyledons provide energy for the developing plant during germination [12]. Within the cotyledons is the embryo, which contains the future root (radicle) and shoot (plumule) of the plant [13]. The hilum and micropyle are small openings on the surface of the seed that facilitate water absorption. Together, these structural components support the chickpea's growth, nutrition, and water uptake during cooking and germination [14].

The water absorption mechanism in chickpeas involves a series of steps that gradually hydrate the seed, altering its texture and composition. When chickpeas are immersed in water, the seed coat first comes into contact with moisture. This fibrous layer, made of cellulose and lignin, slowly absorbs water due to adhesion forces between water molecules and the chickpea surface [15]. Over time, water penetrates the seed coat through natural pores such as the hilum and micropyle. These microscopic openings allow water to enter, though initial absorption is slow, as the seed coat acts as a semi-permeable barrier. As the seed coat softens, water gradually diffuses into the underlying layers [16]. Once water penetrates the seed coat, it begins to move into the cotyledons. Water first enters the spaces between cells in the cotyledons through diffusion, driven by the concentration gradient between the external water and the dry interior of the chickpea [17]. The cellulose and polysaccharides in the cotyledon cell walls absorb water, causing the cells to swell [18]. Osmosis then facilitates water movement across the semi-permeable cell membranes into the cell cytoplasm. As the cells absorb water, they expand, causing the visible swelling of the chickpea [19]. In the later stages of soaking, water continues to penetrate deeper into the chickpea, hydrating the outer layers first, followed by the inner layers [20]. Capillary action assists in moving water through small pores and intercellular spaces. As the soaking process continues, water absorption slows as the internal moisture levels equilibrate with the external water, reducing the concentration gradient [21]. Eventually, the chickpea reaches a state of equilibrium where it cannot absorb any more water. Throughout this process, the texture of the chickpea changes as water hydrates the starches and proteins within the cotyledons, softening the seed [22]. Prolonged soaking or soaking in warm water may cause biochemical changes such as starch gelatinization or protein denaturation, further altering the chickpea's texture and nutritional properties. At the end of the soaking process, the chickpea is fully hydrated and ready for cooking or germination [23].

Peleg's model is used to describe the kinetics of water absorption in food products like chickpeas. It provides a simple equation to predict the amount of water absorbed over time without making assumptions about specific physical processes like diffusion [24]. The model assumes a non-linear rate of water absorption, characterized by an initial rapid uptake followed by a slower, asymptotic phase. Although Peleg's model is often used for short soaking times, it does not provide detailed mechanistic insights into the underlying processes and may be less accurate for prolonged soaking durations [25,26]. Mathematical representation of the model is given in Equation (1) as follows [27]:

$$M(t) = M_0 \pm \frac{t}{k_1 t + k_2} \quad (1)$$

where M(t) is water content at time t, M_0 = Initial water content of the chickpea, k_1 and k_2 are constants related to the rate and capacity of water absorption.

Several studies have investigated the hydration behavior of chickpeas and other legumes under varying soaking conditions. For example, Turhan et al. (2002) examined the influence of soaking time and temperature on winter and spring-planted chickpea genotypes, observing that as temperature increased, the rate constant k_1 decreased while k_2 increased [28]. Shafaei et al. (2016) reported that both k_1 and k_2 declined with rising temperature in bean and chickpea varieties, highlighting varietal differences in response to soaking conditions [29]. Gowen et al. (2007) used a first-order asymptotic model and developed generalized nonlinear models to study the effects of HTST blanching on chickpea hydration across 25–60 °C, introducing uncertainty analysis in model fitting [30]. Ranjbari et al. (2013) demonstrated that ultrasound pretreatment reduced soaking time by approximately 4 hours and altered kinetic constants and leaching behavior [31]. Similarly, Bidkhori and Mohammedpour Karizaki (2022) assessed various kinetic models during chickpea soaking and cooking, identifying the two-term model as the best fit, while reporting a decrease in effective diffusivity over time [32]. Guemra et al. (2024) expanded the scope to include processing treatments like boiling, roasting, and germination, with roasting found to enhance water absorption despite reducing moisture content [33].

While these studies provide valuable insights into how physical treatments and temperature influence water absorption in chickpeas, they largely focus on commercial or well-studied varieties cultivated in different geographic regions. None have specifically examined the hydration kinetics of white chickpeas grown in Oman, which are subject to distinct agro-climatic and soil conditions. Moreover, the application of the Peleg model to this local variety under varying water temperatures and qualities remains unexplored. This study fills that gap by offering a detailed kinetic analysis using the Peleg model, tailored to Omani-grown white chickpeas, thereby contributing new empirical data and model parameters that are critical for optimizing local processing practices and enhancing food system sustainability in the region.

The novelty of this study lies in its targeted application of the Peleg model to characterize the water absorption behavior of white chickpeas (*Cicer arietinum* L.) cultivated in Oman—an area with unique agro-climatic and soil conditions. While the Peleg model has been widely employed to describe hydration kinetics in legumes, its use has not been previously documented for white chickpea varieties grown under the specific environmental conditions found in Oman. These conditions influence seed microstructure, composition, and absorption response, thereby necessitating a localized investigation. By systematically analyzing how Omani-grown chickpeas respond to variations in water temperature, water quality, and hydration time, this study provides novel empirical data and model parameters tailored to this specific variety. This localized modeling approach not only enhances the predictive accuracy for hydration behavior but also offers practical insights for optimizing cooking and industrial processing techniques, contributing to improved food resource management and food security strategies in Oman and similar arid regions. Hence, this study aimed to investigate the water absorption kinetics of four samples of white chickpeas available in Oman using the Peleg model, providing insights for food processing and optimization of soaking practices. The objectives were as follows: (i) To evaluate the water absorption kinetics of locally sourced white chickpea samples (A, B, C, and D) at room temperature until equilibrium is reached, with the aim of understanding their hydration behavior under typical pre-processing conditions; (ii) To calculate the rate constant (k_1) and capacity constant (k_2) for each sample to quantify their hydration efficiency, which are critical for optimizing traditional cooking practices, as well as industrial processes such as boiling, canning, and germination;; and (iii) To assess the goodness of fit of the Peleg model to the experimental data using the coefficient of determination (R^2), thereby validating its use for predicting hydration behavior in Omani-grown chickpeas.

Materials and methods

Sample collection and preparation. Four different samples of chickpeas were purchased from a local market in Salalah, Oman. The chickpeas from the Omani sample were used without any additional processing.

Soaking test. The soaking experiments were conducted using pure distilled water at a constant temperature, with no additives, for each of the four samples: A, B, C, and D. The containers and distilled water were maintained at room temperature prior to the experiments. For each sample, five g of chickpeas were randomly selected, weighed, and placed in glass beakers containing 200 mL of distilled water. At the end of every hour, the chickpeas were removed, excess water was blotted off using tissue paper, and the samples were reweighed. The density of the distilled water was monitored to track the amount of dissolved solids. Moisture content changes for each sample were calculated by comparing the mass of the chickpeas before and after water absorption. This process was repeated at one-hour intervals until equilibrium was reached. The samples were weighed using a precision electronic balance. All tests were performed in triplicate to reduce error, and the average value was recorded as the final result.

Data analysis. The experimental data for each sample were fitted to the Peleg model, which was applied to the time interval from the start of soaking to equilibrium. Since the samples used were moisture-free, M_0 becomes zero, and Equation (1) for water absorption is modified to Equation (2) as follows:

$$M(t) = \frac{t}{k_1 t + k_2}. \quad (2)$$

After linearization, Equation (2) is modified to Equation (3) as follows:

$$\frac{t}{M(t)} = k_1 t + k_2. \quad (3)$$

Microsoft Excel was used to calculate the Peleg model coefficients for each sample using linear fit. The goodness of fit between the experimental and predicted values was determined using the coefficient of determination (R^2), calculated as the ratio of the sum of squares of model (MSS) to the total sum of squares (TSS), as given in Equation (4).

$$R^2 = \frac{MSS}{TSS} \quad (4)$$

Results and discussion

Effect of time on mass of chickpeas for samples:

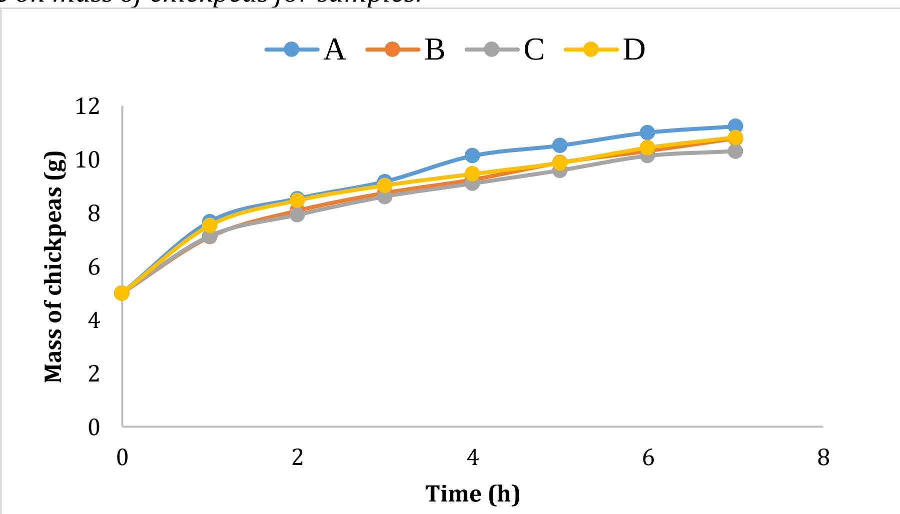

Fig. 1. Change in mass of white chickpea samples (A, B, C, and D) over soaking time at room temperature, illustrating differences in water uptake kinetics

Figure 1 illustrates the water absorption kinetics of four chickpea samples (A, B, C, and D) over a soaking period, with time (in h) represented on the X-axis and the mass of chickpeas (in g) on the Y-axis. The study tracks the changes in mass as a result of water uptake, which is crucial in understanding the hydration behavior of each chickpea sample during soaking. The chickpeas were soaked for approximately 7 h, with the mass increasing as they absorbed water over time. Initially, all four samples exhibit a rapid increase in mass within the first two h, indicating a fast water absorption phase. This steep rise is most pronounced for Sample A, which shows a sharp increase in mass from around 6 g to over 9 g during this period. Samples B, C, and D follow a similar trend, though Sample C shows a slightly slower rate of absorption compared to the others. By the end of the second hour, Samples B, C, and D reach masses of approximately 8–9 g. The initial water uptake is driven by the hydrophilic properties of the seed coat and the large concentration gradient between the dry seed and the surrounding water.

As time progresses beyond two hours, the water absorption rate begins to decelerate for all samples. This phase of slower water uptake is reflected by a more gradual rise in mass between 2 and 4 h. For Sample A, the mass increases to just above 10 g, whereas Samples B, C, and D reach values between 9 and 10 g. The reduction in absorption rate during this phase can be attributed to the diminishing concentration gradient as the internal moisture content of the chickpeas increases. After 4 h, the water absorption approaches equilibrium, as indicated by the flattening of the curves for all samples. By the 6th h, Sample A reaches a final mass of approximately 11.5 g, indicating that it absorbs the most water out of all the samples. Samples B and D display very similar behavior, with both reaching around 10.5 g by the end of the soaking period. Sample C, on the other hand, absorbs the least water, stabilizing at around 10 g. This suggests that Sample C may have a less permeable seed coat or different physical properties compared to the other samples. The equilibrium phase occurs when the chickpeas have absorbed as much water as their internal structures can accommodate, and the mass no longer changes significantly. By this point, the moisture content has equalized between the chickpeas and the surrounding water, resulting in minimal further absorption. The differences in the final mass of the samples may indicate variations in the structural integrity, seed coat thickness, or porosity of the different chickpea varieties.

In summary, Sample A absorbs the most water, followed by Samples B and D, with Sample C absorbing the least. This data is essential for understanding the soaking characteristics of different chickpea samples, particularly for food processing and preparation where hydration affects texture and cooking time. The results also highlight the importance of selecting chickpea varieties based on their water absorption behavior, especially in applications where rapid or maximum water uptake is desired.

Effect of time on percentage moisture content for samples.

Figure 2 represents the moisture content (%) of four chickpea samples (A, B, C, and D) over a period of 7 h, with time along the X-axis and moisture content (%) on the Y-axis. The moisture content increases as chickpeas absorb water over time, which is a critical aspect of their hydration behavior during soaking. In the first two hours, all four samples exhibit a rapid increase in moisture content, as shown by the steep slopes of the curves. Sample A shows the fastest water uptake, with moisture content rising from 0 % to about 100% within this short period. Samples B, C, and D display similar trends, although Sample C appears to absorb water at a slightly slower rate compared to the others. By the end of the second hour, Samples B and D have moisture contents of around 80–90 %, while Sample C lags slightly behind at approximately 70 %. This initial rapid water absorption phase is a result of the large moisture gradient between the dry chickpeas and the surrounding water. The seed coat and internal structures of the chickpeas allow water to diffuse quickly, resulting in significant moisture gain during this period. The high rate of absorption is critical for food processing, where shorter soaking times are preferred.

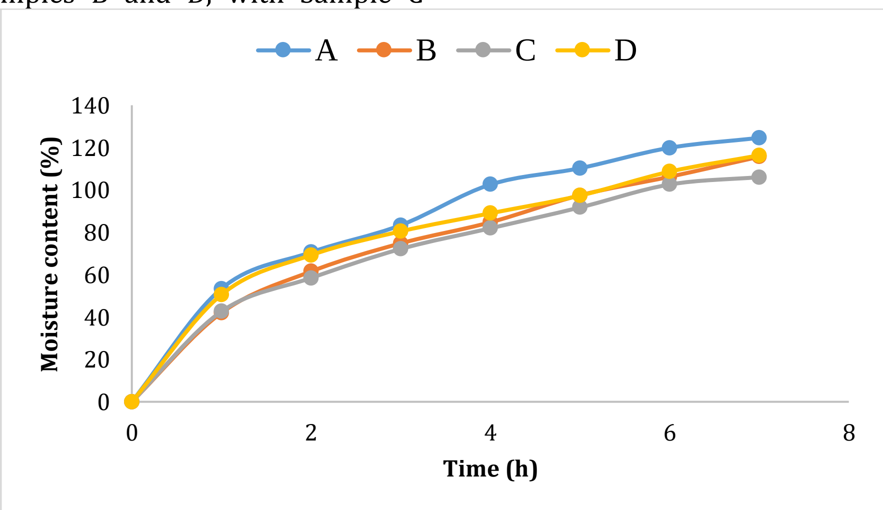

Fig. 2. Percentage moisture content of white chickpea samples (A, B, C, and D) during soaking, showing the hydration progress until equilibrium is reached

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After the initial two hours, the rate of water absorption starts to slow down for all samples, as indicated by the more gradual increase in moisture content between 2 and 4 h. Sample A continues to lead in water absorption, with its moisture content approaching 120 % by the 4-h mark, while Samples B and D follow closely at around 100 %. Sample C continues to absorb water more slowly, with its moisture content reaching only around 90 % by this time. The slower absorption rates at this stage are due to the decreasing concentration gradient as the internal moisture content of the chickpeas increases. From 4 h onwards, the absorption rate further decreases, and the moisture content begins to approach equilibrium. By the 6th h, Sample A has the highest moisture content, reaching about 130 %, while Samples B and D exhibit similar moisture contents of around 110–115 %. Sample C, again showing the slowest absorption rate, stabilizes at around 105 % moisture content by the 6th h. The approaching equilibrium suggests that the chickpeas have nearly reached their maximum water-holding capacity, with minimal additional absorption occurring after this point. By the 7th h, the moisture content for all samples has plateaued, indicating that equilibrium has been achieved. Sample A, with the highest moisture content at around 135 %, shows the greatest water absorption capacity, followed by Samples B and D, which reach approximately 120 %. Sample C, with a final moisture content of about 110 %, absorbs the least amount of water, likely due to differences in its seed coat structure or internal properties.

In summary, Sample A absorbs the most water over the soaking period, while Sample C absorbs the least. The differences in moisture content between the samples suggest variations in their physical and chemical properties, which could affect their performance in different food processing applications. Understanding the moisture absorption characteristics of chickpeas is important for optimizing soaking times and improving the efficiency of food preparation processes.

Fitting of Peleg model and data analysis:

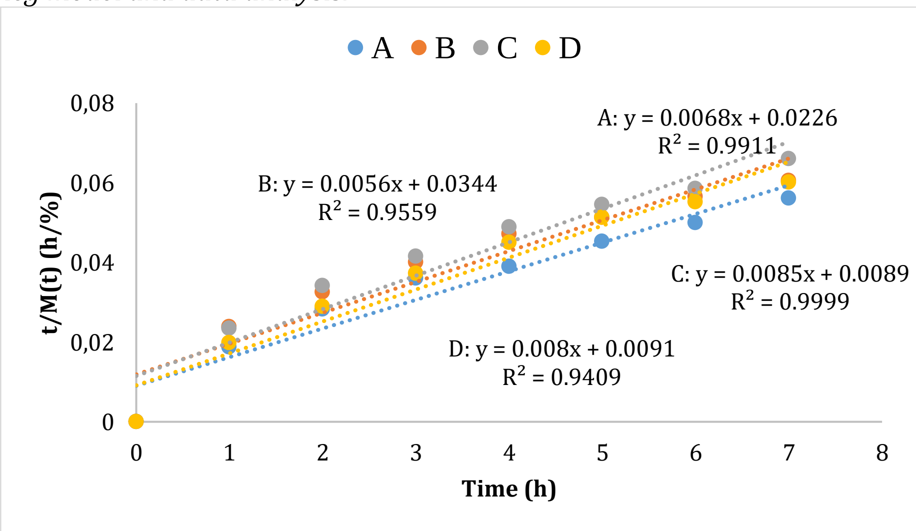

Fig. 3. Fit of the Peleg model to experimental water absorption data for white chickpea samples grown in Oman, demonstrating the model's suitability in describing hydration kinetics

Table 1

Peleg model constants k_1 (rate constant) and k_2 (capacity constant) for white chickpea samples (A, B, C, and D), with coefficients of determination (R^2) indicating model fit quality

sample	Rate constant of water absorption k_1 (1/%)	Capacity constant of water absorption k_2 (h/%)	R^2
A	0.0068	0.0226	0.9911
B	0.0056	0.0344	0.9559
C	0.0085	0.0089	0.9999
D	0.008	0.0091	0.9409

Figure 3 shows the fitting of Peleg model for samples. Table 1 presents key parameters from the Peleg model, showing the rate and capacity constants of water absorption (k_1 and k_2) for four samples of chickpeas (A, B, C, and D), along with their coefficient of determination (R^2), which indicates how well the model fits the experimental data. For Sample A, the rate constant of water

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absorption (k_1) is 0.0068, indicating that it absorbs water at a moderate rate compared to other samples. The capacity constant (k_2) is 0.0226, meaning it reaches its water absorption capacity relatively steadily over time. With a higher R^2 value of 0.9911, the Peleg model shows an excellent fit to the experimental data for Sample A, signifying that the model accurately predicts the water absorption kinetics of this chickpea sample. This suggests Sample A is fairly predictable in terms of how much water it absorbs over time. Sample B has a slightly lower rate constant (k_1 = 0.0056), meaning it absorbs water at a slower pace compared to Sample A. Its capacity constant (k_2) is higher, at 0.0344, indicating it takes more time to reach its full water absorption potential. The R^2 value of 0.9559, though still good, is slightly lower than Sample A, suggesting that the model fits Sample B's absorption data less precisely. This slower absorption rate and longer time to equilibrium could affect processing strategies where rapid water absorption is desirable.

Sample C exhibits the highest water absorption rate, with a k_1 value of 0.0085, meaning it absorbs water more rapidly than any other sample in the study. Its capacity constant (k_2 = 0.0089) is the lowest among all samples, suggesting it reaches its absorption capacity the fastest. Notably, the R^2 value of 0.9999 reflects an almost perfect fit between the experimental and predicted values, making Sample C the most predictable and reliable in terms of water absorption behavior. This sample's rapid absorption rate and excellent model fit make it particularly efficient for applications requiring quick hydration. Sample D also demonstrates a relatively high rate of water absorption, with a k_1 value of 0.008, comparable to Sample C. Its capacity constant (k_2 = 0.0091) is slightly higher than that of Sample C, indicating it absorbs water just a bit slower but still faster than Samples A and B. However, the R^2 value of 0.9409 is the lowest among all samples, indicating the model's fit is slightly less accurate for Sample D compared to the others. While it absorbs water quickly, the predictability of its absorption behavior may not be as precise as with other samples. In summary, Sample C stands out as the fastest in water absorption and has the most accurate model prediction, followed closely by Sample D. Sample A exhibits a moderate rate of absorption with a strong model fit, making it reliable though not as fast. Sample B, while still fitting the model well, has the slowest absorption rate and takes the longest time to reach equilibrium. These distinctions between samples highlight important considerations for selecting chickpeas in food processing, where water absorption rates can affect soaking times and overall processing efficiency.

The discussion is summarized as follows:

a) A comparative analysis of the Peleg rate constant k_1, which inversely reflects the initial rate of water absorption. Lower k_1 values observed in sample B, for instance, indicate faster initial hydration, making it more suitable for time-sensitive processing such as quick soaking or industrial pre-treatment operations.

b) A discussion on the Peleg capacity constant k_2, which relates to the water-holding capacity at equilibrium. Higher k_2 values in sample D suggest lower equilibrium moisture content, which may affect final texture and yield during cooking or canning.

c) An exploration of how the variation in seed morphology, seed coat thickness, and regional cultivation practices could account for the observed differences in kinetic behavior between the samples.

d) Practical implications: faster-hydrating varieties (low k_1) can reduce energy and time costs in food processing; samples with higher hydration capacity (low k_2) may be better suited for applications requiring soft texture or higher water retention, such as hummus or canned chickpeas.

Conclusion

The analysis of water absorption kinetics for the four chickpea samples revealed distinct differences in hydration behavior, which directly impact their suitability for various food processing applications. Sample C exhibited the highest rate of water absorption and the strongest fit to the Peleg model, indicating both efficiency and predictability in soaking performance. Sample D also demonstrated a rapid absorption rate, but with slightly lower model conformity, suggesting some inherent variability that may need to be considered in large-scale applications. Sample A showed moderate absorption behavior with a reliable model fit, making it a stable and consistent choice for standard processing methods. In contrast, Sample B had the slowest absorption rate and took the longest time to reach equilibrium, implying the need for extended soaking durations that may reduce processing efficiency. These findings underscore the practical importance of understanding and selecting chickpea varieties based on their water absorption kinetics to optimize soaking procedures, improve energy and water usage, and enhance product consistency in both traditional and industrial food preparation contexts. Future research should focus on further physicochemical characterization of the chickpeas, including seed coat thickness, porosity, and microstructure, may assist explore the observed differences in hydration behavior.

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