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|RESEARCH ARTICLE

Effects of native and defatted Julie mango kernel flour on bread staling kinetics and physical properties: Optimizing wheat flour substitution for enhanced shelf life

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|Abstract

Defatted mango seed flour (DMSF) is a natural ingredient derived from mango fruit kernels. This flour is vegan, gluten-free, and protein-rich, presenting potential applications in bread formulation and dietary supplements. However, concerns remain regarding flavor characteristics and anti-nutritional factors, while processing optimization requires further investigation. This study examined the effects of partial wheat flour substitution with native and defatted Julie mango kernel flour on bread physical properties and shelf-life stability. Breads were prepared with substitution levels ranging from 0% to 10% and evaluated for baking loss, specific volume, moisture content, and crumb firmness over five days of storage. Native mango kernel flour reduced baking loss and maintained specific volume up to 7.5% substitution, whereas defatted flour immediately decreased loaf volume. At 5% substitution, native flour significantly reduced staling rate and enhanced crumb moisture retention. Conversely, defatted flour accelerated staling, likely due to enzyme inactivation and lipid removal during processing. Crumb firming kinetics followed the Avrami model, with native flour reducing staling rates by up to 5%. Bread shelf-life, based on crumb firmness criteria, ranged from 24 to 86 hours depending on substitution level and flour treatment. Results demonstrated that partial substitution with native Julie mango kernel flour enhanced bread quality and shelf stability, with optimal performance at 5% substitution. However, delipidation negatively impacted both bread characteristics and shelf-life. These findings demonstrate the potential of native mango kernel flour as a functional ingredient in bread production, offering improved nutritional value while maintaining acceptable quality parameters.

Keywords: Julie" mango kernel flour | Bread staling | Wheat flour substitution | Starch retrogradation

1|Introduction

Following the baking process, all bakery goods experience a sequence of chemical and physical transformations referred to as staling (Cauvain, 1998). Oxidation results in a decrease in product freshness and quality during storage.

Staling is primarily characterized by the gradual hardening of bread due to starch retrogradation, macromolecular interactions leading to chain entanglements, and the movement of moisture from the crumb to the crust. The studies conducted by Rosell & Gomez (2007), Mandala et al. (2007), and Mandala & Sotirakoglou (2005) have demonstrated that an increase in the water content of bread crumb slows down the process of staling due to its plasticizing effect. In their study, Baik et al. (2003) successfully prevented bread staling by using low-amylose flours. In addition, amylases decrease the likelihood of starch retrogradation by breaking down the osidic bonds in starch. This process helps to slow down the staling of bread (Goesaert et al., 2009; Gray & Bemiller, 2003). Saturated fatty acids coat starch and gluten thus preventing migration of water and slowing starch retrogradation, thereby maintaining soft texture. Polyphenols are also known to be protective for fats and proteins due to their antioxidant activity. In addition, they form complexes with starch which inhibit retrogradation. Together, they help to maintain the texture or flavor of the food and increase the shelf-life of the product (Smith & Johansson, 2004; Smits et al., 2003; Wu et al., 2009).

Studies indicate that mango kernel flour (MKF) typically has an amylose content of less than 20%, which is beneficial for improving the texture and shelf-life of baked products. Lower amylose levels contribute to reduced retrogradation and staling in starch-based foods (Vihishima et al. 2024). MKF exhibits a significant water absorption capacity, which aids in retaining moisture in baked goods, thereby delaying staling. This characteristic is crucial for maintaining the freshness and palatability of products such as bread and pasta (Vihishima et al. 2024). The presence of saturated fatty acids and phenolic compounds in MKF enhances its functional properties. These compounds are known for their antioxidant properties, which can help in maintaining the quality of food products over time (N'Guessan et al. 2023; Yee and Mohamad 2021). The enzymatic activity associated with MKF can further contribute to its anti-staling effects. Amylases break down starches into simpler sugars, which can improve texture and prolong freshness by preventing the hardening of baked goods (Ikechukwu et al. 2024). Therefore, substituting wheat flour with mango almond flour would effectively mitigate bread staling. The substitution of ingredients in bread-making is expected to have a significant impact on the physical properties of the bread, especially in terms of its volume and the distribution of water between the inner part and the outer crust. This conclusion is based on the research conducted on bread-making using different types of flours (Axford et al., 1968; Balla et al., 1999; Menon et al., 2014; Vittadini & Vodovotz, 2003). Under these circumstances, and taking into account the recent work of Zomegni et al., (2022) on the composition and functional effect of mango (*Mangifera indica* L.) almond flours on the rheology of wheat dough, the current article seeks to examine the physical attributes and storage modes of breads made from a combination of wheat and mango "Julie" almond flour.

2|Materials and methods

2.1| Origin and processing of the sample

The "Julie" mango variety (Figure 1), which is extensively cultivated and consumed in the savannah zone of northern Cameroon, was collected from two peri-urban orchards in Maroua, the capital of the Far North region of Cameroon. The fruits, harvested when they reached their optimal ripeness were carefully stripped of their skin and pits, and the stones were extracted using knives. The two cotyledons of the shelled almonds were isolated and dehydrated in an electric forced-convection dryer at a temperature of 40°C ± 1°C for a duration of 72 hours, until the remaining water content was less

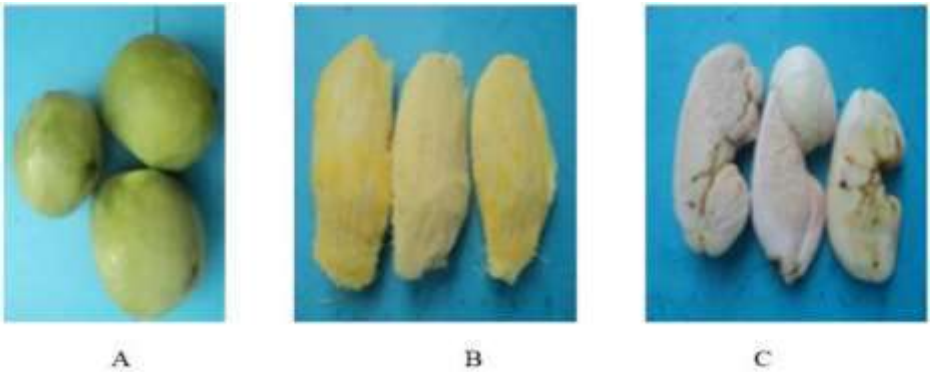

Figure 1 (A-C): "Julie Mangifera indica variety, with pits and kernels used

than 10 % (The specific 10% threshold represents a critical point below which most spoilage microorganisms cannot grow effectively, making it a widely accepted standard in food processing for dried ingredients intended for flour production or long-term storage).

The desiccated kernels were subsequently pulverized using a Culatti hammer mill (Janke and Kunkel), sifted through a 200 µm mesh filter, and divided into two groups: one group remained unprocessed, while the second group underwent delipidation through hexane oil extraction using Soxhlet (UICPA, 1979). Following fat extraction from mango kernels, the resulting flours were dried in a ventilated oven at 70°C for 30 minutes to ensure complete removal of solvent residues. Commercial wheat flour (Pelican Rouge brand, La Pasta S.A.) was purchased from Ngaoundere market, representing a brand commonly utilized by local bakers in the region. The composite flours, consisting of wheat and Julie mango kernels, were formulated by manually dry-mixing them on a plate for one minute. The mixture was then turned, similar to the winnowing process, to ensure that it was evenly mixed. The substitution ratios of wheat using native and defatted mango kernel flours were as follows: 0%, 2.5%, 5%, 7.5%, and 10%.

This was done based on the work of Zomegni et al., (2022), which showed through alveographic analyzes that a substitution of up to 10% of wheat with mango almond flour is likely to be used appropriately in bread making, given the potential reduction in staling. For the bread preparation experiments, tap drinking water from "Société Camerounaise des Eaux (CDE)", culinary salt made and distributed by "Société Camerounaise de Purification de sel", and baker's yeast (Saccharomyces cerevisiae) (Saf-Instant France) was used.

2.2| Determination of process factors

The French baguette processing method was employed. Prior to implementation, process parameters were established through preliminary trials based on existing literature and consultation with expert bakers. Substitution of wheat flour with non-wheat flour typically alters dough rheological properties due to compositional differences in the composite flour. Consequently, specific process parameters require optimization (Shittu et al., 2007).

2.2.1| Parameters for kneading

The Severin mixer shown in Figure 2 has a dough capacity of 1.5 kg, rated power of 1500 W, and variable speed control with twelve discrete settings

(V1-V12). The kneading element consists of a stainless-steel hook that rotates helically within a stationary stainless-steel bowl.

Figure 2: Severin mixer

Speeds of the kneader

The machine does not provide information about its speeds in rpm, nor is this information included in the supplied data sheet. To determine the speeds, we used a tachometer which allowed to measure the number of revolutions within a one-minute time interval for each speed point V. Five measurements were conducted for each data point, and the average value plus or minus the standard deviation was calculated and recorded in Table 1.

Table 1: Severin mixer speed indicator

Gear markers (Positions)	Speeds (rpm)
1	18 ± 1
2	31 ± 1
3	43 ± 3
4	58 ± 4
5	71 ± 5
6	84 ± 5
7	95 ± 6
8	110 ± 6
9	132 ± 7
10	156 ± 6
11	175 ± 8
12	196 ± 10

Table 2: Moisture content of wheat – Julie mango almond flour blends

Wheat substitution ratio (%) 33	Hydration ratio of composite paste (%)	
	Wheat - Julie's native almond	Wheat - Julie's defatted almond
0.0	60.0	60.0
2.5	61.5	62.0
5.0	63.0	64.0
7.5	64.5	66.0
10.0	66.0	68.0

Selection of velocities

There are three distinct forms of kneading: conventional, enhanced, and intensified. The kneading method selected for our investigation was enhanced kneading, a frequently employed technique in the production of traditional French breads. This method consists of two steps, as described by Feillet (2000).

Based on initial experiments, we selected a speed of 43 rpm (position 3 on the mixer) for the first stage. This speed was used for 5 min to break and knead the components, ensuring optimal mixing and absorption of water by the gluten and starch in the flour. The experiment used the visual perception of the dough's homogeneity as a criterion for determining the appropriate speed and duration.

The second phase, involving the texturing of the dough, was conducted at a high velocity of V2= 95 rpm (position 7 on the mixer) for a duration of 10 minutes. The selection of these values was based on the rheological qualities observed during this stage, which were evaluated through tactile and visual assessment (smooth, non-sticky dough).

Hydration ratio

Initial experiments using the baker's fingertips allowed to determine the hydration ratio for kneading by comparing the proportions of wheat flour and mango almond flour, in order to attain a consistent dough texture. The dough consistency utilized as a reference in this investigation was that of a 60% hydrated wheat flour dough, commonly referred to as bastard dough. The hydration ratio used for our wheat-mango almond mixtures, determined by the reference consistency, are provided in Table 2.

2.2.2| Parameters of fermentation

The yeast dose was 2% of the flour based on a literature review (Guinet, 1979; Namoune, 1996). The fermentation process was conducted at room temperature, specifically at 25±2°C, in a closed chamber. The process was divided into two periods. The first period, called "pointage", lasted for 30 min and took place in a ball. The duration of the second fermentation period, also conducted in the mould, was determined based on preliminary tests of dough rise kinetics during fermentation, using the modified method of Havet et al. (2000). A 100 g doughball, with a thin Polyvinyl chloride (PVC) disk placed on top, was compressed at the bottom of a 50 mL measuring cylinder. The disk, which moves horizontally as fermentation advances, serves as a gauge of the dough's degree of expansion. The fermentation duration selected was 90 minutes, which corresponds to the average time required for the dough to ceases increasing in volume.

2.2.3| Baking parameters

The baking temperature was set at 220°C following Lecoq (1965). Preliminary experiments confirmed this temperature as optimal, and the baking duration was subsequently determined. A baking time of 50 minutes was required to achieve crust coloration comparable to commercially available breads. Optimal color development was assessed through visual evaluation by an experienced baking technician.

The bread-making protocol was chosen based on the process parameters. The mass of kneaded dough was adjusted to 450 g to align with the equipment's performance for producing a loaf. Once the dough was kneaded, it was shaped into a spherical form and allowed to undergo fermentation at a temperature of 25±2°C for a duration of 30 min. After shaping the dough directly in the mold, it was then placed in a closed room for 90 min, which is the second step of fermentation or priming. The baking process took place in an electric oven at a temperature of 220°C for a duration of 50 min, without the use of steam injection. After being taken out of the oven, the loaves were removed from their molds and permitted to get cold again for 120 min before analysis. The breads were cooled and stored in low density polyethylene plastic films at a temperature of 22±2°C at a relative humidity of 78.60±4.25%. This allowed the loaves to attain a state of hydrothermal equilibrium with the surrounding environment.

2.3| Physico-chemical study of doughs and breads

2.3.1| Evaluation of water loss during baking

The mass loss (ML), which accounts for the reduction in weight throughout the cooking process, was determined using the following formula:

$$M_L(\%) = \frac{dough\ mass - bread\ mass}{dough\ mass} \times 100 \quad (1)$$

The mass of the bread was measured following the proving period, whereas the mass of the dough was determined to be 450 g (because the weight of the bread dough affects the baking time), which is calculated as the combined mass of all the dough pieces.

2.3.2| Measurement of the volume of a loaf and its specific volume

The loaf volume was determined using the modified AACC (2000) method, which involved measuring the volume of sorghum seeds with a diameter of 3.50±0.50 mm.

A receptacle greater in size than the bread was filled with sorghum grains. The measurement involves partially emptying the container of its grain, then placing the loaf in the container and topping it with the previously removed grains. Once the surface of the container is leveled using a flat ruler, the surplus spherical grains are collected. Their volume, denoted as V in cm^3, was measured using a graduated cylinder and was equivalent to the volume of the loaf. The specific volume of the bread (Vsb), measured in cm^3/g, was calculated by dividing the volume of the bread (Vb) by its mass (Mb) in grams.

$$V_{sb}\left(cm^3/g\right) = \frac{V_b}{M_b} \quad (2)$$

2.4|Staling kinetics

2.4.1| Analysis of the moisture content in the crumb and crust

The moisture content of the crumb and crust was measured using the AOAC (1990) method. The crust of the bread was defined as a 3 mm thickness from the outer surface, while the crumb samples were taken from the central portion of the loaf. A total of 5 grams were used for each analysis, conducted at 0, 24, 48, 72, 96, and 120 h, to evaluate the interaction of water between the crumb and crust during bread preservation.

2.4.2|Ability of a texturometer to withstand compression

The crumb's compressive strength was quantified using an LRFA Brookfield (USA) texturometer (Figure 3). This apparatus facilitates the performance of compression tests on a 25 mm-thick slice of bread.

Figure 3: Texturometer LRFA Brookfield (USA)

The tests are conducted using a flat-ended cylindrical probe with a diameter of 35 mm, which moves at a speed of 1 mm/s. These tests adhere to the AACC (1984) method. The peak load is the amount of force needed to decrease the thickness of the sample by a maximum of 40% from its original value. It is employed to characterize the product by instrumental measurement and to track variations in crumb softness over time. This parameter enables effective discrimination among different bread types and correlates closely with sensory evaluations conducted during mastication prior to swallowing (Balla et al., 1999). Measurements were acquired from three radial slices located in the center of the bread, using a serrated knife. The thickness of the slices was measured using a ruler with centimeter markings (2.5 cm). A square was employed to achieve uniform thickness and provide a level surface for the bread slice. A marker was used to indicate the cutting positions for slice preparation.

Compression measurements were conducted at 0, 24, 48, 72, 96 and 120 h on the bread slices without any change or alteration. The loaves were stored at an ambient temperature of 25±2°C in low-density polyethylene bags. The compression force (F), denoted in Newton (N), was determined by the equation:

$$F(N) = M \times g \qquad (3)$$

The F number represents the maximum compressive force or hardness, measured in Newtons

(N). M represents the mass of the load causing compression, measured in kilograms (Kg), as indicated by the texturometer. g represents the gravitational constant, which is 9.81 Newtons per kilogram (N/Kg).

2.5| Monitoring starch retrogradation in Julie mango kernel almond breads

The Avrami (1940) model, which is derived from the retrogradation of crumb starch, is commonly employed to characterize the kinetics of bread hardening during storage. Equation 4, in the form of a dimensionless ratio (FR), represents the progression of crumb hardening as a function of time.

$$FR = \frac{F_\infty - F_t}{F_\infty - F_0} = \exp(-k \times t^n) \qquad (4)$$

F0, Ft, and F∞ represent the crumb firmness at the initial time, t, and infinite time, respectively. The rate constant is denoted as k, and "n" represents the crystal development index in the crumb during staling.

In this model, n-values approaching unity indicate that crumb firming results primarily from starch retrogradation-induced crystal formation. This has been shown in studies by Kim & D'Appolonia (1977), MacIver et al. (1969), and Axford et al. (1968). On the other hand, when other chemicals are involved in crystal formation, the value of "n" is more than

The Avrami model is applicable when crumb firmness measurements are taken at equilibrium, extending to infinity. However, in our study, this condition was not met. Indeed, we took into account the threshold value of the crumb compression force, which is set at 15 N, as the maximum acceptable limit for breads (Randriamiharison, 1984). Once the compression force reached 15 N, we determined that the bread was no longer edible. We then conducted one or two measurements to reflect the preservation of the loaves for 5 days. These data were used to estimate the apparent force of compression as it approaches infinity in this study. Within this framework, these data provide relative rather than absolute values for staling rates (k) and crystal growth indices (n).

2.6| Data processing

Measurements were performed in triplicate, and results are reported as mean ± standard deviation. Data were analyzed using Analysis of Variance (ANOVA) to evaluate the effects of flour processing type, wheat substitution level, and storage duration on the measured responses. Duncan's multiple range test was subsequently applied to identify significantly different means ($p < 0.05$).

3| Results and discussion

3.1| Impact of Julie mango kernel flour on some bread properties

Figure 4A demonstrates the relationship between water loss and mango kernel flour substitution level. Water loss increased significantly with increasing mango flour proportion, with dough containing 10% mango kernel flour exhibiting the highest baking loss.

Nevertheless, mango kernel flour incorporation induced some structural stress within the gluten matrix.

Figure 4B illustrates the relationship between specific volume and substitution level. At substitution ratios below 12.5%, specific volume remained relatively constant, followed by a sharp decline beyond this threshold. This decrease in specific volume corresponds to denser loaves at higher mango kernel flour concentrations. This pattern can be attributed to several factors.

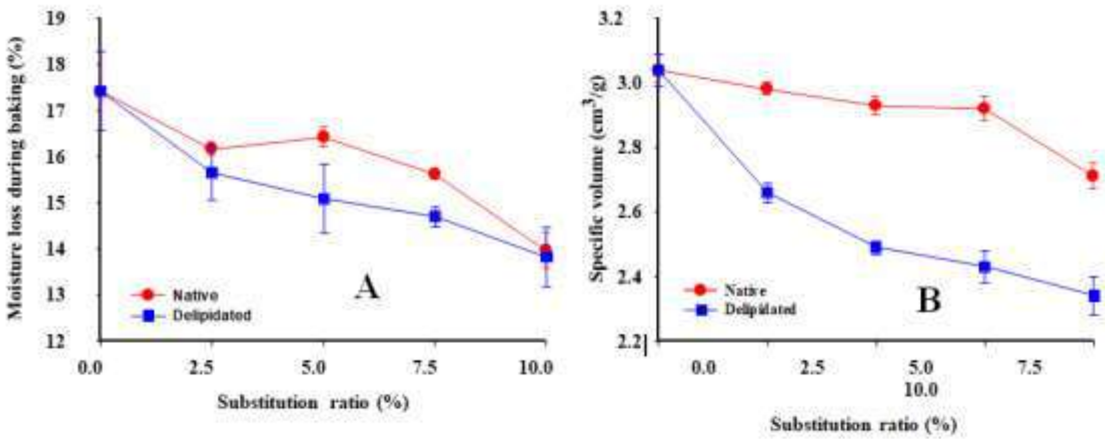

Figure 4: Variations in oven mass loss (A) and specific volume (B) of loaves as a function of mango kernel flour substitution ratio

This trend indicates that higher substitution levels enhanced water retention in the dough, subsequently increasing evaporation rates during baking. At 10% substitution, an exponential increase in moisture loss occurred, suggesting severe disruption of the gluten network and compromised dough retention capacity. This structural degradation accelerated water evaporation during the baking process. At lower substitution levels (0-5%), evaporation rates remained relatively stable due to minimal flour addition and preserved dough structure, which maintained moisture retention capacity.

At low substitution levels, mango kernel flour does not significantly impair gas retention or dough expansion capacity. However, higher substitution levels cause an abrupt reduction in specific volume due to the distinct functional properties of mango kernel flour compared to wheat flour. The starch and fiber components in mango kernel flour exhibit suboptimal binding with gluten, resulting in reduced gas retention during fermentation and baking processes. Consequently, these properties contribute to lower specific volumes and increased loaf density.

The trends observed in both figures are consistent with the existing literature on ingredient substitution patterns in bread preparation. It has been reported that the use of non-conventional flours such as those obtained from fruits or seeds affects the rheology of the dough and quality of bread (Capelli et al., 2020). Non wheat flours for example, frequently have greater levels of fiber as well as starch that is not of the same type as wheat which affects the water and gas retention characteristics (Xin et al. 2022; Culetu et al., 2021). Indeed, the moisture loss in Figure 4A is consistent with the evidence that suggests that gluten formation could be affected by the use of alternative flours due to their structural feature (Chisenga et al., 2020). Also, the water holding capacity of gluten further weakens when traditional wheat flour is partially inclusive of mango kernel flour because of the reduction in the overall protein content (Awolu et al., 2018). This also would cause higher mass loss due to higher evaporation rates which may be caused due to such disruption.

Similarly, the high fiber contents in alternate flours can be observed negatively affecting the loaf volume as discussed previously by Wang et al. (2002). This, in turn, validates the drop in specific volume as presented in Figure 4_B. Fats modify the crystallization of starch, thus forming emulsion droplets with the gluten which retain the gas. Therefore, fibers exacerbate a dense crumb structure as they do not aid in gas retention. Excessive soluble fiber can also result in moisture absorption which can hinder dough processing and also the fermentation (Struyf et al., 2017).

In addition, mango kernel flour is hypothesized to work with other compositional ingredients synergistically which should be also taken into consideration. For instance, if non-conventional flours such as mango kernel flour are included in the dough, then the enzymes which are already present in the yeast might act differently which will alter the fermentation process and the specific bread characteristics (Menon et al., 2014). Such Interactions need to be well understood when altering traditional formulations in order to achieve the desired bread quality.

3.2| Impact of Julie mango kernel flour on bread staling process

Figure 5 depicts the changes in bread crumb (A) and crust (B) moisture content during storage. High moisture concentrations are present immediately after baking. Following baking, the bread crumb moisture content exhibits a progressive decline throughout the storage period. This decreasing trend in crumb moisture follows a curvilinear pattern. Moisture loss is considerably greater during the initial storage period, but gradually decreases with extended storage time. The moisture curves approach equilibrium content asymptotically, though the time required to reach equilibrium varies depending on sample characteristics and storage conditions.

Conversely, the moisture content of the bread crust exhibited an opposite pattern, displaying relatively lower moisture content immediately after baking and increasing progressively during storage. This increasing trend in crust moisture content suggests a complex mechanism involving moisture migration from the internal crumb as well as moisture uptake from the external environment. During the initial storage period, the rate of moisture absorption by the crust appears to be higher compared to later stages. Over time, there is a gradual trend toward equilibrium moisture distribution between the crumb and crust regions.

Bread crumb moistness is a critical quality attribute, shaped by a complex interplay of

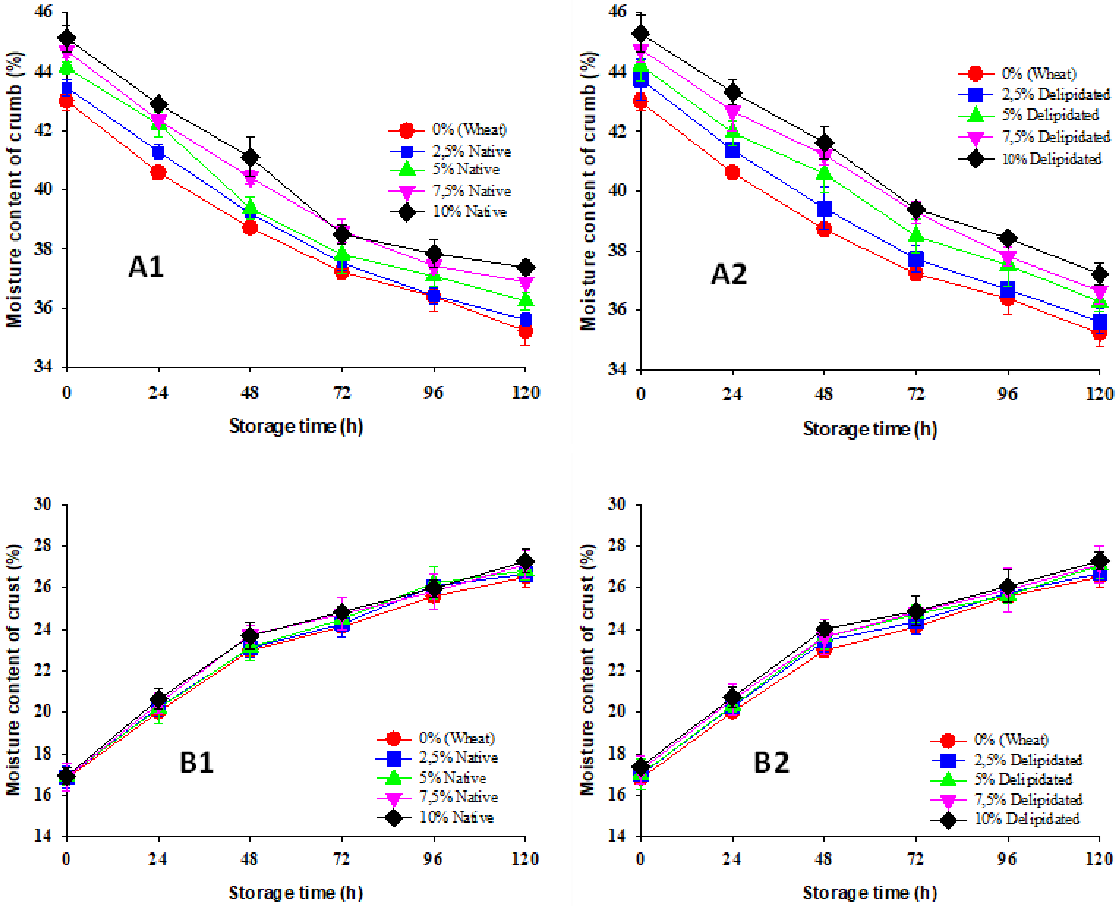

Figure 5: Dynamics of water content in bread crumb (A) and crust (B) during storage time

physicochemical factors such as water content, starch retrogradation, protein interactions, and ingredient composition. Low crumb moisture is closely linked to staling and reduced bread quality, primarily due to starch retrogradation and moisture migration (Aguirre et al. 2011). Hu et al. (2023) have further demonstrated that the rebuilding of amylopectin granules is associated with moisture accumulation within the bread structure which on the other hand influences the capacity and mobility level significantly.

The moisture content in the crust area gradually rises as a result of the vapor pressure gradient developed between the crust and the crumb or vice versa. Moisture is absorbed and transported throughout the bread structure via intricate capillary systems fueled by these gradients as reported by Besbes et al. (2014) in their observations. Microscopic repercussions associated with the glass transition in the crust area also affect the rate and pattern of moisture movement in the baked bread that is stored, as pointed out by Narsimhan (2023).

Remarkably, the nature of these dynamics between crumb and the crust seems to be quite complex and has implications on the quality of the bread as a whole. Scott & Awika (2023) have recently demonstrated how protein-starch interactions influence the water-holding capacity during the storage of bread. Along with alterations to the gluten network structure, these interactions promote a moisture transfer cycle that has an impact on the bread's quality characteristics such as texture and freshness after being stored.

According to Tao et al. (2024), environmental aspects such as the temperature and the relative humidity, affect the repartition between the crumb region and the crust region of the bread. These authors also argue that shelf-life and quality attributes can be affected by the way the product is stored. Wang et al. (2024) have also proven water movement and migration patterns in different regions of the bread were able to affect its mechanical properties which suggest higher quality of control and the development of the product.

3.3| Investigating the process of crumb firming in Julie mango kernel almond breads

The experimental data for crumb firmness of the breads produced in this study fit well to the Avrami model, as shown in Figure 6.

Kulp, 1996). The examination of variations in the firming rate constant (k) and crystal development index (n) reveals the notable impact of kernel processing (native or defatted), and substitution ratio on the process of staling. The values of "n" and 'k' drop when the substitution ratio of Julie variety native almond flour increases from 0 to 5%. However, replacing regular flours with defatted flours results in a consistent rise in these variables. The results suggest that including local mango almond flour can effectively slow down the staling process, with the optimal substitution ratio being 5%.

Conversely, the use of mango almond defatted flour is more likely to exacerbate the process of bread staling. The adverse impact of defatted flour may be ascribed to the delipidation process of mango kernel flour, which potentially deactivates the amylases present in the mango kernel.

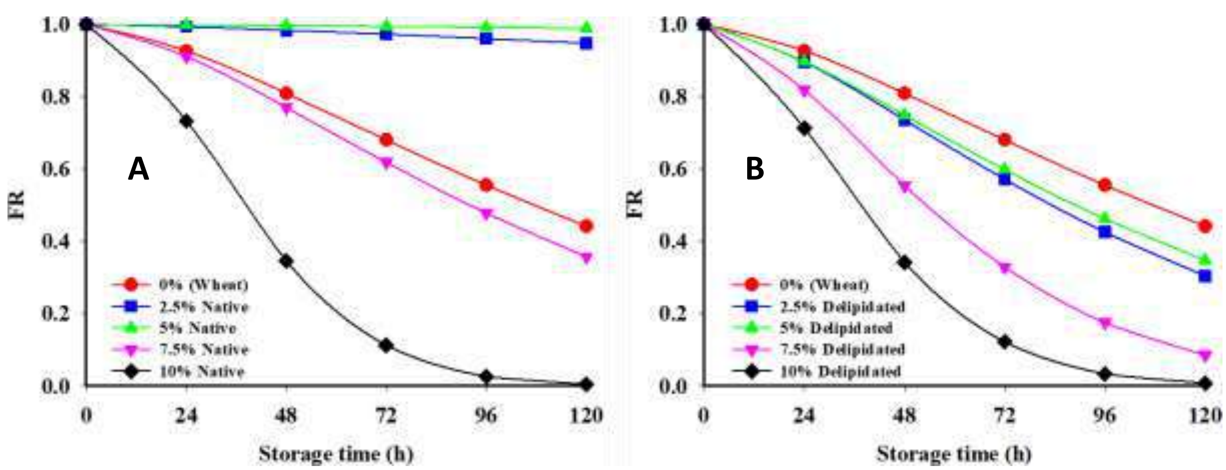

Figure 6: Dimensional adjustment of the effect of wheat substitution by native (A) and defatted (B) Julie mango almond flour as a function of storage time (shelf life) using the Avrami model

The R^2 values, as presented in Table 3, are equal to or greater than 0.99. For every loaf, the crystal development index (n) is more than 1, suggesting that the staling of the loaves is caused by both starch retrogradation and other events (Zobel & Kulp, 1996).

Lipid extraction with hexane is very probable to deactivate enzymes by causing denaturation of their protein structure, as demonstrated by Asaduzzaman & Chun (2014) and Ogino et al. (1994).

Table 3: Characteristics of the Avrami model fitted to crumb firmness data for breads made with wheat and Julie mango kernels flour during storage

Samples	Substitution ratio	k (h^{-n})	n	R^2
Natif	0%	$0,7*10^{-3}$	1,4751	0,9995
	2,5%	$0,10*10^{-3}$	1,3122	0,9971
	5%	$0,02*10^{-3}$	1,3159	0,9981
	7,5%	$0,8*10^{-3}$	1,4956	0,9977
	10%	$1,1*10^{-3}$	1,7757	0,9908
Defatted	0%	$0,7*10^{-3}$	1,4751	0,9995
	2,5%	10^{-3}	1,4791	0,9983
	5%	$1,2*10^{-3}$	1,4166	0,9986
	7,5%	$1,4*10^{-3}$	1,5613	0,9985
	10%	$1,7*10^{-3}$	1,6653	0,9960

With k the staling rates constant and n the crystal development index.

In addition, the extraction process conducted at a temperature of 69°C for a duration of 10 hours is likely to have caused the enzymatic inactivation. This is because the temperature used exceeded the ideal temperature for the activity of amylases found in mango kernels. The absence of lipids, particularly saturated fatty acids, can contribute to the staling effect of defatted mango kernel flour. Lipids, such as saturated fatty acids, promote the formation of a lipid-starch complex that reduces starch retrogradation and prevents the hardening of bread crumbs. Without these lipids, the amylose chains in the flour are more prone to crystallization, leading to increased staling. This explanation is supported by studies conducted by Krog et al. (1989) and Knightly (1988).

The observed threshold effect at 5% substitution ratio with native mango kernel flour can be attributed to two factors. Firstly, the higher substitution ratio of wheat result in a more compact crumb, which increases the compressive strength of the bread. Secondly, the specific volume of the bread with mango kernel flour (2.71 cm^3/g) is significantly lower than that of the control bread (3.04 cm3/g).

Axford et al. (1968) demonstrated that the rise in crumb firmness is contingent upon the specific volume of the bread, but Armero & Collar, (1997) established a negative relationship between crumb firmness and specific volume.

From the Avrami equation, we obtained Ft, which leads to equation 5, which we used to calculate the consumption duration of the loaves in this study:

$$F_t = F_\infty - (F_\infty - F_0) * e^{-kt^n} \quad (5)$$

Figure 7, which is a graphical depiction of the Ft fit, indicates that the firmness of each loaf rises with storage time, which is supported by the data in Table 4.

Julie mango kernel flour's pre-treatment (native or defatted) and the ratio of wheat flour substitution determine the acceptable range of bread hardness (15N) (Randriamiharison, 1984), which varies from 24 to 72 h.

Table 4 presents the effects of defatted mango kernel flour on bread production, examining the relationships between lipid content, amylase activity, and bread firmness.

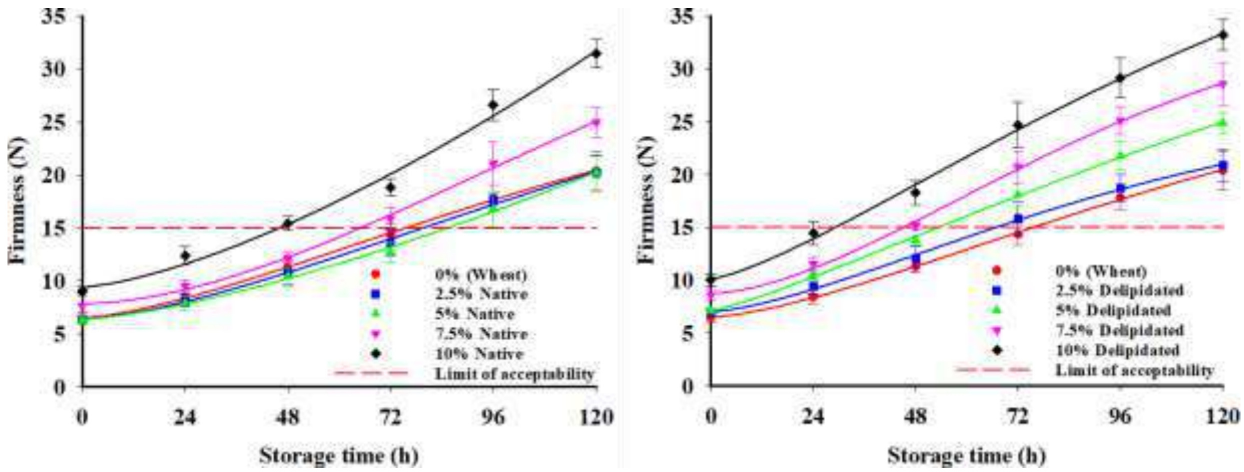

Figure 7: Evolution of the Firmness of bread crumbs (wheat-Julie native mango kernel (A) and wheat-Julie defatted mango kernel (B)) as a function of storage time.

The results demonstrate that native mango kernel flour can produce bread with acceptable texture at substitution levels up to 10%, with hardness comparable to the 100% wheat flour control at 5% substitution. Conversely, defatted mango kernel flour produces significantly harder bread at all substitution levels, suggesting that lipids play a crucial role in maintaining bread softness.

Table 4 : Shelf life of breads made with composite wheat/mango almond flours of the Julie variety

Substitution ratio	Native	Defatted
0%	75 h	75 h
2.5%	78 h	69 h
5%	86 h	53 h
7.5%	78 h	43 h
10%	42 h	29 h

According to Pareyt et al. (2022), lipids are known to influence the rheological properties of the dough while they can prolong the bread's shelf-life by improving moisture preservation, thus reducing the rate of staling of the bread. In this case, the activity of the amylase enzyme is important too, since it catalyzes the hydrolysis of starch into more soluble sugars which can work alongside gluten and lipids to affect the texture (Jòzef, 2007). The type of accelerated staling which was noted in the case of defatted flour may possibly stem from decreased lipid content which then results in diminished emulsifying properties that assist in the moisture retention and retrogradation of starch (Chiravi et al., 2023). The threshold effect observed for Julie variety mango flour at 5% substitution level indicates that further replacement with native mango flour would significantly alter wheat flour characteristics, suggesting that higher lipid concentrations may counteract staling effects on bread texture. This corresponds to earlier results which suggested that lipid content is extremely crucial for the maintenance of the quality of bread during its shelf-life (Harshitha et al., 2024). Hence, it can be concluded that while replacement of the wheat flour with the mango kernel flour can lead to diversity in the ingredients and also possess nutritional benefits, the amylase activities and the lipid contents have to be taken care of for the texture and the shelf-life to be optimized.

5| Conclusion

The study comes to the conclusion that "Julie" mango kernel flour has a great potential to enhance the physical qualities and shelf-life of bread when used as a partial substitute for wheat flour. By enhancing water retention and reducing starch retrogradation, natural mango kernel flour successfully decreased bread staling at substitution ratios of up to 5%. Because natural mango kernel flour contains saturated fatty acids, it helped establish an oil-water interface that stabilized gas bubbles during baking, producing a bread with a finer crumb structure and a larger specific volume. Higher replacement ratios (above 7.5%), however, resulted in faster staling and less bread volume. The inferior performance of defatted mango kernel flour can be attributed to the removal of beneficial fatty acids and the inactivation of amylases during processing. The findings indicate that natural Julie mango kernel flour can be commercially viable as a 5% wheat flour substitute in bread production, offering enhanced quality and extended shelf life while promoting sustainability through waste utilization. However, careful process control is essential as exceeding 7.5% substitution negatively impacts bread quality. This creates opportunities for innovative product development in commercial bakeries.

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Not applicable.

|Conflict of interest

The authors declare that they have no conflict of interest.

|Data availability statement

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

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