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**ARAŞTIRMA MAKALESİ** **RESEARCH ARTICLE**

# Vegan Ice Cream Production from Roasted Almonds Using Hot Air and Microwave Roasting Techniques and Determination of Some of Its Properties

Sıcak Hava ve Mikrodalga Kavurma Teknikleri ile Kavrulmuş Bademlerden Vegan Dondurma Üretimi ve Bazı Özelliklerinin Belirlenmesi

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## Abstract

Advancements in technology and evolving living conditions have prompted individuals to pursue healthier dietary habits. Furthermore, vegan diets have gained significant popularity for a variety of reasons. For these reasons, the research into and the utilization of nutrient-dense nuts, such as almonds, within vegan products are becoming increasingly prevalent. Almond is widely consumed nuts globally, and contain various beneficial nutrients. This study examined the effects of traditional (hot air) and innovative (microwave) roasting methods on vegan ice cream production. In this study, almonds were roasted in a hot air oven (100°C for 60 min, 130°C for 15 min, 150°C for 5 min) and in a microwave oven (300W for 15 min, 600W for 7 min, 800W for 3 min). Milk derived from roasted almonds was used in making vegan ice cream, and the physicochemical, rheological, textural, and sensory properties of the final products were assessed. The total fat content of the ice creams increased with the roasting process (ranged from 3.22±0.18 to 27.20±1.19, g 100g), while the pH (ranged from 6.42±0.04 to 5.63±0.01) and $L^*$(ranged from 70.14±2.43 to 83.91±4.09) values decreased (P≤0.05). Nevertheless, the $L^*$ value of the ice cream produced from almond milk roasted in a microwave at 800 W was found to be similar to the control ice cream. All samples displayed shear thinning flow behaviour, and the K values exhibited considerable variation, with a range of 9.13±0.19 to 28.01±2.98 (Pa.s) (P≤0.05). The utilisation of almond milk and roasting processes in the production of ice cream resulted in a notable reduction in hardness values (P≤0.05). The panelists indicated that the ice creams produced from hot air-roasted almonds exhibited a burnt taste, whereas the ice creams produced from microwave-roasted almonds were similar general acceptability score to the control. The evidence of this work highlights the significance of the roasting method employed in the development of vegan almond ice cream, particularly in relation to both instrumental and sensory analysis.

**Keywords:** Vegan ice cream, Almond, Hot air and microwave roasting, Rheology, Colour, Sensory evaluation

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## Öz

Teknolojideki ilerlemeler ve değişen yaşam koşulları, bireyleri daha sağlıklı beslenme alışkanlıkları edinmeye yöneltmiştir. Dahası, vegan diyetler çeşitli nedenlerle önemli bir popülerlik kazanmıştır. Bu nedenlerden dolayı, badem gibi besin değeri yoğun kuruyemişlerin vegan ürünlerde kullanımı ve araştırılması giderek yaygınlaşmaktadır. Badem, dünya çapında yaygın olarak tüketilen bir kuruyemiştir ve çeşitli faydalı besinler içerir. Bu çalışmada, vegan dondurma üretiminde geleneksel (sıcak hava) ve yeni (mikrodalga) kavurma tekniklerinin etkileri incelenmiştir. Bu kapsamda, bademler sıcak hava fırınında (100°C'de 60 dk, 130°C'de 15 dk, 150°C'de 5 dk) ve mikrodalga fırında (300W'da 15 dk, 600W'da 7 dk, 800W'da 3 dk) kavrulmuş ve bu bademlerden elde edilen sütlerle dondurma üretilmiştir. Dondurma örneklerinin fizikokimyasal, reolojik, tekstürel ve duyusal özellikleri değerlendirilmiştir. Dondurmaların toplam yağ içeriği kavurma işlemiyle artarken (3.22 ± 0.18 ilâ 27.20 ± 1.19 g/100g), pH (6.42 ± 0.04 ilâ 5.63 ± 0.01) ve $L^*$ (70.14 ± 2.43 ilâ 83.91 ± 4.09) değerleri ise azalmıştır ($P \leq 0.05$). Bununla birlikte, mikrodalgada 800 W'da kavrulmuş badem sütünden üretilen dondurmanın $L^*$değerinin kontrol dondurma örneğiyle istatistiksel olarak fark olmadığı bulunmuştur ($P>0.05$). Tüm örnekler kayma inceltme akış davranışı göstermiştir ve K değerleri 9.13±0.19 ila 28.01±2.98 (Pa.s) ($P\leq0.05$) aralığında önemli bir değişiklik göstermiştir. Dondurma üretiminde badem sütü ve kavurma işlemlerinin kullanılması sertlik değerlerinde önemli bir azalmaya neden olmuştur ($P\leq0.05$). Panelistler, sıcak havada kavrulmuş bademlerden üretilen dondurmaların yanık bir tada sahip olduğunu, mikrodalgada kavrulmuş bademlerden üretilen dondurmaların ise kontrol ile benzer genel kabul edilebilirlik puanına sahip olduğunu belirtmişlerdir. Bu çalışmanın bulguları, özellikle hem enstrümantal hem de duyusal analiz açısından vegan badem dondurmasının geliştirilmesinde kullanılan kavurma yönteminin önemini vurgulamaktadır.


**Anahtar Kelimeler:** Vegan dondurma, Badem, Sıcak hava ve mikrodalga kavurma, Reoloji, Renk, Duyusal değerlendirme

## 1. Introduction

Roasting treatment is typically performed at temperatures above 100 °C to remove the kernel membrane, reduce moisture content, and inactivate enzymes and bacteria, and it allows for the development of colour, texture, and taste in food products (Marzocchi et al., 2017). The roasting process results in physical and biochemical changes, as well as non-enzymatic browning, which leads to the release of pyrazine compounds responsible for the roasted flavour (Marzocchi et al., 2017). Almonds, hazelnuts, coffee beans, peanuts, chickpeas, and other seeds or beans can be roasted using traditional methods such as pan, oven, and sand roasting, or novel methods such as microwave, infrared, superheated, and forced convection continuous tumble (FCCT) roasting (Sruthi et al., 2021).

Almonds are widely consumed nuts in the world, and contain high number of beneficial nutrients including vitamin E, monounsaturated fatty acids, fibre, and protein (Esfahlan et al., 2010). Owing to their palatability and high energy content, almonds can be employed as an appetiser or incorporated into baked goods, culinary dishes, and snacks (Hojjati et al., 2016). Almonds are known for their antioxidant and anti-inflammatory properties, which are based on to their relatively high levels of phenolic compounds, phytochemicals, vitamin E, MUFAs and PUFAs and have potential to diminish the risk of cardiovascular disease. As a result, almond-based products have gained popularity (Kot et al., 2021).

The popularity of veganism is increasing due to various reasons such as health concerns, ethical preferences, religious beliefs, or living conditions. Vegans strictly avoid consuming any products that are derived from animals (Bekiroglu et al., 2022). Ice cream is a popular food due to its sensory properties, cooling effect, and nutritional benefits (Pehlivanoğlu et al., 2024). However, it is not consumed by vegans and individuals with lactose intolerance or milk protein allergy. So, there is an increasing interest in plant-based nutrition and finding alternative options for daily consumption (Kot et al., 2021). In this context, various non-dairy vegan products made from nuts have been developed. For example, Ozturkoglu-Budak et al. (2016) focused on yogurt made from walnut, hazelnut, almond, and pistachio, while Dogan et al. (2022) created yogurt from walnut, almond, and pistachio. Conversely, Gocer and Koptagel (2023a, 2023b) studied kefir produced from almonds, peanuts, hazelnuts, walnuts, and cashews. Similarly, nut-based ice creams have been developed by Yüksek et al. (2017) using hazelnut, almond, walnut, and pistachio. Bekiroglu et al. (2022) and Aydemir et al. (2025) also developed ice cream from walnut and hazelnut, respectively. Among these plant-based options, almonds are considered a promising choice for ice cream production.

Using various nut types in vegan product production offers a promising foundation. However, raw nuts often have undesirable sensory traits, such as a "beany" or "grassy" taste and a pale color, which may reduce consumer acceptance. Roasting improves digestibility and palatability and enhances color, aroma, flavor compounds, and antioxidants (Sruthi et al., 2021). Thus, roasting is a well-known method for developing desirable nutty flavors and improving the overall sensory profile of hazelnuts. So far, no studies have examined how different roasting techniques impact the quality of almond-based vegan ice cream. Therefore, this study primarily aims to compare how traditional (hot air) and innovative (microwave) roasting methods influence the final physicochemical, textural, rheological, and sensory properties of vegan ice cream. This research will highlight the benefits of roasting over raw almonds and explore how various industrial heating techniques can be used to develop new and better vegan products.

## 2. Materials and Methods

### *2.1. Plant Materials and Roasting Conditions*

Raw, unsalted, and unroasted almonds with broken shells were purchased in vacuum bags from Ardıçlı Bahçe (Elmalı, Antalya) and stored at 4 ºC until use. This study examines the roasting of almonds using two different techniques: hot air and microwave. A laboratory-scale oven (Mikrotest, MST-55, Turkey) was used to roast approximately 500 g of almond samples at different temperatures and times: 60 min at 100 ºC, 15 min at 130 ºC, and 5 min at 150 ºC (*Figure 1A*). Similarly, approximately 200 g of almond samples were roasted in the microwave (Samsung, Solo Microwave Oven, MS23F300EEK, Malaysia) at different W and times: 300 W for 20 min, 600 W for 7 min, and 800 W for 3 min (*Figure 1A*). Each roasting technique was applied twice. This study identified the temperature-time and W-time parameters for hot air and microwave roasting techniques through sensory analysis. The same panelists who conducted the ice cream sensory evaluation performed this assessment. Panelists were asked to

consider the presence of burnt flavor and the removal of raw almond aroma (data not shown). Preliminary screening trials were conducted prior to the final selection of roasting conditions. Sensory evaluation indicated that longer roasting times at lower temperatures resulted in insufficient aroma development and persistence of raw almond notes. Conversely, higher temperature–shorter time combinations led to excessive darkening and pronounced burnt flavor formation. Therefore, the selected temperature–time and W–time combinations were determined as the most appropriate conditions for further analyses. In addition, extreme microwave power–time combinations resulted in non-uniform heating and local overheating.

### *2.2. Preparation of Roasted Almond Milk*

Roasted almond samples were mixtured with drinking water (1:2, g $mL^{-1}$, almond/water) and left to stand for 2 h. The outer shell of the almond samples was removed manually. The almonds were then crushed using a hand blender and filtered using a cheesecloth. The resulting supernatant was centrifuged (5000 rpm, 5 min) to obtain a clearer roasted almond milk, then stored at -18 ºC for use in ice cream production. Totally, seven different almond milks obtained: a) unroasted almond milk (URA), b) hot air roasted almond milk at 100 ºC for 60 min (HRA100), c) hot air roasted almond milk at 130 ºC for 15 min (HRA130), d) hot air roasted almond milk at 150 ºC for 5 min (HRA150), e) microwave roasted almond milk at 300 W for 15 min (MRA300), f) microwave roasted almond milk at 600 W for 7 min (MRA600), and g) microwave roasted almond milk at 800 W for 3 min (MRA800) (*Figure 1B*).

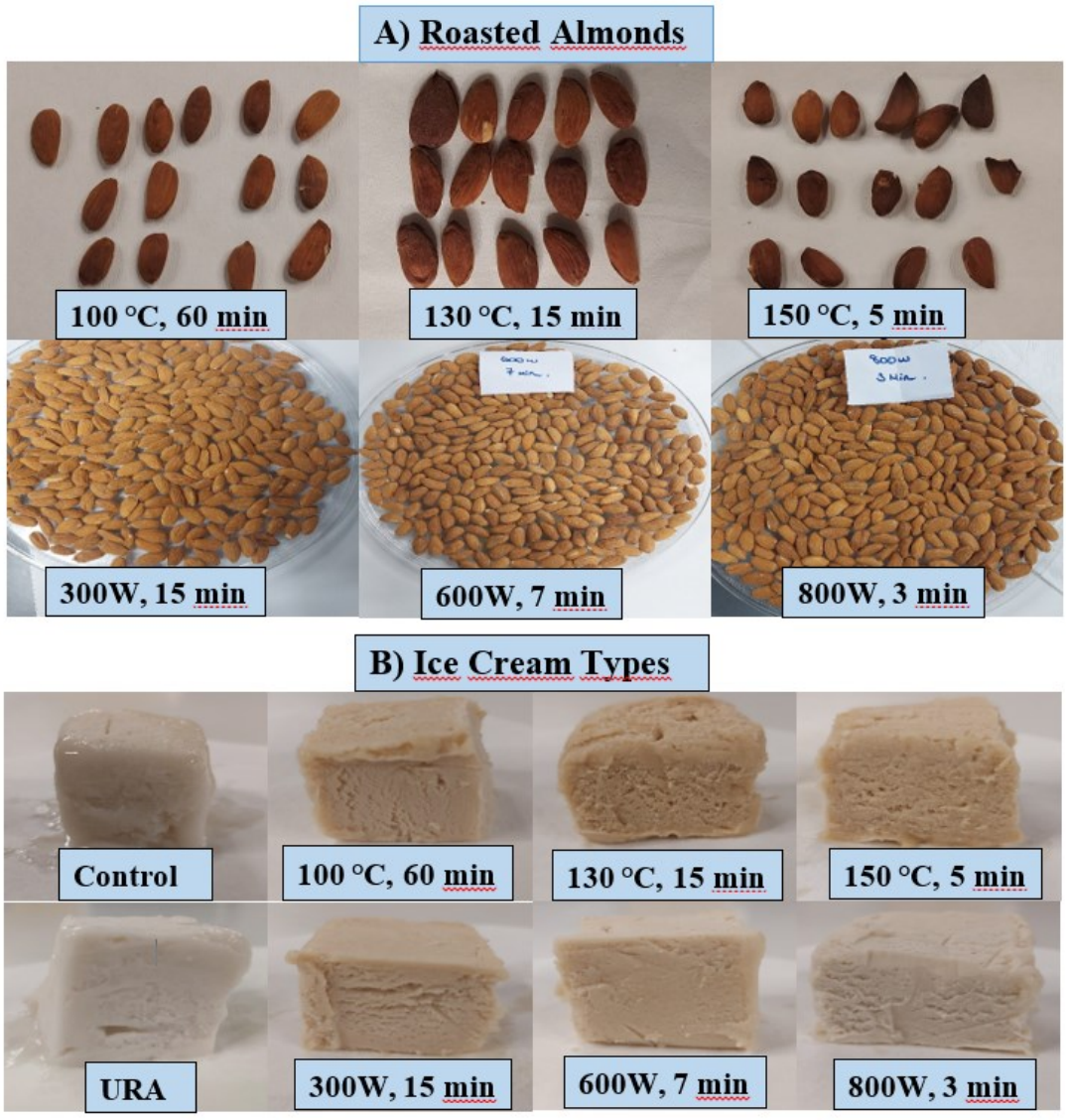



***Figure 1. Roasted almonds and produced ice cream types***

### *2.3. Development of Ice Cream Samples*

Eight different types of ice cream were developed using cow milk, unroasted almond milk, and roasted almond milks. The ice cream formulations included 22 g of sugar, 1 g of salep (stabilizer), and 0.3 g of mono and diglycerides (emulsifier) for every 100 mL of milk. The milk was heated to 40 ºC before adding the sugar, emulsifiers, and stabilizers. All ingredients were pasteurized at 72 ºC for 15 min. After cooling the ice creams to room temperature, which were aged at 4 ºC for 24 h. Then, the ice cream was produced by an ice cream machine (Vosco, ICM-15A, Turkey) with the following hard ice cream mode: mixing for 5 min, soft mode for 32 min and hard mode for 25 min. The samples were stored in plastic vessels of 10×10×5 cm sizes and kept at a temperature of -18 ºC for analysis.

### *2.4. Physicochemical Characteristics of Ice Creams*

The samples were melted to determine total dry matter (TDM), pH, titratable acidity (TA), protein and fat content. A pH meter (Hanna HI2002-02) was used to identify the pH values of the samples. The samples were analyzed for their TDM and TA values using the methods specified by Williams (1984). The total protein content of the samples was determined using the Kjeldahl method, and a protein conversion factor of 6.38, which is used for milk and dairy products, was applied (Bekiroglu et al., 2022). Additionally, the total fat content of the ice cream samples was determined according to the Solvent Extractor device (Velp Scientifica, Usmate, Italy) operating instructions.

### *2.5. Colour Characteristics of Ice Creams*

The colour characteristics of the samples were identified using a colorimetric device (3nh NR200, Shenzhen, China). Two replicates of $L^*$, $a^*$, and $b^*$values were recorded for each ice cream, and the measurements were reported as the mean standard deviation.

### *2.6. Melting Characteristics of Ice Creams*

In order to ascertain the melting behaviour, the DSC procedure with a TA Instrument Q100 (New Castle, USA) was employed (Molina et al., 2004). Approximately 8-10 mg of sample was placed into aluminium pans and hermetically sealed. Melting behaviours were identified from -20 to 10 ºC, and the results were recorded as two parallel of each sample.

### *2.7. Rheological Properties of Ice Creams*

The shear stress and shear rate of the samples were measured by a temperature-controlled rheometer (Anton Paar, MCR 302, Austria) (Bekiroglu et al., 2022). These parameters were set to the Ostwald de Waele model (Eq.), and the K (Pa.sn) and n values were calculated:

$$\text{Eq: } \sigma = K(\gamma)n \qquad \text{(Eq. 1)}$$

where σ is shear stress (Pa) and γ is shear rate ($s^{-1}$).

### *2.8. Textural Properties of Ice Creams*

The texture device (TA-XT Express Stable Micro Systems) equipped with a 10 kg load cell and P/36R cylindrical aluminium probe was used to identify the hardness and adhesiveness values of the samples (Goktas, 2023). Prior to measurement, the ice creams were cut into cubes and kept at -18°C for 24 h. The following test steps were used to determine the textural parameters: first/test/last speeds: 2.00/2.00/10.00 mm $s^{-1}$, distance 40.00 mm and force 0.1 N. Textural properties of ice cream samples were analyzed in 3 replicates.

### *2.9. Sensory Evaluation of Ice Creams*

The panelists were presented with ice cream samples for evaluation in terms of sensory parameters, including appearance, odour, taste, burnt taste, melting quality, mouthfeel, and general acceptability. The panel consisted of 25 individuals, 15 women and 10 men. Prior to the evaluation, the panelists were informed of the purpose of the study, the points to be considered when scoring, and the sensory parameters. Approximately 25 grams of samples were offered to the panelists in transparent plastic containers bearing three randomly selected numbers. During the evaluation, the panelists were instructed to rinse their mouths with water before tasting each sample. The panelists were then asked to score the samples on a scale of 1 to 5 for each of the sensory parameters (1: never liked, 2: dislike, 3: acceptable, 4:

liked, 5: very liked, for burnt taste 1: intensely felt, 2: slightly felt, 3: felt, 4: not felt, 5: never felt). The sensory evaluation form was prepared in accordance with the method specified by Soukoulis et al. (2010) and subsequently modified to incorporate a burnt taste, in accordance with the specific objectives of the study.

### *2.10. Statistical Analyses*

The statistical evaluation of the results obtained in the study was conducted using the JMP Pro 14.0 statistical program (SAS Institute, USA). The results were presented as mean standard deviation. The statistical significance level was identified by Student's t test at the 95% importance level.

## 3. Results and Discussion

### *3.1. Physicochemical Properties*

The TDM values of the ice creams produced from hot air-roasted almond milk were found to be similar to the control sample (P>0.05) (*Table 1*). However, the TDM values of the ice creams produced from unroasted almond milk and microwave-roasted almonds were found to be higher than that of the control (P≤0.05). The highest TDM value was determined for MRA800, with a value of 38.62±0.25, g/100g. Bekiroglu et al. (2022) declared that the TDM values of walnut milk ice creams were higher than those of the control. Furthermore, Atalar et al. (2021) indicated that the TDM values of the ice creams produced with hazelnut milk were higher than the control. The volumetric heating from microwave roasting results in more effective moisture removal, thereby increasing total dry matter. In their study on almonds, Hojjati et al. (2016) reported that microwave roasting caused a greater moisture reduction compared to hot air roasting. The higher TDM values obtained for the MRA 800 ice cream sample in this study may be due to this effect. The higher TDM values observed in MRA800 ice cream indicate that microwave roasting promotes more uniform moisture removal through volumetric heating, increasing total dry matter while preserving structural integrity (Hojjati et al., 2016; Wu et al., 2025), which likely contributes to improved texture and sensory acceptability.

***Table 1. Physicochemical properties of the ice cream samples produced with roasted and unroasted almond milks***

| Ice Cream Samples | TDM (g/100g) | pH | TA (%) | Protein (g/100g) | Fat (g/100g) |
|---|---|---|---|---|---|
| URA | 35.64±0.07$^{b}$ | 6.38±0.01$^{a}$ | 3.42±0.01$^{d}$ | 4.33±0.24$^{a}$ | 19.90±2.06$^{d}$ |
| HRA100 | 34.34±0.03$^{e}$ | 5.85±0.24$^{b,c}$ | 3.65±0.06$^{c}$ | 2.67±0.05$^{d}$ | 21.12±1.66$^{c,d}$ |
| HRA130 | 34.51±0.08$^{e}$ | 5.63±0.01$^{d}$ | 3.62±0.09$^{c,d}$ | 1.84±0.06$^{e}$ | 23.37±1.16$^{b,c,d}$ |
| HRA150 | 34.69±0.38$^{d,e}$ | 5.68±0.04$^{c,d}$ | 3.53±0.09$^{c,d}$ | 1.85±0.07$^{e}$ | 23.88±1.97$^{a,b,c}$ |
| MRA300 | 35.06±0.29$^{c,d}$ | 5.95±0.04$^{b}$ | 4.50±0.12$^{a}$ | 3.47±0.07$^{c}$ | 24.94±1.39$^{a,b}$ |
| MRA600 | 35.36±0.03$^{b,c}$ | 5.98±0.04$^{b}$ | 4.19±0.06$^{b}$ | 3.62±0.23$^{bc}$ | 25.74±1.71$^{a,b}$ |
| MRA800 | 38.62±0.25$^{a}$ | 6.01±0.01$^{b}$ | 4.14±0.12$^{b}$ | 3.91±0.01$^{b}$ | 27.20±1.19$^{a}$ |
| Control | 34.27±0.03$^{e}$ | 6.42±0.04$^{a}$ | 2.34±0.13$^{e}$ | 3.88±0.04$^{b}$ | 3.22±0.18$^{e}$ |

The pH values of the samples exhibited a range of 6.42±0.04 to 5.63±0.01. The pH value of the unroasted almond milk ice cream was determined to be 6.38±0.01, which is in close proximity to the control sample. Nevertheless, a diminish in pH values was identified in the ice creams subjected to the roasting process (P≤0.05). The pH values of the ice creams produced with hot air-roasted almonds exhibited a greater decrease than those produced with microwave-roasted almonds. Conversely, the TA values of the samples demonstrated an increase in comparison to the control sample when unroasted or roasted almond milk was utilised in the ice cream production process (P≤0.05). In their study, Atalar et al. (2021) and Bekiroglu et al. (2022) indicated that the incorporation of hazelnut milk and walnut milk into ice cream production resulted in a diminish in the pH value of the resulting product. On the other hand, Oh and Lee (2024) reported that roasting caused a decrease in the pH value of nut-based milks and that this was related to the applied heat treatment. The decrease in pH and the rise in TA values in ice cream samples made from roasted almonds are explained by two main mechanisms that occur

during almond heat treatment: the formation of organic acids and the effect of concentration. The formation of acidic byproducts such as volatile organic acids (e.g., acetic and propionic acids), lipid degradation products (free fatty acids), and Maillard reaction byproducts during roasting results in increased overall acidity of the almond milk and, consequently, the ice cream mix (Starowicz and Zieliński, 2019; Zhang et al., 2022). Additionally, the moisture content of the almonds drops significantly during roasting, which raises the concentration of naturally occurring organic acids (Adimas and Abera, 2025). This increase in concentration boosts the amount of free hydrogen ions in the ice cream matrix, leading to a lower pH and higher TA values.

The total protein content of ice cream produced using unroasted almond milk was found to be the highest. Similarly, Atalar et al. (2021) and Bekiroglu et al. (2022) stated that the protein content of ice creams produced with hazelnut milk and walnut milk was higher than that of the control. However, a notable reduction in protein content was observed in ice creams produced from hot air-roasted almonds ($P \leq 0.05$). The protein content was decreased with an increase in temperature, particularly in the case of hot air roasting. Conversely, while a reduction in protein content was observed in the ice creams subjected to microwave roasting, only the decrease in MRA300 was found to be significant. In contrast, microwave roasting, due to rapid volumetric heating, resulted in less pronounced protein loss in some samples (e.g., MRA600 and MRA800), suggesting a more uniform thermal effect that may help preserve protein functionality (Hojjati et al., 2016). Similarly, Santos et al. (2018) and Tu et al. (2021) declared a reduction in the protein content of nuts during the roasting process. The decrease in total protein content observed in ice cream samples made from roasted almonds is mainly due to chemical changes such as the Maillard reaction. Roasting, which is a high-temperature heat process, promotes the Maillard reaction, a non-enzymatic browning process between reducing sugars and the amino groups of proteins. The products created by this reaction attach to the amino groups, making the protein nutritionally unavailable and leading to a visible reduction in protein content as measured by total nitrogen-based tests like the Kjeldahl method (Guo et al., 2020; Shkhidem et al., 2024). Research has shown that roasting significantly lowers protein quality in nuts like peanuts and reduces total protein levels in almonds, cashews, and walnuts (Maleki et al., 2000; Santos et al., 2018; Shkhidem et al., 2024). This chemical process explains the decline in protein content without causing any physical damage to the structure.

The incorporation of almond milk into ice cream production led to a notable elevation in the overall fat content of the resulting ice creams. Furthermore, the fat content of the ice creams increased in conjunction with the roasting process, in comparison to the ice cream produced from unroasted almond milk. The highest fat content was identified as 27.20±1.19 (g/100g) for the MRA800 ice cream. Microwave roasting likely promotes more uniform moisture removal and preserves lipid distribution, contributing to the higher fat content and potentially enhancing texture and sensory acceptability (Hojjati et al., 2016; Wu et al., 2025). Many studies have demonstrated that the fat content of various nuts increases during the roasting process (Alasalvar et al., 2010; Ghafoor et al., 2020; Hojjati et al., 2016; Santos et al., 2018; Tu et al., 2021). Furthermore, Hojjati et al. (2016) indicated that the fat content of almonds roasted in a microwave was greater than that of almonds roasted in hot air. Atalar et al. (2021) and Bekiroglu et al. (2022) have declared that the total fat content of ice creams produced with hazelnut milk and walnut milk has increased. In a separate study, it was demonstrated that the total fat content of kefir samples produced with different nut milks was higher than that of the control (Gocer and Koptagel, 2023b).

### *3.2. Colour Properties*

One of the most crucial factors influencing consumer perception in new product development is colour (Bebek and Yangılar, 2025). Colour values of ice cream samples (cow's milk and almond milks) are presented in the *Table 2*. The control (cow's milk) and HRA150 ice cream samples exhibited the highest (83.91±4.09) and lowest (70.14±2.43) brightness values, respectively. As anticipated, as a consequence of the roasting process, the brightness values of ice cream samples obtained from roasted almond milk were found to be lower than those of raw almond milk and cow's milk ice cream samples ($P \leq 0.05$). Nevertheless, the brightness value of the MRA800 ice cream sample was found to be similar to that of the ice cream sample obtained from cow's milk and raw almond milk ($P > 0.05$). The brightness values obtained from hot air and microwave roasted almond milks were found to be similar, with the exception of MRA800. The reduction in the $L^*$values derived from roasted almond samples is attributable to the maillard reactions that occur during the roasting treatment (Hojjati et al., 2016).

The roasting process resulted in an increase in redness ($a^*$) and yellowness ($b^*$). The highest $a^*$(6.81±0.15) and $b^*$(20.91±0.56) values were determined for the HRA130 and HRA150 ice cream samples, respectively. Conversely, the lowest $a^*$(0.66±0.24) and $b^*$(8.71±0.50) values were recorded in cow's milk and raw almond milk ice cream samples, respectively. The application of distinct roasting techniques yielded disparate $a^*$and $b^*$values. The $a^*$and $b^*$values of the ice cream samples obtained from hot air-roasted almond samples were found to be higher than those of the ice cream samples obtained from microwave-roasted almond samples. These results are consistent with those of previous studies conducted by Hojjati et al. (2016), Agila and Barringer (2012) and Abdeldaiem et al. (2023). Hojjati et al. (2016) reported that the $L^*$value in almonds decreased and the $a^*$and $b^*$values increased as a result of the hot air and microwave roasting processes. Similarly, Agila and Barringer (2012) reported that the $L^*$ value of almonds decreased as a consequence of the microwave and hot air roasting processes. In a study, Abdeldaiem et al. (2023) used roasted corn powder as a milk fat substitute in ice cream production. The utilisation of roasted corn powder resulted in a reduction in the $L^*$values of ice cream samples, whereas it resulted in an increase in the $a^*$and $b^*$values of ice cream samples. This indicates that the roasting technique applied is an important factor in achieving the desired colour parameters in roasted products. Finally, the study demonstrated the significance of temperature-time (hot air roasting) and W-time (microwave roasting) relationships in achieving the desired colour values. The observed reduction in $L^*$ and increase in $a^*$ and $b^*$ values with roasting are consistent with changes reported for nuts roasted using both air fryer and microwave oven methods, where non-enzymatic browning (Maillard and caramelization) drives colour development during heat treatment (Ha et al., 2024; Hojjati et al., 2016; Agila and Barringer, 2012; Abdeldaiem et al., 2023).

### *3.3. Melting Characteristics*

The $T_{onset}$, $T_{peak}$ and $T_{end}$ values represent the temperatures at which melting commenced, reached its maximum and ended, respectively. The highest and lowest $T_{onset}$ values were determined to be -13.52±0.60 and -16.31±0.57 (ºC), respectively, for HRA100 and MRA800 (*Table 2*). The $T_{onset}$ values of ice creams produced from unroasted almonds and hot air-roasted almond milk were found to be higher than those of the control ice cream sample and microwave-roasted almond milk ice creams. The use of different roasting techniques in ice cream production was found to significantly affect the $T_{onset}$ values ($P \leq 0.05$). Although the $T_{onset}$ values of the microwave-roasted almond milk ice creams were more closely aligned with the $T_{onset}$ values of the control ice cream, they were lower than those observed in the hot air-roasted almond milk ice creams. The $T_{peak}$ and $T_{end}$ values of the ice cream samples exhibited a range of -0.35±0.55 to -1.21±0.79 and 4.53±1.47 to 6.01±0.00 (ºC), respectively. Nevertheless, no notable discrepancy was observed between the $T_{peak}$ and $T_{end}$ values of the ice cream samples ($P>0.05$). The Δh values of the ice cream samples exhibited a range between 129.80±5.79 and 147.95±4.74, (J/g). The highest and lowest Δh values were identified in ice cream samples produced using microwave-roasted almond milk (MRA600 and MRA800). The use of unroasted or roasted almond milk in the production of vegan ice cream did not result in a notable difference in the Δh value of the ice cream in comparison to the control. No regular decreasing or increasing trend was observed with increasing temperature in hot air roasting and with increasing W in microwave roasting. Bekiroglu et al. (2022) stated that although the $T_{onset}$, $T_{end}$ and Δh values of vegan walnut milk ice creams were lower than those of the control sample, there was no significant difference. The melting characteristics of ice cream are associated with various factors, including the ice crystal structure, the quantity of air incorporated, and the network of fat globules created during freezing (Muse and Hartel, 2004). Recent comprehensive evaluations have further emphasized that the structural organization of ice crystals, air cells, and fat destabilization governs structural collapse and melting stability in frozen desserts (Wu et al., 2025). In frozen dairy and non-dairy systems, Tonset is generally associated with the stability and distribution of ice crystals within the matrix, while Δh reflects the proportion of freezable water in the system (Goff and Hartel, 2012). Higher Δh values indicate a greater amount of frozen water, which may contribute to increased melting resistance; however, melting behavior is not solely governed by ice content but also by the structural organization of the fat and air phases. A well-developed fat destabilization network and stable air cell structure can mechanically restrict ice crystal mobility and delay meltdown (Sofjan and Hartel, 2004; Muse and Hartel, 2004). Therefore, the relatively similar Tpeak and Tend values among samples suggest that roasting treatments did not markedly alter the overall phase transition profile, whereas variations in Tonset may reflect differences in matrix interactions and water binding capacity induced by thermal processing of almond milk proteins. These findings highlight that melting stability in vegan ice cream systems results from complex phase interactions rather than solely from differences in thermal transition enthalpy.

***Table 2. Colour and melting properties of the ice cream samples produced with roasted and unroasted almond milks***

| Ice Cream Samples | Colour properties | | | Melting properties | | | |
|---|---|---|---|---|---|---|---|
| | $L^*$ | $a^*$ | $b^*$ | $T_{onset}$ (ºC) | $T_{peak}$ (ºC) | $T_{end}$ (ºC) | Δh (J/g) |
| URA | 81.67± 4.32$^{a}$ | 1.07±0.21$^{d}$ | 8.71±0.50$^{d}$ | -13.64±0.36$^{a}$ | -0.57±0.79$^{a}$ | 5.53±1.35$^{a}$ | 130.05±10.96$^{c}$ |
| HRA100 | 73.02±3.43$^{b,c}$ | 5.20±0.10$^{b}$ | 16.89±0.32$^{b}$ | -13.52±0.60$^{a}$ | -0.79±0.97$^{a}$ | 5.25±1.47$^{a}$ | 132.35±7.42$^{b,c}$ |
| HRA130 | 74.06±1.52$^{b,c}$ | 6.81±0.15$^{a}$ | 20.47±0.39$^{a}$ | -13.61±0.23$^{a}$ | -0.67±1.00$^{a}$ | 5.76±0.49$^{a}$ | 130.45±8.27$^{c}$ |
| HRA150 | 70.14±2.43$^{c}$ | 6.66±0.19$^{a}$ | 20.91±0.56$^{a}$ | -13.81±0.65$^{a}$ | -0.35±0.55$^{a}$ | 5.80±0.56$^{a}$ | 145.30±1.69$^{a,b}$ |
| MRA300 | 74.68±3.69$^{b}$ | 5.39±0.55$^{b}$ | 17.19±1.41$^{b}$ | -14.25±0.55$^{a}$ | -1.21±0.79$^{a}$ | 4.53±1.47$^{a}$ | 135.00±5.09$^{a,b,c}$ |
| MRA600 | 73.15±2.04$^{b,c}$ | 5.23±0.48$^{b}$ | 17.19±1.23$^{b}$ | -15.55±0.17$^{b}$ | -0.55±0.00$^{a}$ | 5.44±0.04$^{a}$ | 147.95±4.74$^{a}$ |
| MRA800 | 81.54±1.36$^{a}$ | 2.27±0.10$^{c}$ | 11.83±0.69$^{c}$ | -16.31±0.57$^{b}$ | -0.76±0.81$^{a}$ | 5.68±0.56$^{a}$ | 129.80±5.79$^{c}$ |
| Control | 83.91±4.09$^{a}$ | 0.66±0.24$^{d}$ | 10.57±1.47$^{c}$ | -15.60±0.10$^{b}$ | 0.48±0.37$^{a}$ | 6.01±0.00$^{a}$ | 135.20±0.84$^{a,b,c}$ |

### *3.4. Rheological Properties*

The shear rate of the ice cream mixes increased more than the shear stress, thus, all the mixes exhibited shear thinning flow behavior, which is considered to be the typical flow behavior for ice cream mixes (*Figure 2*). Shear thinning flow behaviour is an important factor in selecting the appropriate pump size for mixing.

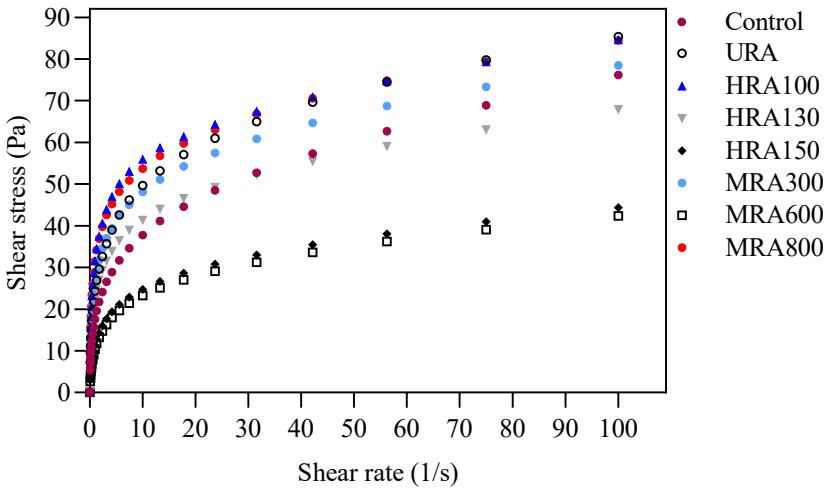



***Figure 2. Flow curve of the ice cream samples produced with roasted and unroasted almond milks***

The shear stress and shear rate data of the mixes were adapted to the Ostwald de Waele rheological model and the rheological parameters, K and n, were calculated (*Table 3*). Furthermore, the $R^2$ values of the mixes were calculated, and it was established that the $R^2$ values were greater than 0.96, which confirmed the suitability of the selected rheological model (Tekle et al., 2025). The K and n values of the mixes exhibited a range of 9.13±0.19–28.01±2.98 Pa.s and 0.27±0.00–0.37±0.00, respectively. Dairy products generally have an n value less than 1 and are characterized by shear thinning flow behaviour. The n values were found to be less than 1 for all ice cream mixes, indicating that they exhibit non-newtonian pseudoplastic flow behaviour. The MRA600 ice cream mix had the highest n value. The n values of the vegan ice cream mixes produced using almond milk and/or roasted almond milk were lower than control sample, with the exception of HRA150 and MRA600. Similarly, it was reported that the n values of hazelnut, walnut and almond milk ice creams were lower than the control sample (Atalar et al., 2021; Bekiroglu et al., 2022; Hidas et al., 2023). The consistency values of ice cream mixes were found to be significantly affected by both almond milk and the roasting process ($P \leq 0.05$). In contrast to the n values, the K values of the ice cream mixes, with the exception of HRA150 and MRA600, were found to be higher than that of the control sample. A reduction in K values was observed with an increase in temperature during the hot air roasting process. Nevertheless, a comparable correlation was not observed with increasing W during the microwave

roasting process. Similarly, it was reported that the K values of hazelnut, walnut and almond milk ice cream mixes were higher than the control (Atalar et al., 2021; Bekiroglu et al., 2022; Hidas et al., 2023). The rheological behaviour of the mixes is of significance for a number of reasons, including its impact on sensory acceptance, the efficacy of mixing and pumping processes, and the potential for reducing energy requirements (Kurt and Atalar, 2018).

***Table 3. Rheological and textural properties of the ice cream samples produced with roasted and unroasted almond milks***

| Ice Cream Samples | Rheological properties | | | Textural properties | |
|---|---|---|---|---|---|
| | *K* | *n* | $R^2$ | Hardness (g) | Adhesiveness |
| URA | 21.76±0.31$^{b,c}$ | 0.33±0.00$^{c}$ | 0.98 | 4818.96±5.69$^{b,c}$ | -5383.64±132.78$^{c}$ |
| HRA100 | 28.01±2.98$^{a}$ | 0.27±0.02$^{e}$ | 0.96 | 4580.21±218.36$^{d}$ | -5143.71±430.60$^{c}$ |
| HRA130 | 19.94±0.53$^{c}$ | 0.29±0.00$^{d}$ | 0.98 | 4902.37±3.49$^{b,c}$ | -4652.14±20.49$^{a,b}$ |
| HRA150 | 9.89±0.29$^{e}$ | 0.36±0.01$^{a,b}$ | 0.97 | 4152.09±82.14$^{e}$ | -4230.59±247.50$^{a}$ |
| MRA300 | 23.29±0.89$^{b}$ | 0.29±0.00$^{d}$ | 0.97 | 4782.92±33.55$^{c}$ | -5071.68±109.19$^{b,c}$ |
| MRA600 | 9.13±0.19$^{e}$ | 0.37±0.00$^{a}$ | 0.97 | 4448.76±19.52$^{d}$ | -4610.29±203.61$^{a,b}$ |
| MRA800 | 27.70±0.45$^{a}$ | 0.27±0.00$^{e}$ | 0.97 | 4981.03±14.37$^{b}$ | -5172.80±27.92$^{c}$ |
| Control | 16.12±0.03$^{d}$ | 0.35±0.00$^{b}$ | 0.99 | 5412.12±27.05$^{a}$ | -5288.36±105.65$^{c}$ |

### *3.5. Textural Properties*

The hardness values of the ice cream samples ranged from 5412.12±27.05 to 4152.09±82.14 g, as documented in *Table 3*, with the highest and lowest values observed in the control and HRA150 ice cream samples, respectively. Incorporation of almond milk in vegan ice cream production and the application of roasting processes significantly influenced hardness ($P \leq 0.05$). Specifically, hot air roasting at 150 ºC caused a notable decrease in hardness, whereas microwave roasting at 800 W increased hardness. No consistent trend was observed with incremental increases in roasting temperature or microwave power. The primary factors affecting ice cream hardness include overrun, ice crystal size, ice phase bulk, and the degree of fat destabilization (Muse and Hartel, 2004).

The observed reduction in hardness for ice creams produced with hot air-roasted almonds (e.g., HRA150) is consistent with moisture loss during roasting, which softens the ice cream matrix (Hojjati et al., 2016). Conversely, the increased hardness in MRA800 aligns with sensory panel evaluations, where these samples were perceived as firmer and more structured. These results indicate that roasting not only modifies rheological properties but also directly affects perceived texture, emphasizing the interplay between physicochemical changes and sensory acceptability. Previous studies on nut-based ice creams and functional yoghurts support these observations, showing variable hardness depending on nut type, concentration, and roasting method (Atalar et al., 2021; Hidas et al., 2023; Ozturkoglu-Budak et al., 2016). Furthermore, adhesiveness values ranged from -4230.59±247.50 to -5383.64±132.78, with higher adhesiveness detected in ice creams produced from roasted almond milk, reflecting increased interactions within the ice cream matrix. Overall, these findings demonstrate that roasting technique and intensity play a critical role in modulating both mechanical and sensory properties of almond milk-based ice creams.

### *3.6. Sensory Evaluation*

The sensory evaluation was conducted, with consideration given to the following parameters: appearance, odour, taste, melting quality, burnt taste, mouthfeel and general acceptability (*Figure 3*). The appearance values of the ice creams produced with almond milk and roasted almond milk were scored with lower scores compared to control. No notable differences were observed in the odour and mouthfeel characteristics of the ice cream samples in comparison to the control ($P > 0.05$). In terms of taste, the URA, HRA100 and MRA800 were assigned lower scores ($P \leq 0.05$). With regard to the melting quality, only URA was assigned a significantly lower score ($P \leq 0.05$). High burnt taste scores (e.g., 4 or 5) indicate no burnt taste is felt, while low scores (e.g., 1 or 2) suggest

a strong burnt taste is felt. In this regard, the panelists did not detect a burnt taste in URA and MRA800 ice creams, which received scores similar to the control sample (P>0.05). The utilisation of unroasted almond milk or roasted almond milk in the production of ice cream has been affected the general acceptability scores. The control ice cream sample was scored with the highest score in terms of general acceptability, followed by MRA800 and MRA600 (P>0.05). The ice cream samples produced from unroasted almond milk and hot air-roasted almond milk were evaluated with the lowest scores (P≤0.05). However, the ice cream samples produced from almond milk roasted using the microwave roasting method were rated more highly by the panelists. The low scores awarded to hot air-roasted almond milk ice creams can be attributed to the formation of a burnt taste during the roasting process. Finally, the findings of this study indicated that the roasting process is a significant factor influencing the sensory evaluation of the ice creams, and ice cream samples produced with microwave-roasted almonds were rated more favourably. Chemical changes, such as lipid oxidation and the Maillard reaction, that occur during the roasting process affect the taste and texture of the products, and also cause the formation of various aroma compounds (Adelina et al., 2024). When the instrumental findings were evaluated together with the sensory results, a consistent relationship between textural measurements and perceived attributes was observed. The lower hardness values of almond milk-based ice creams compared to the control sample were not reflected as significant differences in mouthfeel perception (P>0.05), suggesting that the reduction in instrumental firmness remained within the sensory discrimination threshold. Similarly, samples exhibiting lower consistency index (K) values, such as HRA150 and MRA600, did not demonstrate inferior sensory mouthfeel scores, indicating that moderate variations in flow behaviour did not negatively affect consumer perception. On the other hand, despite some samples (e.g., MRA800) presenting relatively high hardness and consistency values, their general acceptability scores were comparable to the control, suggesting that flavour development and aroma formation during microwave roasting may have compensated for textural differences. These findings demonstrate that while rheological and textural parameters provide objective indicators of structural properties, sensory perception is governed by a complex interaction of texture, flavour, and melting characteristics.

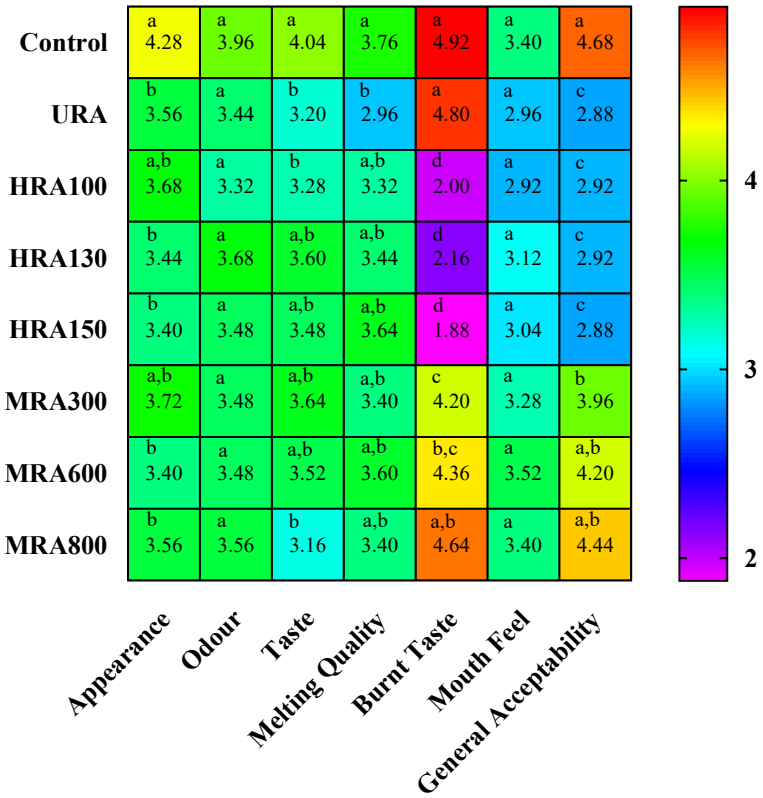



***Figure 3. Results of sensory evaluation of the ice cream samples produced with roasted and unroasted almond milks***

## 4. Conclusions

The roasting process induces substantial alterations in the colour, texture and sensory characteristics of foods. The roasting process is particularly applicable to nuts. In this study, hot air (different degrees and durations) and microwave (different W and durations) roasting methods applied to fresh almonds and obtained milk to produce vegan ice cream. A notable increase was observed in the total fat content of ice creams produced from roasted almonds. Furthermore, the brightness values of ice creams produced from roasted almonds exhibited notable alterations. The roasting process had a notable impact on the rheological and textural properties of the ice creams. Furthermore, it was indicated that ice creams produced from almonds roasted using hot air had a burnt taste, whereas those produced using a microwave roasting method were rated more favourably by the panelists. The findings of this study demonstrated that temperature and W were pivotal parameters in hot air and microwave roasting methods, with ice creams produced with microwave being nearly identical to the control.

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**Ethical Statement**

There is no need to obtain permission from the ethics committee for this study.

**Conflicts of Interest**

We declare that there is no conflict of interest between us as the article authors.

**Authorship Contribution Statement**

Concept: Agan Saricicek, C., Gunden, S., Duman, N., Goktas, H., Bekiroglu, H., Kasapoglu, M. Z., Sagdic, O.; Design: Agan Saricicek, C., Gunden, S., Duman, N., Goktas, H., Bekiroglu, H.; Data Collection or Processing: Agan Saricicek, C., Gunden, S., Duman, N., Goktas, H., Bekiroglu, H.; Statistical Analyses: Goktas, H.; Literature Search: Agan Saricicek, C., Goktas, H. Bekiroglu, H.; Writing, Review and Editing: Agan Saricicek, C., Goktas, H. Bekiroglu, H.

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